CHANGES IN LONG TERM VARIABILITY OF THE RAINS OF SUDAN

RUARI IAN RHODES

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A dissertation submitted in partial fulfilment of the requirement for the degree of

MSc Applied Meteorology

13th August 2012

Abstract

Several recent studies have indicated a marked decline in the rains of East Africa in recent decades, associated with modifications to the zonal circulation patterns of the tropics caused by changes in sea surface temperatures. Recent research has focussed primarily on equatorial regions of east Africa; however the rainy season generated by the passage of the Inter-tropical Convergence Zone penetrates as far north as the Sahel, influencing a region which experiences extreme water stress. Changes in rainfall patterns in this region may have severe consequences concerning the livelihoods of local populations, and it is vital that rainfall variability is accurately documented and predicted to avoid future humanitarian crises.

Sudan was chosen as a case study for analysis. This region spans a variety of climates, and a large portion of the region is accounted for by semi-arid Sahel where water stress is at its highest. Several studies have suggested a recent decline in rainfall in this region. A relatively dense, long running network of rain gauge data is available for this region, which was used in conjunction with the newly released TARCAT African rainfall climatology dataset to determine past variation in rainfall. This data was compared with previous studies to determine the extent of long term variability in rainfall in the Sudan together with likely driving mechanisms behind rainfall in the region. Rainfall over Sudan was found to have declined from 1960-80, with a previously undocumented recovery from 1980-2011.

Data from the NCEP 40 year reanalysis project was correlated against a time series of rainfall over Sudan derived from TARCAT, and anomalies in a number of variables were analysed during exceptional years in terms of rainfall in the Sudan. Rainfall was found to be associated with the strength and humidity of low level circulations, in addition to the positioning of the upper level tropical easterly jet. Sea surface temperatures in the Atlantic, Indian Ocean and Mediterranean were found to be strongly associated with rainfall in Sudan, suggesting a degree of predictability in the rainfall based on sea surface temperature.

Trends in these variables were analysed, with the conclusion that many variables have changed in recent years to produce more favourable conditions for rainfall in this region. This recent shift to a favourable state relates well to studies in global circulation models which indicate a potential increase in precipitation over north-eastern Africa under anthropogenic climate warming.

Abbreviations

AR4	Assessment Review 4 (IPCC)
CCD	Cold Cloud Duration
EEA	Equatorial East Africa
ENSO	El Niño Southern Oscillation
ESRL PSD	Earth Systems Research Laboratory; Physical Science Division
GCM	General Circulation Model
GCOS	Global Climate Observing System
GHCN	Global Historical Climatology Network
GSN	GCOS Surface Network
HadISST	Hadley Centre Sea Ice and Sea Surface Temperature
IPCC	Intergovernmental Panel on Climate Change
ITCZ	Inter-Tropical Convergence Zone
JJAS	June, July, August & September
LOWESS	Locally Weighted Scatter-plot Smoothing
MAMJ	March, April, May & June
MJO	Madden-Julian Oscillation
MSLP	Mean Sea Level Pressure
NAO	North Atlantic Oscillation
NCDC	National Climatic Data Centre
NCEP	National Centre for Environmental Prediction
NOAA	National Oceanographic and Atmospheric Administration
PCA	Principle Component Analysis
SJ	Somali Jet
SON	September, October & November
SST	Sea Surface Temperature
TAMSAT	Tropical Applications of Meteorology using Satellite data
TARCAT	TAMSAT African Rainfall Climatology and Time-series
TIR	Thermal Infra-Red
WAM	West African Monsoon
WAWJ	West African Westerly Jet
WMO	World Meteorological Organisation

Acknowledgements

I would like to thank a number of people whose support in various forms has made this dissertation and Masters' degree possible.

My supervisors, Ros Cornforth and Emily Black have supported me through their tireless work in developing this project with me despite their busy schedules, and have been a source of inspiration with their enthusiasm for African meteorology.

Thanks go also to my family, whose encouragement led me to the decision to study for this degree, and whose support throughout this intense process has been invaluable.

Finally, thank you to all of my friends who have made this an amazing year.

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Foreword: Unless otherwise specified, "Sudan" hereafter refers to the geographical area covered by the Republic of the Sudan and the Republic of South Sudan, and referenced by the World Meteorological Organisation as "Sudan". Where it is necessary to refer to the two countries according to their current political boundaries, the terms "Sudan (Rep.)" and "South Sudan" will be used. Due to recent political developments in this region and the formation of South Sudan as an independent state in July 2011, some graphics may reflect outdated or disputed political boundaries.

1 Introduction

Rainfall is commonly regarded to be the most important meteorological variable throughout the African nations, especially in regions straddling the Sahel, a semi-arid region lying to the south of the Sahara desert. Following several extended periods of drought in East Africa and the Sahel over the last century where the rainy season failed to initiate fully, there is an increased interest from many parties as to whether there are any long term trends reflected in more frequent drought conditions.

Agriculture in the southern regions of Sudan is heavily rainfall dependent and is vital for supporting the livelihoods of the local population (Mattsson & Rapp 1991). Given the limited economic resources of the region, it is essential that any projected changes in rainfall are determined with a sufficient lead time to allow the people affected to adapt their agricultural practices appropriately. This is particularly necessary in the northern reaches of viability of rain-fed agriculture, as the productivity of un-irrigated land varies heavily with the availability of rainfall, and in the long term land may be rendered permanently unsuitable for cultivation through the process of desertification, exacerbated by long periods of drought. Rain fed agriculture dominates South Sudan, with agriculture transferring predominantly to a fully irrigated system between 10-12°N in the semi-arid Sahel of southern Sudan (Rep.), limiting agriculture to the vicinity of permanent water sources in the majority of Sudan (Rep.) (Dawelbeit et al. 2010). This lessens the dependence of agriculture on rainfall; however water stress persists for a number of other uses.

Long running political tension in the region exacerbates the problems associated with water stress, and likewise it is believed that water stress can aggravate political strife. Kevane and Gray (2008) note several theories associating drought and long term declining trends in rainfall availability with raised levels of aggression throughout African countries, whilst the 2003 Darfur conflict in Sudan is cited as a case study of conflict exacerbated by the limited water resources available.

Rainfall in most of east Africa has a bi-modal seasonal cycle, with the majority of precipitation accumulating during the “Long Rains” of the boreal spring (MAMJ) as the inter-tropical convergence zone (ITCZ) moves northward. A less intense but more thoroughly researched rainy season occurs in the autumn (SON) as the ITCZ returns to the south (see Figure 1[b]). The short rains show good correlation with the El Niño Southern Oscillation (ENSO) signal, allowing for a significant degree of predictability and early warning for drought conditions (Janicot et al. 1996; Schreck & Semazzi 2004). However, the long rains are relatively poorly researched and have demonstrated little correlation with ENSO in several studies (Camberlin & Okoola 2003; Lyon & DeWitt 2012). Sudan is an exceptional case in that it straddles the northernmost extent of the ITCZ travel, leading to a range of seasonal rainfall cycles varying by latitude (Figure 2) and an approximately meridional gradient in rainfall volume (Figure 3). The manner in which the ITCZ changes direction over Sudan results in a mono-modal rainy season for most of the region (Figure 1[a]), since rainfall is not brought about by the distinct northerly and southerly advance of the ITCZ but rather by a stationary period in its cycle. Studies of rainfall in parts of East Africa experiencing distinct rainy seasons in boreal spring and autumn may not be applicable to the single rainy season of Sudan in boreal summer.

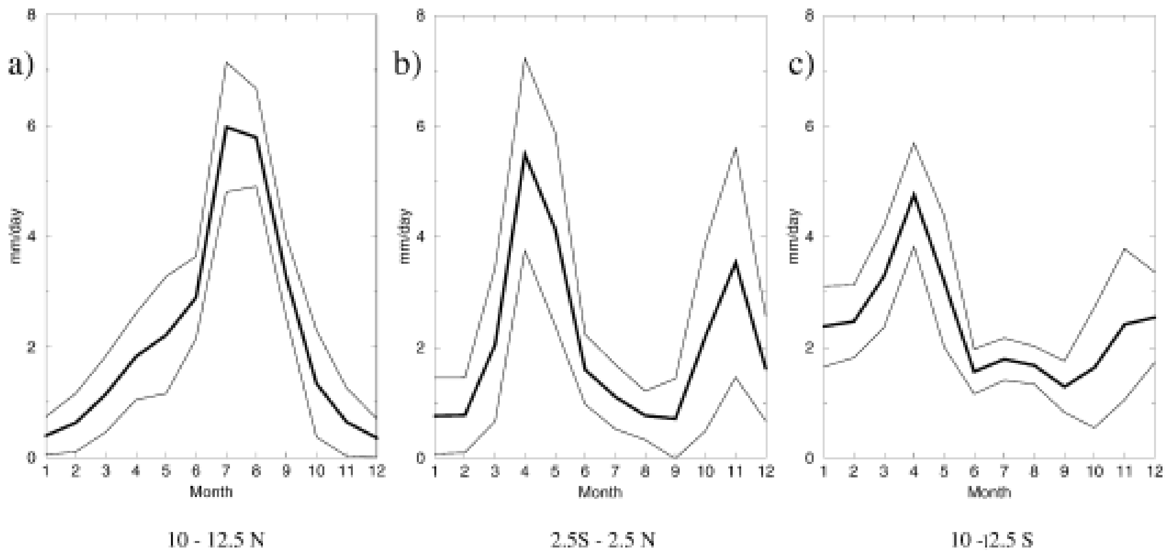


Figure 1: East African seasonal rainfall cycle averaged between 37.58 - 41.258E for [a] northern (10.8–12.58N) [b] equatorial (2.58S–2.58N) [c] southern (10.8–12.58S) latitudes. Sudan lies approximately between 4-23N Thick line denotes the climatological mean, and the thin lines show one standard deviation of the interannual variability. From Black et al (2003) Figure 1.

Current research into east African rainfall trends and teleconnections tends to focus on equatorial east Africa (EEA) and the highlands of Ethiopia, with little research having been conducted in and around Sudan. Several theories have been proposed for projected trends in lower latitude regions of east Africa, ranging from a projected rainfall increase (Boko et al. 2007) to a projected decrease (Williams & Funk 2011), and with hypothesised teleconnections including the El Niño Southern Oscillation (ENSO) (Janicot et al. 1996; Schreck & Semazzi 2004), Indian and Atlantic Ocean sea surface temperatures (SST's) (Williams & Funk 2011) and variability in the Asian monsoon circulation (Cook et al. 2012; Rodwell & Hoskins 1996). However, the rains of Sudan are a vital yet under researched topic. From a meteorological perspective, Sudan's latitudes mark the transition of the east African rains from a bi-modal system to an annual rainy season associated with the northernmost extent of ITCZ movement. Any changes in intensity or seasonality of the rainy season at this latitude must reflect on the intensity or timing of the ITCZ (Fontaine et al. 2011), affecting the rest of East Africa. Therefore determining controls and teleconnections in this region may prove vital in projecting both the long- and short-rains of EEA.

The opportunity now exists to address this research gap. This research project is largely motivated by the findings of Lyon & DeWitt (2012), who indicate that the rainfall in EEA has undergone a rapid, significant decline since approximately 1990. The motivation of this project is to analyse to what extent these findings impact on Sudan, which lies on the northern and western edge of the region considered by the aforementioned study. Zhang et al (2011) focussed on Sudan, finding a reduction in annual rainfall totals in the latter half of the 20th century. This project will first analyse recent trends in rainfall in Sudan in order to investigate the extent to which Sudanese rainfall correlates with rainfall in EEA and with the findings of Zhang et al (2011), before considering the factors which influence Sudanese rainfall and the mechanisms by which this occurs. The project will be aided by the use of the recently released TAMSAT African Rainfall Climatology and Time Series (TARCAT) dataset, which for the first time provides consistent monthly climatological rainfall data over Africa for a thirty-one year period (1981-2012) based on ground-calibrated Meteosat observations (Grimes et al. 1999).

This project will investigate the current literature in order to determine a consensus on patterns in rainfall variability and on the controlling factors in the East African region, before discussing in more detail the climate of Sudan. Following this, independent analysis will be developed demonstrating the variability in the rains of Sudan, utilising both the GHCN and TARCAT datasets. The resulting rainfall time series from TARCAT will be analysed against SST, MSLP, geopotential height, zonal and vertical winds through the use of correlation and composite analysis, before investigating any trends in these variables which may impact on rainfall in Sudan.

2 Climate of Sudan

The far south of Sudan experiences some aspects of the bimodal rainfall regime experienced in equatorial east Africa (albeit with less clearly defined modes), whilst the centre of the region is affected by a single rainy season as the ITCZ reaches the far north of its travel (see Figure 2 The northern region of Sudan is predominantly arid year round, however regions close to the Red Sea coast, such as Port Sudan (Figure 2) experience some rainfall in the boreal winter. This rainfall associated with northerly winds from the Arabian Peninsula, advecting moisture from the Red Sea during the boreal winter and spring (Kassas 1957). This is likely a localised effect and unrelated to the ITCZ movement associated with the rainy season in other regions of Sudan. As discussed in section 1, the main Sudan rainy season can be attributed to the turning point of the ITCZ dividing the long- and short rains of the lower latitudes of east Africa. Changes in this "turning point" may prove to have implications for regions in lower latitudes; for example modifications to the ITCZ structure as it begins to move southward from Sudan may affect the short rains (SON) of countries in the EEA region.

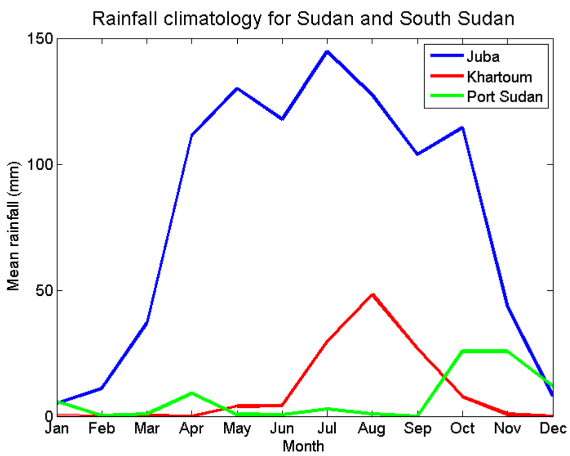


Figure 2: Climatology for selected stations in Sudan: mean monthly rainfall totals over all years where station data was available. Station locations as highlighted in Figure 3. Data from NOAA NCDC (2012)

Sudan's climate is affected by relatively little topography, being mainly comprised of flat plains with isolated clusters of mountains, and bordered by mountain ranges to the south, east and west (Metz 1991). The smooth nature of the terrain means that localised influences are minimised unlike neighbouring Ethiopia where extremely high spatial variation in rainfall is noted due to the complex orography (Gissila et al. 2004).

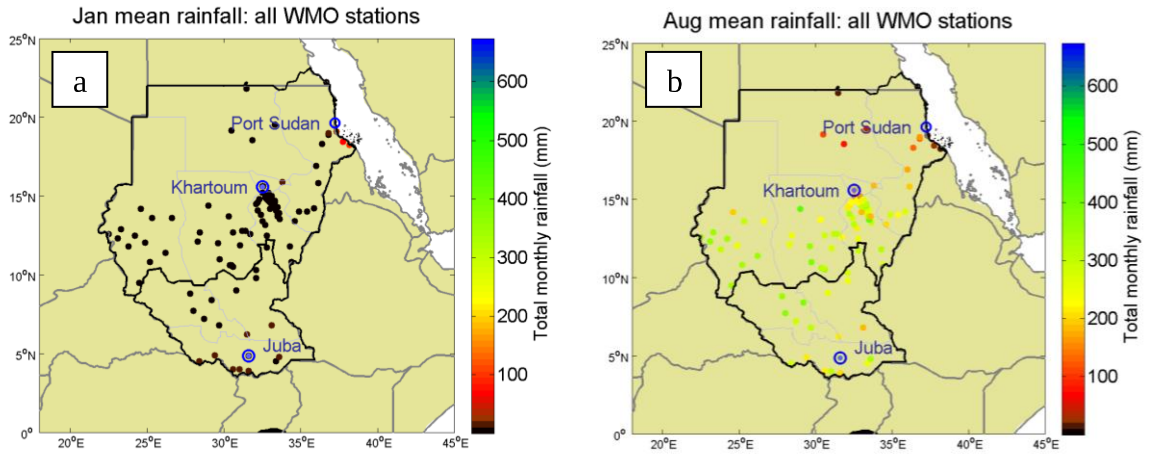


Figure 3: Rain gauge stations as recorded in the GHCN: representative months during January and August (left and right respectively). Stations are coloured according to mean total rainfall volume recorded during the month. Note localised influence of Red Sea systems in January. Data from NOAA NCDC (2012)

Figure 3 demonstrates the contrast in observed long term climatological rainfall as recorded by WMO monitored raingauge stations in the Global Historical Climatology Network (GHCN). Figure 3[a] shows stations colour-coded by their mean January totals. Very little rainfall is recorded during January, with the exception of stations on the Red Sea coast where localised weather systems from the Red Sea and the Mediterranean influence the rainfall total in the winter months (Metz 1991). Figure 3[b] represents August; this is the peak of the rainy season throughout the majority of Sudan, with upwards of 200 mm/month falling as far north as Khartoum, and some increases in rainfall reaching as far north as the Sudan-Egypt border.

Figure 2 demonstrates the three broad categories of rainfall regime seen in Sudan. Juba, in South Sudan, demonstrates some of the modality observed in equatorial regions, with visible peaks in May and August surrounding the main rainy season which peaks in July. These peaks are indicative of the movement of the ITCZ throughout the year; however in areas with discernible “long” and “short” rains further to the south a trough would be evident clearly defining the two rainy seasons.

Khartoum’s observations are consistent with most central and northern regions; arid for much of the year, with the exception of a peak from June to September. The onset of the rainy season tends to be more gradual than the withdrawal, which occurs rapidly throughout

September. By November the rains have entirely retreated from northern and central regions, whilst the south experiences its rainfall minimum between December and January.

Port Sudan shows a pattern common to the Red Sea coast, whereby the peak rains occur in November as a result of weather systems developing as a result of Red Sea Troughs (Krichak et al. 1997). These systems only affect localised coastal regions and are unrelated to the ITCZ-related rainy season further south, and therefore lie beyond the focus of this research project.

This chapter has outlined the main features of rainfall climatology and variability in Sudan. The following chapter will put this into the context of variability in the wider East African region, whilst considering more focussed studies in the literature concerning precipitation in Sudan and East Africa. Atmospheric circulation patterns throughout the tropics will be considered, with a focus on key circulations in the vicinity of Africa and on any controls or projected modifications to these circulations.

3 Current literature and theories: East African rainfall and tropical circulation patterns

As mentioned in section 1, the majority of current research focuses on equatorial east Africa (EEA), which has undergone a well documented decline in total rainfall in recent years (Hulme et al. 2001; Lyon & DeWitt 2012; Schreck & Semazzi 2004). Sudan is influenced by many of the same systems as EEA, and in particular the rainy season in Sudan is caused by, and moderated by the intensity of, the meridional travel of the ITCZ. Any reduction in rainfall throughout EEA would indicate a reduction in the intensity of the ITCZ as it passes across the region, or an alteration in the timing of the ITCZ, directly influencing Sudan at the northernmost point of the ITCZ travel. However, Sudan is an under-represented region in the literature with notably different rainfall climatology to EEA, and thus warrants separate investigation. In this chapter the accepted mechanisms governing atmospheric circulation (including wind intensity, location and direction along with moisture advection and convergence/divergence) will be discussed, followed by an analysis of recent theories and speculations on potential changes in circulation mechanisms under climate change.

The majority of African rainfall is associated with mesoscale convective systems (Mohr et al. 1999); however precipitation is strongly moderated by local influences such as moisture availability and diurnal heating. Most theories for anomalies and trends in rainfall centre around features which will alter the intensity of convective activity. In particular, these theories tend to look for mechanisms causing anomalous vertical wind ("omega"), moisture advection, and convergence / divergence at various pressure levels. The interaction of jets and prominent wind flows tends to be highly important to these theories, since wind direction, moisture advection and interaction between flows has the potential to significantly affect the intensity of convective activity (Hulme & Tosdevin 1989; Stensrud 1996). As with all tropical regions, sea surface temperatures and their gradients can have a large impact on circulation patterns, and thus convection, throughout tropical Africa (e.g. Rowell et al 2003, Williams & Funk 2011).

3.1 Observed trends in east African rainfall

3.1.1 Reduction in March - June rainfall

Several studies have been published recently which demonstrate an observed decline in the long rains (MAMJ) of EEA (Funk et al. 2008; Lyon & DeWitt 2012; Williams & Funk 2011).

Lyon and Dewitt (2012) demonstrated negative precipitation anomalies throughout East Africa, with the decline beginning abruptly around 1990. The study correlated rainfall across East Africa (defined as 10°S-12°N, 30°E-52°E) with SST's in the Indian and Pacific Oceans, finding a positive correlation with Indian Ocean SST's and a negative correlation with west Pacific SST's (Figure 4[a]). However, this study demonstrates considerably stronger teleconnections with SST changes in the tropical Pacific than previous research (such as Williams & Funk 2011). The authors note that the recent warming in the Pacific (since the late 1990s) is not representative of modifications to ENSO, although they leave room for further investigation regarding the origins of this SST increase. The findings of this study are a key motivation for this project; in particular it is interesting to relate the observed changes in the MAMJ rainy season of EEA to the JJAS rainy season of Sudan and other northern areas of East Africa.

Figure 4[b] (taken from Lyon & DeWitt 2012, Figure 1) indicates a clear anomaly in the atmospheric circulation over East Africa during the dry years in EEA from 1999 – 2009. Enhanced low-level northerlies are evident over Sudan, and the Somali Jet appears to be strengthened in these years. The authors note particularly that there is a large scale anomalous precipitation pattern evident throughout the tropics for dry years in EEA, with a dry central- and southern- Indian Ocean and a wet western Pacific and northern Indian Ocean.

Whilst this article forms much of the motivation behind this research project, it should be noted that Lyon and Dewitt (2012) are investigating a rainy season which differs both spatially and temporally to that experienced in Sudan, which lies to the north-west of the EEA study area presented here and experiences a later, mono-modal wet season. This introduces the question: to what extent do the mechanisms presented by Lyon and DeWitt (2012) affect rainfall in Sudan? And what other influences are Sudanese rainfall subject to? The analysis presented later in this study will attempt to investigate the level of coherence applicable between EEA and Sudan, whilst suggesting further mechanisms that may be responsible for any alterations in Sudan's rainfall.

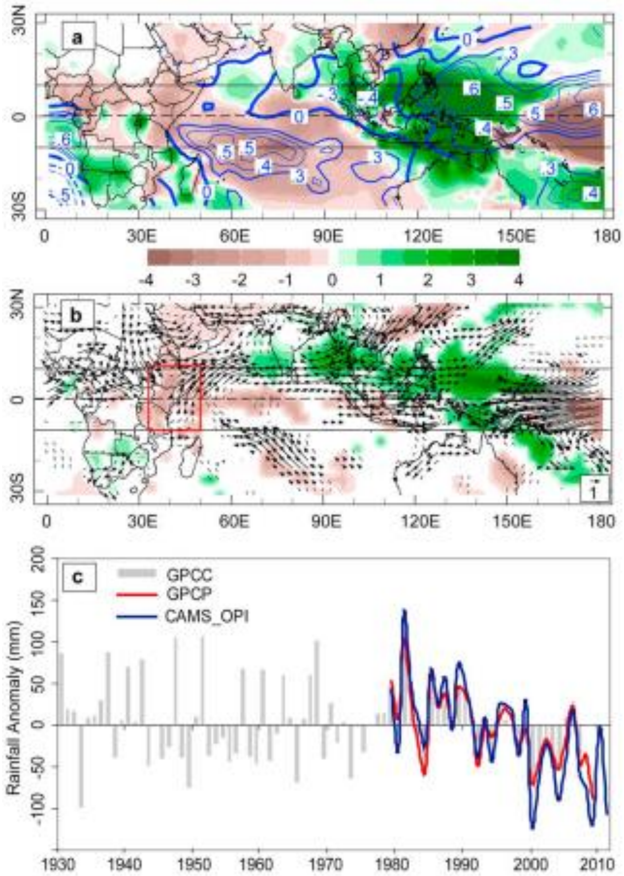


Figure 4: From top: [a] Precipitation anomalies during MAM 2011 from the CAMSOPI dataset (shaded), correlation between MAM GPCP rainfall and ERSST SST anomalies (contours). [b] 1999-200 anomalies in rainfall during MAM, and vector wind anomalies (significance p < 0.10). [c] MAM precipitation anomaly relative to 1979-2010 average over East Africa as defined in section 3.1.1. Figures from Lyon & Dewitt (2012) figure 1.

3.1.2 Intensifying dipole rainfall pattern under climate change

The IPCC AR4 report on East African rainfall projections indicates an expected amplification of a rainfall variability dipole pattern whereby rainfall should increase in the northern regions of East Africa (including Sudan) and decrease in southern regions (Boko et al. 2007). The report notes that the short rains (SON) of EEA are expected to increase due to an expected increase in El Niño events, whilst much uncertainty remains in the long rains (MAMJ). However, this report also notes a lack of robustness in the main general circulation models' (GCMs') representation of rainfall in the Sahel (Biasutti et al. 2008). This is a critical region in terms of water stress for the local population, as well as being extremely susceptible to the effects of desertification (Warner 2004), which may itself influence climate change (Paeth et al. 2009).

It is acknowledged by several authors that GCMs currently tend to overestimate the response of the eastern Pacific to anthropogenic forcing, leading to an "El Niño" like state which may prove to be anomalous when compared to observations (Cane et al. 1997; Hoerling et al. 2010). In addition to the misrepresentation of the dominant forcing throughout the tropics, GCMs may misrepresent the response to this forcing through teleconnections, and convective parameterisation schemes may prove to be inaccurate (Randall et al. 2007). In general, GCMs are sensitive to inaccuracies in the representation of physical processes, poor quality or insufficient observations, and by the difficulties in representing the interactions between mechanisms of varying scales. In order to assess and improve such models, it is important to improve the understanding of the mechanisms responsible for causing precipitation, which may vary significantly over localised areas.

3.1.3 Studies specific to Sudan

As mentioned previously, rainfall in Sudan is underrepresented in the literature, and particularly little analysis has been performed in recent decades where it has been possible to utilise satellite derived time-series. Much of the more in depth literature focussing on Sudan presently dates prior to the early 1990's, leaving much scope for updated analysis of the situation in this region.

Trilsbach and Hulme (1984) provided an analysis of rainfall in central Sudan (12-16°N with a particular focus on the region around Khartoum and the confluence of the White and Blue Niles). This study had strong leanings towards the civil impacts of fluctuations in rainfall, but noted the presence of "dry" and "wet" spells lasting a number of years. However, statistical analysis indicated that these spells could be caused by simple random fluctuations as opposed to forcings acting on an interannual – decadal time scale. The authors conclude that at the time of publication there was no statistical trend in rainfall.

Hulme (1990) provides a study of rainfall data from gauges beginning in 1900, concluding that severe reduction in rainfall was evident in the semi-arid central latitudes of Sudan, associated with a shortening of the rainy season. The study attributes the reduction in rainfall to a decrease in frequency of rainfall events rather than a reduction in the intensity of individual events.

Mattsson and Rapp (1991) conducted a study into the periods of droughts affecting Sudan and Ethiopia in 1968-73, 1979-84 and 1990-91, noting associations between northern East African droughts and weakened sea currents in the Atlantic and Indian Oceans, and high SST abnormalities in the eastern Pacific and Gulf of Guinea.

In one of the more recent papers directly investigating Sudanese rainfall, Zhang et al. (2011) analysed a reconstruction of the precipitation over Sudan using data from NCEP Precipitation Reconstruction (PREC) between 1948 and 2005. The authors note abrupt changes to annual and peak season precipitation during the late 1960's, and a significant decrease in rainfall in central Sudan during the entire period analysed. In particular, this study indicates a maximal decline in precipitation during August, particularly in central Sudan.

3.2 Atmospheric dynamics

3.2.1 Walker & Hadley circulations and the El Niño Southern Oscillation

The broad scale Walker and Hadley circulations determine much of the large scale atmospheric circulation in the tropics. The Walker circulation (Figure 5), in particular, appears regularly in the current literature concerning long term trends in precipitation in east Africa (e.g. Schreck and Semazzi 2004, Williams and Funk 2011). The Walker cell is a large scale zonal circulation evident particularly over the tropical Pacific as a result of the SST gradients found in the equatorial Pacific Ocean. The classical view of the Walker circulation in a "normal" state (i.e. ENSO in a "neutral" phase, Figure 5[a]) is that of an ascending branch bringing convection over the Maritime Continent, with large scale descent over the eastern Pacific and central Indian Ocean. Under El Niño conditions (Figure 5[b]), ascent and convection moves eastward to the central Pacific, ultimately altering the dynamics of the circulation over Africa (McIlveen 1998). This is associated with an increase in rainfall in EEA, however it is believed that En Niño conditions may suppress convection in more northerly regions such as Sudan (Boko et al. 2007).

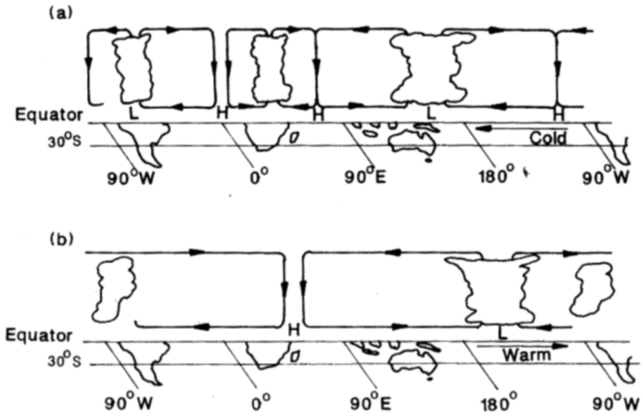


Figure 5: Walker circulation in cross section along the equator. (a) normal circulation (b) El Nino mode. From McIlveen (1998) figure 12.16.

The Walker circulation has been studied extensively owing to its fundamental role in driving weather systems in the tropics, particularly with respect to the effects of ENSO, a major source of inter-annual variability. Current literature is conflicted as to whether the Walker circulation should increase or decrease in intensity with a projected increase in mean SST's in the Indian and Pacific oceans. Two main theories are proposed; an intuitive theory states that as the SST increases so does the zonal SST gradient. The literature repeatedly demonstrates this increasing gradient (Cane et al. 1997; Compo & Sardeshmukh 2010), combined with an overall increase in tropical mean sea surface temperatures (Cane et al. 1997; Deser et al. 2010). Acknowledging that the gradient is on average increasing, an enhanced MSLP dipole is generated and zonal winds must increase accordingly. Observational evidence exists to support a strengthening of the Walker circulation over recent years, i.e. the study by Chen et al (2002) based on satellite observations of reflected and emitted radiation over tropical regions. An alternative theory on the impact of Indian Ocean SSTs is proposed by Chung & Ramanathan (2006), proposing that changes to the Indian Ocean SST gradient will weaken the westerly component of the monsoon circulation, drying India but providing more moisture to sub-Saharan Africa.

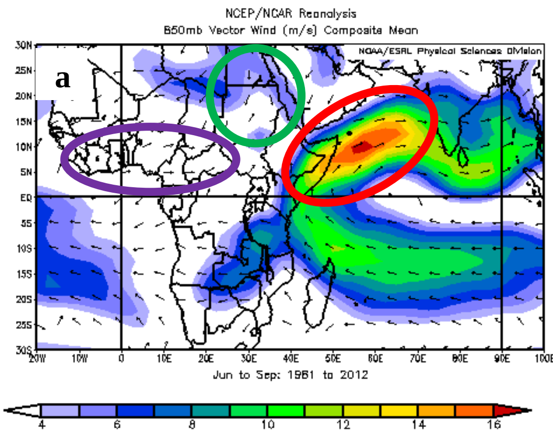
However, a counter-theory is proposed by a number of authors whereby an exponential increase in atmospheric water vapour must accompany any increase in SST according to the Clausius-Clapeyron rule. This leads to diabatic heating aloft and a more stable tropical atmosphere. The associated decrease in vertical transport is proposed to weaken the Walker circulation, regardless of pressure gradients at the surface level (Chou & Chen 2010; Deser et al. 2010; Vecchi & Soden 2007; Vecchi et al. 2006). This weakening of the tropical circulations is indicated by IPCC based on results from all models concerned (Vecchi &

Soden 2007). This weakening is also believed to have been observed based on records of MSLP from the Indo-Pacific region (Vecchi et al. 2006).

The IPCC AR4 indicates a projected increase in ENSO toward more warm, “El Niño” like events under anthropogenic forcing., which would likely impact on East African rainfall as noted in section 1. However, this has been disputed (i.e. Williams & Funk 2011), on the basis that GCMs are known to overestimate warming in the eastern Pacific.

3.2.2 Jets: Somali, African Easterly, Tropical Easterly and West African Westerly

Sudan is influenced by a number of climatological circulation features, and is affected by systems which would usually be associated with eastern, northern or western regions of Africa due to its location within Africa. Figure 6 demonstrates the main circulation features during JJAS over Africa. Several important features are visible.



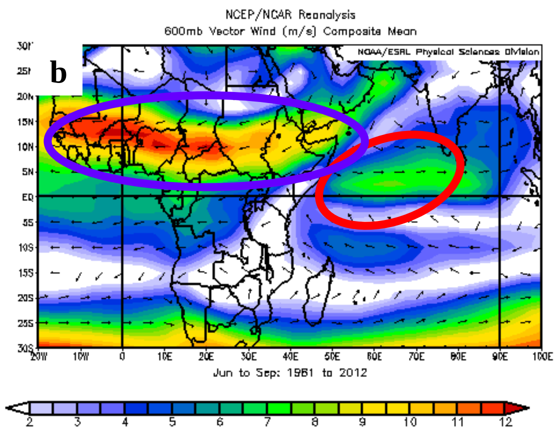
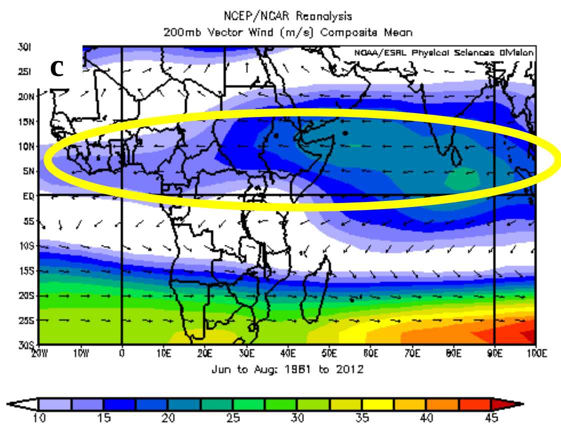


Figure 6: Mean JJAS vector winds in the African region. Clockwise from top left: [a] 850 mb showing WAM westerly circulation (purple), northerly trade winds (green), SJ (red). [b] 600 mb showing AEJ (purple), high altitude extent of SJ (red). [c] 200 mb showing TEJ (yellow). Shading indicates wind speed in ms^{-1}. From NCEP 40-year reanalysis (NOAA ESRL PSD 2012a)



In Figure 6[a], the dominant flow at 850 hPa (circled in red) is the Somali Jet (SJ). This cross-equatorial flow is vital for moisture transport from the Indian Ocean to the East African region. The purple circle indicates the West African Monsoon (WAM) circulation; whilst not particularly prominent on this image, this low level westerly flow incorporates the West African Westerly Jet (WAWJ), and is responsible for transporting moisture from the Atlantic Ocean and the Gulf of Guinea across West Africa, providing much of the moisture required for convective rainfall in the WAM (Janicot et al. 2008). Northerly trade winds are circled in green over Egypt and northern Sudan (Rep.). These trade winds blow from the Mediterranean, and are an important source of atmospheric moisture across the Sahara.

Low level jets are widely acknowledged to be a major source of atmospheric moisture and a fuelling mechanism for convective rainfall (Pu & Cook 2010; Stensrud 1996), whilst in a study over West Africa the mid-level African Easterly Jet (AEJ) was demonstrated to remove moisture from the African landmass (Cook 1999). However, Stensrud (1996) notes that the interaction between a high- and low-level jet can be a driving mechanism behind the production or suppression of convection, through the creation of regions of divergence and convergence throughout the vertical profile of the atmosphere. Considering the large number of jets affecting northern Africa, the strengths, locations and interactions between the jets may prove highly significant in analysing the extent of the rainy season in Sudan.

The West African Westerly Jet (WAWJ) is a recently defined low level jet found over West Africa at approximately 10°N, embedded within the larger scale West African Monsoon (WAM) westerly circulation (Grodsky et al. 2003). The WAM circulation is well known for being a major moisture transport into West Africa and the Sahel, however little research has been undertaken to determine its effects on the eastern Sahel (i.e. central Sudan). Druyan and Koster (1989) describe the effect of the WAM circulation on various portions of the Sahel, noting that south-westerly monsoon flow from the Gulf of Guinea is conducive to increased central Sahel rainfall. The West African westerly circulation, together with westerly flow inland from the tropical north Atlantic appears to be highly important to the supply of moisture in the Sahel in general (Lele & Lamb 2010), and warrants further investigation in order to establish its impact on the eastern Sahel.

The Somali jet is known for its influence on the Indian monsoon on account of the long path followed by the jet, directly above the warm surface of the Indian Ocean and Arabian Sea (Bannon 1982). The Somali jet is a rare example of a cross-equatorial flow, and before turning to become a westerly flow, the easterly and southerly motions directly cross the Horn of Africa bringing high levels of atmospheric water vapour. Vizy & Cook (2003) suggest a teleconnection between East African rainfall and the intensity of the Indian Monsoon, brought about by the strength of the Somali Jet and SST's in the Arabian Sea, however the findings of this study relate to Ethiopia and therefore more focussed research may be required in order to draw correlations between the intensity of the SJ and rainfall in Sudan. It is clear, however, that the SJ is of key importance to moisture transport into the East African region, and any changes in location, intensity and humidity of the SJ have the potential to significantly impact upon rainfall levels in Sudan. It is also worth noting that the Turkana Jet is believed to transport atmospheric moisture between the SJ and southern Sudan (Hulme & Tosdevin 1989). This is a localised low level jet over the Turkana valley in northern Kenya and is believed to be an important component of local atmospheric moisture distribution (Kinuthia & Asnani 1982). Very little research has been carried out on the impact of this jet on Sudanese rainfall, however being highly localised this phenomenon falls beyond the scope of the broad scale investigation carried out in this study.

In Figure 6[b], at 600 hPa the predominant is the African Easterly Jet (AEJ) (circled in purple). The AEJ is often associated with modifications to the West African Monsoon (WAM) through variations in location and intensity and the formation of African Easterly Waves (AEW) within the jet. However, the easterly flow extends across Sudan from the Arabian Sea and has the potential to alter Sudanese rainfall. Also visible is the highest altitude extent of the SJ.

The African Easterly Jet (AEJ) is normally associated with its impact on the monsoon of West Africa, with a combination of jet strength, location and the intensity of African Easterly Waves (AEW) carried by the AEJ being key factors determining the intensity of the WAM (Cook 1999; Cornforth et al. 2009; Ferreira et al. 2000; Hsieh & Cook 2005). The influence of the AEJ is rarely considered in studies of Sudan and other East African regions as the jet core lies to the west of Sudan (Hulme & Tosdevin 1989), however a notable easterly flow is evident over Sudan at 600 hPa (Figure 6[b]), leading to the possibility of a role in moisture transport or altered convective dynamics over East Africa. Recent research suggests that the AEJ itself extends significantly further to the east than previously thought, with origins as far east as the Red Sea (Agusti-Panareda et al. 2010). This may have implications for Sudan's rainfall, and its effects warrant further investigation. Cook (1999) notes that the AEJ is associated with mid-tropospheric water advection from east to west across Africa, leading to the speculation that precipitation over Sudan in the east may be negatively correlated with

AEJ intensity. The influence of the AEJ on WAM circulation may also generate a teleconnections feeding back on regions further to the east of the main AEJ circulation.

In the 200 hPa image (Figure 6[c]) the Tropical Easterly Jet (TEJ) is visible, with a maximum intensity over the Indian Ocean and extending across tropical Africa. The TEJ affects upper level convergence/divergence, indicating that its position is responsible for the suppression or enhancement of convective activity. It is also noted as a mechanism for removing atmospheric moisture from the African continent (Hulme & Tosdevin 1989).

The TEJ is an upper level jet found between 200 and 100 hPa. This jet has its origins in the vicinity of the Maritime Continent and extends to northern Africa, weakening rapidly across Sudan. Hulme & Tosdevin (1989) provide a comprehensive review of the mechanisms by which the TEJ is believed in influence rainfall over Sudan, concluding that rainfall is controlled by the location of the TEJ relative to the ITCZ, waves in the TEJ flow and changes in moisture transport to the region. A 3-5 day cycle in westward propagating precipitation disturbances has been noted by a number of authors, associated with upper-tropospheric easterly waves of a similar periodicity (Hammer 1973; Mishra & Tandon 1983). The upper level divergence generated to the south of the TEJ is said to enhance convection within the ITCZ, with suppression to the north of the jet generated by upper level convergence. This maintains the division between the wet south and the dry north, and suggests that both the intensity and latitude of the jet core may affect rainfall in Sudan. Whilst less researched than the African Easterly Waves (AEW, found within the AEJ and mainly affecting areas of Africa to the west of Sudan), waves within the TEJ have been found to impact greatly on the characteristics of the wet season in Sudan (Hammer 1973). Hulme & Tosdevin (1989) conclude that in dry years in Sudan the TEJ tends to be relatively weak and flows at a more southerly latitude than in wet years

3.2.3 Role of sea surface temperatures in circulation over East Africa

Williams and Funk (2011) note that the Indian Ocean has warmed by a rate of up to three times faster than the central tropical Pacific over the last thirty years, and therefore deduce that warming in the Indian Ocean region is likely to be the dominant driver of variability under climate change when compared to changes in the ENSO patterns. This study extends earlier work (Funk et al. 2008; Funk et al. 2003), which established a decreasing trend in East

African rainfall and noted the potential severity of the consequences of this decrease. The study notes that convection over equatorial east Africa has decreased over the last 30 years, whilst it has increased over the Indian Ocean, and proposes the theory that diabatic heating over the Indian Ocean is causing an easterly flow of dry air aloft over EEA, suppressing convection in the region. Tropical circulation above the Indian and Pacific Oceans was analysed through principle component analysis (PCA) of zonal and vertical winds, 2m air temperature and precipitation. This analysis concluded that the majority of variability in these variables is related strongly to warming in the Indian Ocean, and more weakly with warming in the Pacific Ocean. This warming of the Indian Ocean generates increased convective activity in the local region, whilst decreasing precipitation over the Pacific via an increased zonal overturning circulation with an ascending branch over the Indian Ocean and a descending branch over the Pacific. The second greatest variability demonstrated from the PCA related to ENSO, with La Niña conditions generating a similar situation to a warm Indian Ocean in the primary PCA.

Further analysis was performed in the Williams and Funk (2011) study using a GCM to confirm the projected impact of warming in the Indian Ocean on precipitation during MAMJ. Figure 7 illustrates their findings of vertical velocity changes over the last century, associated with the previously mentioned warming of the central and southern Indian Ocean. The authors note increased ascent over the Indian Ocean and decreased ascent over much of the central Pacific and northern East Africa. Descent is also enhanced over EEA. The reduced ascent over northern East Africa is particularly pronounced in this figure, which could have significant implications on the level of convective rainfall over Sudan during MAMJ.

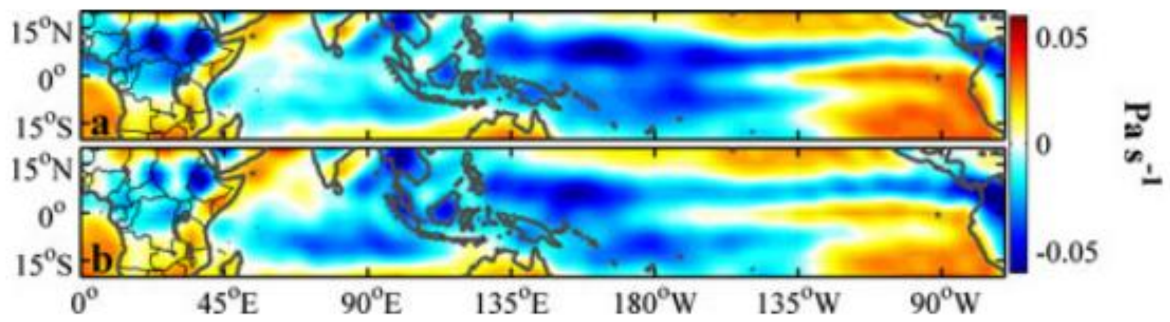


Figure 7: Mean atmospheric vertical velocity (Pa s^{-1}) during MAMJ between 700 and 400 hPa for (a) 1948-1978 and (b) 1979 - 2009. From Williams & Funk (2011) figure 11.

Correlation between Indian Ocean positive SST anomalies and decreases in rainfall over the Sahel is also noted by Janicot et al (1996), where the drying is attributed to an anomalous easterly flow generated by the increased gradient between Indian and Atlantic SST's. This flow is presumed to generate an increase in low level divergence, thus suppressing convection in the region. It should be noted that this study is focussed primarily on the West African Sahel, where the rainfall is dependent on somewhat different dynamics to that of Sudan. However, the authors draw conclusions for the entire Sahel during the boreal summer, which would indicate some influence on the central latitudes of Sudan.

Williams and Funk (2011) propose a theory whereby the warming of the Indian Ocean has altered the structure of the Walker circulation, with the ascending branch being positioned further to the west under the influence of climate change. The theory rests on a change in structure, rather than altered intensity in the circulation. However, mention is given to the fact that current global climate models (GCM's) overestimate the warming rates in the Pacific and Indian Oceans, and that when initialised with observed rates of warming the models tend to indicate a strengthened circulation. By extending the Walker circulation further into the Indian Ocean, the ascending branch is brought further to the west, forcing the descending branch toward east Africa and suppressing convection in the region.

In contrast to Williams and Funk (2011), the study by Camberlin and Okoola (2003) concerning the onset and cessation of the long rains of east Africa indicates that a cool Indian Ocean, when taken in conjunction with a warm Atlantic ocean, is conducive to a late onset of the long rains. This relationship is derived through the maintenance of strong equatorial easterlies due to high and low mean sea level pressure (MSLP) anomalies over the Indian and Atlantic oceans respectively. The authors present a theory that this enhanced easterly holds the ITCZ's meridional branch further to the west than normal, hence delaying the onset of the rains in the study's target region of Kenya and north-eastern Tanzania.

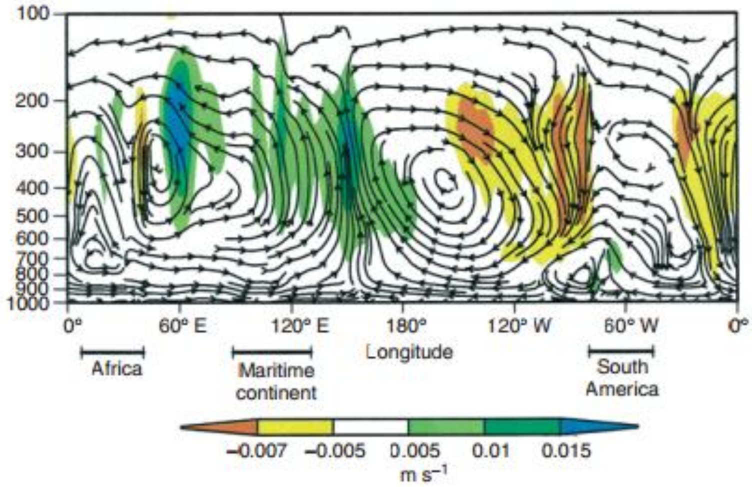


Figure 8: Vector wind vertical profile (m s^{-1}) along the equator, mean values for July 1949-99. Adapted from Lau and Yang (2003) figure 2. Raw data from NCEP reanalysis.

Figure 8 demonstrates a vertical cross section of the mean vector winds along the equator for July 1949-1999. A small but intense zone of descent is visible near the easternmost extent of the African continent; it is this descending branch to which the Williams & Funk study refers as a mechanism for suppressing convection over East Africa. Any westward shift or broadening of this descent would likely be associated with a reduction in convective activity.

A further study on the influence of Indian Ocean SST's on African rainfall was conducted by Bader & Latif (2003) in the form of a modelling study designed to test the influence of Indian Ocean SST's on western Sahelian rainfall. The study first demonstrates clearly a warming trend in the Indian Ocean, with an increase of over 0.5°C over 50 years (Figure 9). By running an atmospheric general circulation model (GCM) with forced SST anomalies in the Indian, Atlantic and Pacific Oceans the influences of the SST in each area on Sahelian rainfall were examined. Particular emphasis was placed on the western Sahelian region although data was published for the majority of northern Africa. The authors associate a relatively cool Indian Ocean with wet periods in the western Sahel, citing modifications to the Walker cell over Africa as a probable mechanism. The theory proposed states that a cool Indian Ocean suppresses convection and upward motion over the Ocean, generating upper level convergence and strengthening a meridional circulation over northern Africa, encouraging upper level divergence and ascent over the western Sahel. However, the authors note a greater response in the eastern Sahel (a category which applies to most of central Sudan) when the Pacific Ocean SST's were modified in the GCM, indicating an increase in East African rainfall with decreasing Pacific Ocean SST's. However, no further analysis is

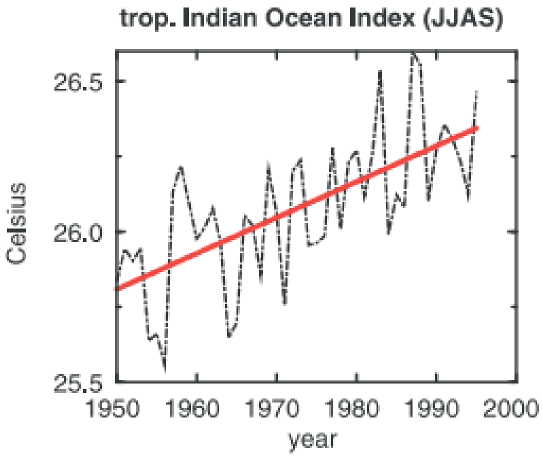


Figure 9: Observed tropical Indian Ocean SST Index for JJAS. Average from east coast of Africa to 120°E, 30°S to 30°N. From Bader & Latif (2003) figure 1.

performed and no mechanism is proposed for this teleconnections, leaving several questions unanswered when considering the eastern region.

Whereas the Pacific, Indian and Atlantic Oceans are regularly referred to in studies of sub-Saharan African rainfall, the Mediterranean appears rarely in literature as an influence on East Africa. However, SST in the Mediterranean is regularly cited as a controlling factor on rainfall in northern regions of Africa. Understanding that Sudan is influenced by the northerly trade winds flowing southward from the Mediterranean, it appears likely that SST's in this region may be an important source of variability in circulation and atmospheric moisture content. Rowell (2003) indicates that the impact of Mediterranean SST on rainfall in the Sahel is comparable to that of the Pacific (i.e. ENSO) and Atlantic Oceans. Statistical analysis was used to demonstrate this link, and a GCM was used to add robustness to the conclusion that Mediterranean SST influenced precipitation rates across the Sahel.

Based on output from the GCM, a mechanism is proposed whereby increased temperature in the Mediterranean leads to increased evaporation. Prevailing northerly winds advect this moisture across the eastern Sahara. On reaching the Sahel, moisture convergence leads to increased convection, which itself triggers a series of feedback effects. In particular, westerly winds are enhanced due to the low level convergence increasing moisture advection from the tropical Atlantic. The African Easterly Jet (AEJ) also decreases in intensity, reducing moisture export from the eastern Sahel and encouraging the maintenance of convection.

3.2.4 North Atlantic Oscillation

Following on from the discussion of the role of SSTs in altering atmospheric circulation around Africa, a phenomenon which greatly influences the circulation over Africa and thus the moisture transport and divergence associated with it is the SST and pressure differential between the Atlantic and Indian Oceans (Camberlin & Philippon 2002). The dominant mechanism for MSLP change in the Atlantic Ocean is the North Atlantic Oscillation (NAO) (Hurrell et al. 2003). The NAO is the changing pattern of MSLP between the northern and tropical Atlantic; regions which are dominated by the Icelandic Low and the Azores High respectively (Portis et al. 2001). The difference between anomalous MSLP values in the northern and tropical Atlantic is captured by the NAO Index, where a “positive” NAO indicates that the Icelandic Low and the Azores High are recording particularly low and high MSLP respectively. The NAO is most commonly associated with changes in European, north Atlantic and North American weather patterns. However many studies (e.g. Flohn 1987, Bader 2003, Camberlin & Okoola 2003) have drawn associations between pressure differentials between the Indian and Atlantic Oceans and rainfall over Africa, indicating that the state of the NAO may correlate well with precipitation in Sudan.

Bader & Latif (2003) note a positive correlation of the NAO with SST’s in all of the tropical oceans, indicating that, for example, the NAO may be expected to increase with the projected increases in Pacific and Indian Ocean SST’s. However, this study did not isolate individual tropical ocean regions, indicating that only weak conclusions may currently be drawn and that further research into the role of individual ocean basins would be beneficial. A trend in both magnitude and polarity in the NAO is noted since the 1970’s, whereby the oscillation tends toward a strong positive phase, with this upward trend expected to continue under the effects of climate change (Gillett et al. 2003). This association should be considered when debating the future of atmospheric mechanisms dependent on the NAO.

3.3 Concluding remarks on current literature

The current literature, whilst conflicted on a number of matters, appears to suggest that a decline in rainfall has been observed recently in Sudan. A number of authors suggest that this decline may be likely to continue under the effects of climate change; however the authors of the IPCC AR4 indicate that the current GCM modelling studies project an increase in precipitation under the influence of anthropogenic climate change. Some doubt has been indicated as to the validity of these results, however, on account of the excessively warm Pacific SST demonstrated in historical simulations of the climate (Williams & Funk 2011).

Whilst few studies directly investigated controls on Sudanese rainfall, other areas in northern Africa were shown to be affected by a number of circulations, including the Somali Jet, WAM westerly circulation, African Easterly Jet, Tropical Easterly Jet and northerly trade winds. It is likely that these circulations are influenced by SSTs within the tropics, which will also determine the amount of atmospheric moisture carried by the circulations. In particular the El Niño-Southern Oscillation pattern of SST and circulation changes is relevant in most regions of the tropics including much of Africa, whilst Indian and Atlantic Ocean SST's appear to moderate equatorial circulation patterns over Africa. Therefore this project will investigate the influence of SSTs and wind patterns on Sudanese rainfall, whilst considering recent trends and projected changes in these moderating influences in order to determine likely changes in Sudan's rainy season.

4 Datasets used for analysis

4.1 GHCN

Data has been analysed based on three datasets. Firstly, a long term historical climatology was assembled based on rainfall measurements in the Global Historical Climatology Network (GHCN) database (NOAA NCDC 2012). This dataset includes all WMO records of rainfall observations in Sudan between 1891 and 1993 based on data from stations reporting to the Global Climate Observing System (GCOS) Surface Network (GSN). A total of 107 stations have been recorded in Sudan reporting to this dataset (Figure 10), albeit with varying numbers of stations reporting at any given time (Figure 11).

Following the work of Hulme (1990), three "latitude bands" were devised, covering latitudes below 12°N, from 12-16°N, and above 16°N (Figure 10). These latitudes provide a good approximation to the Savannah of the moist south, the semi-arid Sahel and the arid north (including the Sahara and Nubian deserts). These bands of latitude correspond well to the climatology changes described in section 2, and provide scope for analysing trends in the three distinct rainfall patterns in Sudan.

Figure 10 demonstrates the spatial arrangement of the stations reporting in this database. The northern region has a very sparse gauge network, reflecting the low population density and extremely arid environment. The north west of Sudan in particular has no rain gauge stations at all. Coverage is more extensive in the central and southern regions, although in the central region coverage is skewed toward the highly agricultural region to the south of Khartoum.

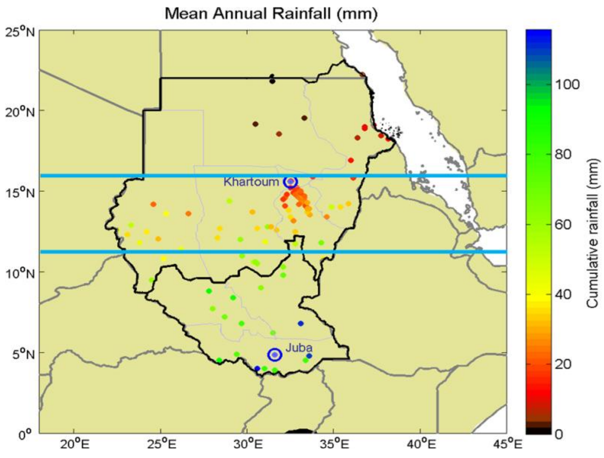


Figure 10: Map of rain gauge stations reporting to the GHCN database as "Sudan", 1891-1993. Stations are coloured according to their mean annual rainfall totals. Blue lines overlaid indicate the division of stations by latitude.

Having filtered the data for clearly anomalous readings (i.e. missing or negative values), an exploratory analysis was conducted on the rain gauge data by first generating maps of the station locations (i.e. Figure 3, Figure 10) and their mean annual rainfall for all years of available data. This demonstrates the level of spatial coverage in the stations, as well as giving an indication of the rainfall distribution across the country.

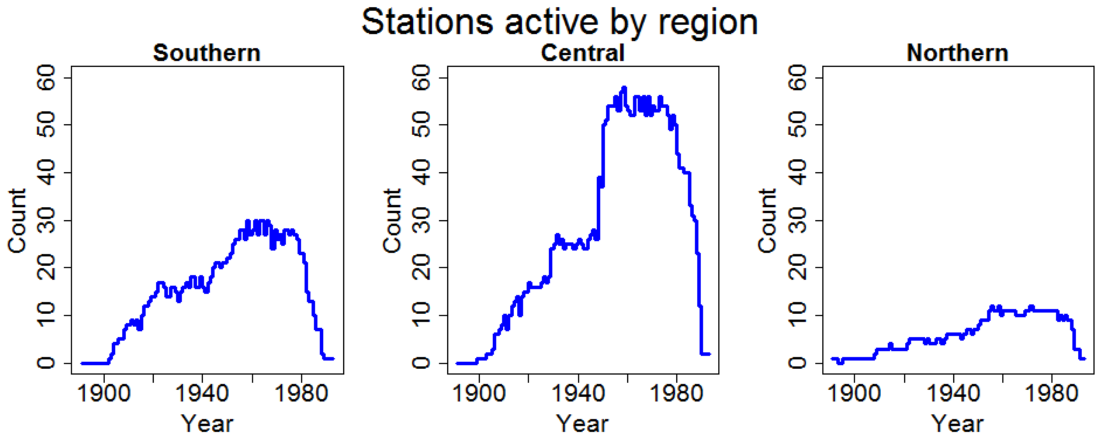


Figure 11: Count of stations reporting consistently for each full year, divided by region. From GHCN data.

Before proceeding to analyse trends in the GHCN data, the reliability and consistency of the stations reporting data to the record was considered as per Figure 11. These graphs indicate the number of stations actively and consistently reporting by region on a yearly basis. Stations are counted only if they have provided a report for every month of a given year, and otherwise are excluded. It becomes clear that there is a gradual increase in stations reporting from the start of the time-series until approximately 1960, with a peak between 1960 and 1980. After 1980 the number of stations providing reliable measurements to the dataset decreases abruptly, indicating that trends considered as the average of reporting stations may become somewhat unreliable in the last decade of the time-series.

4.2 TARCAT

Surface observations are widely known to be limited and often unreliable throughout Africa. Locations of stations reporting to the GSN during a case study period 2001-2002 and the reliability of these stations are indicated in Figure 12, as a demonstration of the low density and poor reliability of climatological data received from surface reports over Africa in recent years. This sample, taken by the Australian Government Bureau of Meteorology between

August 2001 and January 2002, demonstrates the number of monthly reports received from stations worldwide during that period. The majority of stations in northern Africa failed to report consistently throughout this period, with stations being widely spread across the continent.

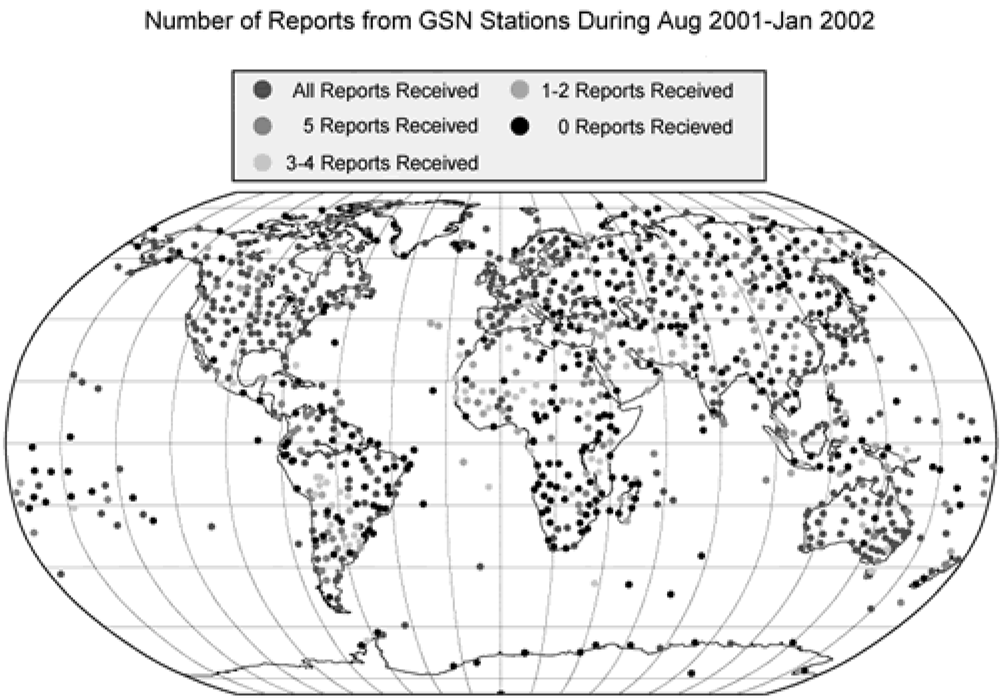


Figure 12: Stations reporting worldwide through GSN during case study period Aug 2001-Jan 2002. Shading represents number of monthly reports received during this six month period. From Australian Government Bureau of Meteorology (2002)

In order to improve on the accuracy of surface reports, a more detailed climatology was produced for the last 31 years based on high quality rainfall data from the recently released TARCAT (TAMSAT Rainfall Climatology and Time-series) dataset. TAMSAT rainfall rates are derived from the thermal infrared (TIR) channel of Meteosat, through a derived statistical relationship between observed cold cloud duration (CCD) over a broad area and records from rain gauges in the vicinity of the observations. The threshold value for classification of cold cloud varies spatially and temporally, but tends to be in the region of -40°C (Dugdale et al. 1995). This spatial averaging eliminates many of the discrepancies associated with point measurements. For example in tropical regions where rain is likely to originate from convective systems, precipitation may be intense and highly localised. This may cause two nearby gauges to record quite different rainfall volumes. By introducing the consistency of a gauge calibrated, spatially averaged statistical algorithm based on pre-determined CCD thresholds, much of this discrepancy can be eliminated (Dugdale et al. 1995).

There are some fundamental limitations to the TAMSAT method, since rainfall is not directly observed but rather is derived from observed CCD via a statistical relationship which varies both in time and space. Reliability of the method reaches a minimum in regions where the rain gauge network is sparse on account of the additional weighting that must be given to satellite derived observations without an appropriate level of calibration (Grimes et al. 1999). The CCD method of rainfall estimation also assumes that all rain is convective in origin; precipitation from stratiform clouds would not be registered since such clouds do not have the high, cold cloud top associated with cumulonimbus systems. Complications may also be caused by cirrus clouds, which register on the "cold cloud" threshold on account of their height, yet are very rarely associated with precipitation. However, since Sudan's rainfall is predominantly convective due to its origins in the ITCZ (see section 3), and the majority of Sudan is covered by a relatively dense gauge network, the TAMSAT methodology is likely to be quite reliable in this region.

TARCAT (TAMSAT African Rainfall Climatology and Time-series) is a recently produced analysis of historical TAMSAT data across the African continent, currently providing a spatially homogeneous dekad (10 day) and monthly climatology for rainfall at a resolution of approximately 4km (TAMSAT Research Group 2012). Data is available from the initiation of TAMSAT in 1981 until the present, and due to the spatial averaging process of TAMSAT, monthly climatology is available for the entire area. This represents a clear improvement on the point measurements offered by rain gauges, as discussed in section 5.1. TARCAT has been calibrated using a number of rain gauge stations throughout Sudan and the surrounding region (R. Maidment, University of Reading, 2012, personal communication). For this study, TARCAT data was taken over an area of 2 – 23°N by 21 – 39°E. This region covers Sudan with a small "border" area of the surrounding countries (see Figure 13).

Figure 13: Relief map of north-eastern Africa indicating TARCAT rainfall study region (red box)

4.3 NCEP 40 Year Reanalysis and HadISST

Finally, NCEP 40-year reanalysis data (Kalnay et al. 1996) was used in conjunction with the TARCAT data to provide an analysis of teleconnections and atmospheric dynamics determining the characteristics of Sudanese rainfall. The NCEP reanalysis data provides full spatial coverage of a number of variables on a grid scale of 2.5° latitude by 2.5° longitude, based on NWP model output. In this study, zonal and vertical wind, MSLP and geopotential height have been drawn from the reanalysis data. The accuracy of the reanalysis data is known to be poor for some variables (for example precipitation rates, i.e. Diro et al 2009) over small spatial areas; however for less localised variables such as general circulation analysis the reanalysis dataset has been demonstrated to show an acceptable level of accuracy. To supplement the NCEP data for statistical analysis of the role of SSTs in altering Sudanese rainfall, global SST data was provided by the HadISST (Hadley Centre Sea Ice and Sea Surface Temperature) dataset. This data is provided as a monthly mean on a grid scale of 1° latitude by 1° longitude, and is derived from a number of sources including satellite observations (Rayner et al. 2003).

This chapter has outlined obtaining the appropriate data and defining the spatial and temporal limits of each dataset, and exploratory analysis of the contents of the datasets. The following chapter outlines how analysis was performed to determine the observed characteristics of the rainfall variability in Sudan from GHCN and TARCAT, prior to analysis against related variables from the NCEP Reanalysis and HadISST datasets.

5 Determining recent trends

5.1 WMO reported monthly raingauge data

As described in section 4, data was obtained from the GHCN dataset, divided by latitude Figure 10) and analysed to consider the number of stations reporting per region at any given time (Figure 11). Time-series were then produced of the average peak wet season (JJAS) recordings per year for all stations in each region (Figure 14). To produce these time-series, the anomaly (in standard deviations) for each station was calculated for every year relative to that station's mean JJAS recording. The mean anomaly over all stations per region was then plotted as a time series. A further set of plots was produced, limited between 1940 and 1980, in order to limit the analysis to a sample of years during which a sufficient number of stations were reporting to ensure an appropriate level of accuracy (see Figure 11).

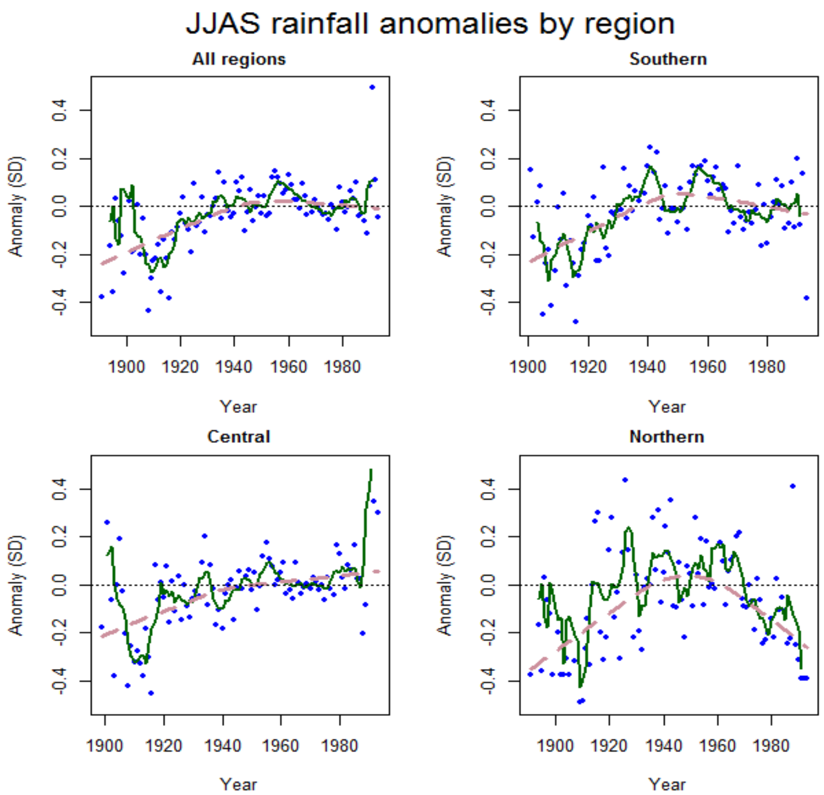


Figure 14: Mean JJAS rainfall anomaly by year for all stations by region. Anomalies calculated for each reporting station by year from its own full time series mean. All available stations used for all years. Overlays are a low pass LOWESS fit (dashed pink) and a five year running mean (green). From GHCN rain gauge data.

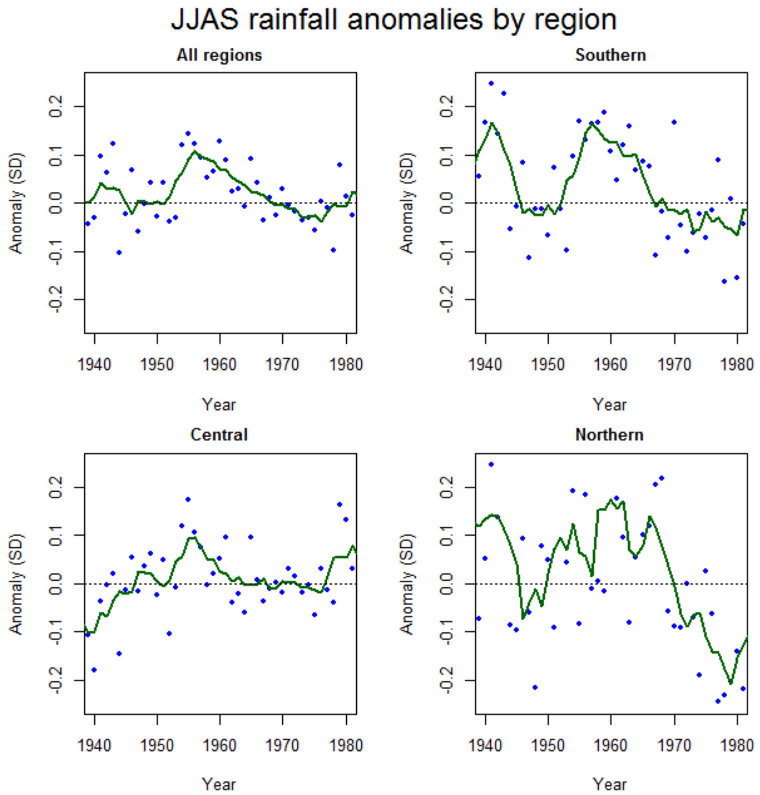


Figure 15: Mean JJAS rainfall anomaly by year for all stations by region. Method as per Figure 14, limited to years between 1940 and 1980.

Figure 14 appears to indicate that the central latitudes of Sudan have on average been experiencing an increase in rainfall throughout the duration of the gauge records, whilst the southern region appears to have experienced little overall change in rainfall, with the low pass filter (in pink, a Locally Weighted Scatter-plot Smoothing [LOWESS] fit) indicating an increase in the early part of the 20th century and a slight decrease in the later part. However this may be attributed by the relatively high level of variance in the data at the start of the time series. This may in turn be attributable to the low number of stations reporting during this period (see Figure 11). Therefore, Figure 15 has been limited to the years 1940-80 where a consistently high number of stations were reporting. During the 1960-1980 period, a steep decline in rainfall is evident in the southern and northern regions of Sudan, whilst the central region experiences approximately consistent levels of rainfall.

In order to begin to investigate any change in seasonality in the main rainy season, time series graphs were produced of all rain gauges by month. Any trend in individual months may indicate a change in the timing of the rainy season.

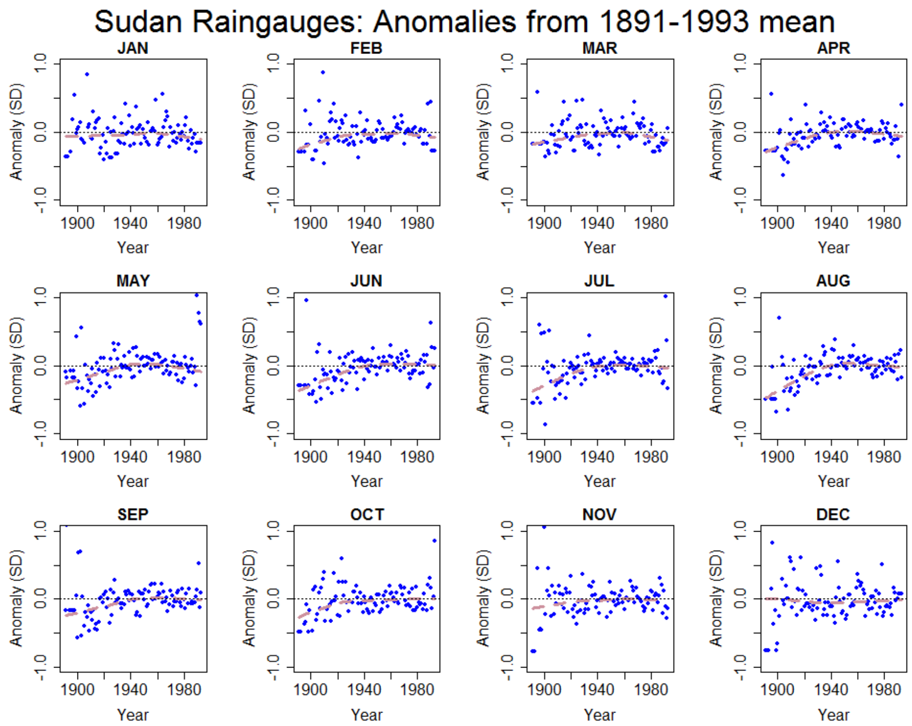


Figure 16: Mean anomaly in raingauge recordings across Sudan. All active rain gauges 1891-1993, anomalies in standard deviations from the mean

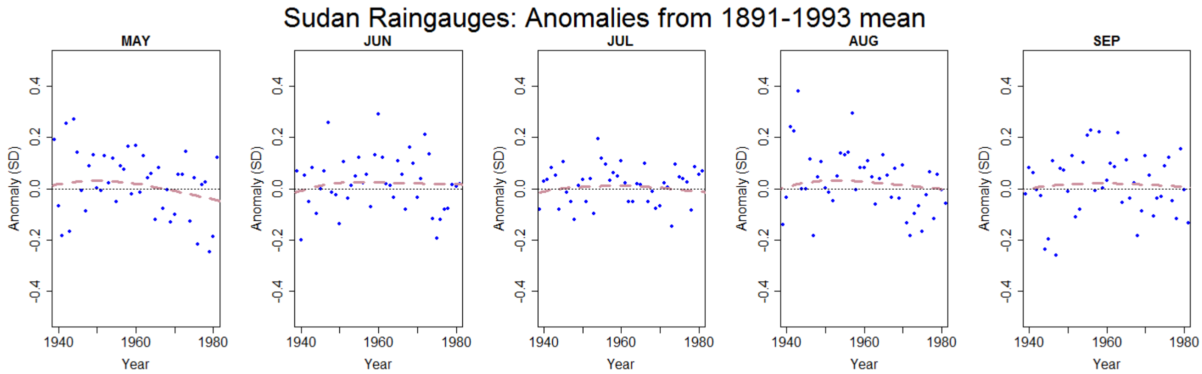


Figure 17: As figure 15, but limited to years from 1940-1980, summer months (MJJAS) to data based on sufficient number of reports for reliability (see section 4)

Figure 16 and Figure 17 demonstrate the results of the seasonal analysis. Most months show little discernible trend over time. However, the summer months all appear to have experienced a strong increase in rainfall prior to 1940 followed by a stabilisation toward the later part of the series. April and May appear to have been reducing slightly since approximately 1940, following an initial increase in rainfall amounts. Few conclusions may be drawn from the winter months (November to February), since these months are almost entirely arid for the majority of the region (e.g. Figure 3). It is interesting to compare any reduction in MAM rainfall with the study by Lyon & DeWitt (2012) referenced in section

3.1.1; however the “abrupt” decline in the long rains observed by this study in EEA did not begin until the early 1990s, outside the period of this rain gauge analysis.

Investigation of trends in the GHCN data reveals an increase in peak season (JJAS) rainfall during the early part of the 20th century, followed by a decline in rainfall volume from 1960-1980, particularly in the northern and southern regions, consistent with Hulme (1990) and Zhang et al (2011).

5.2 TARCAT satellite product analysis

Data from the TAMSAT/TARCAT project was used over an area as defined in section4.2, covering Sudan and a small border region of neighbouring countries. The TARCAT dataset runs from 1981 to the present day, essentially continuing from the end of the gauge data considered reliable in section 5.1. The data was analysed in a similar fashion to data from the WMO rain gauges, in order to determine any changes in rainfall patterns by region and for the region as a whole, as well as any changes in seasonality. Figure 18 demonstrates the rainfall anomalies in JJAS by region in Sudan relative to the 1981-2012 mean, overlaid with a low pass LOWESS filter in pink and a five-year running mean in green. All regions show an increase in rainfall throughout the thirty year time period for peak wet season rainfall. It should be noted that the spread of anomalies from year to year is large during the latter part of the time series, particularly in the central and northern regions. However, all regions follow a similar pattern of rapid increase during the late 1980’s and a more moderate increase or stabilisation in the early years of the 21st century.

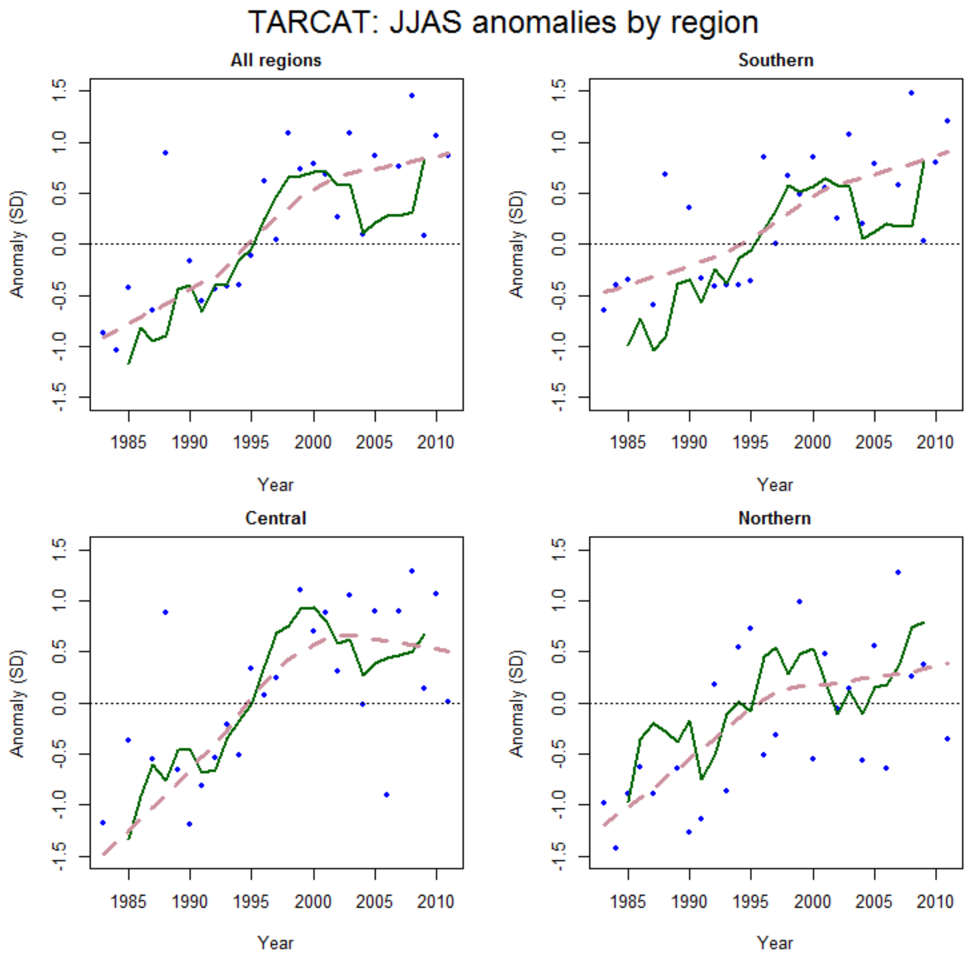


Figure 18: JJAS rainfall anomalies (standard deviation) from the 1981-2012 mean from TARCAT data by region. Pink dashed line is a low pass LOWESS filter. Green line is a 5 year running mean.

Having established that all regions of Sudan are experiencing similar patterns of rainfall anomaly, investigation was performed into any changes in seasonal cycle. Figure 19 shows rainfall divided by months for every year in the TARCAT time series, over the entire Sudanese region, overlaid with a low pass LOWESS filter in pink.

These seasonal graphs demonstrate increases in rainfall between April and September, indicating that the entire wet season in Sudan may have been intensifying in recent years. A slight decrease is noted in January, March and December; however these months experience little rainfall in Sudan and hence the data is fairly "noisy" in comparison to the peak rainy season months of JJAS. This indication of consistently increasing rainfall is notably different to a number of studies published in the East African region, and to the declining rainfall observed in the GHCN data from 1940-80.

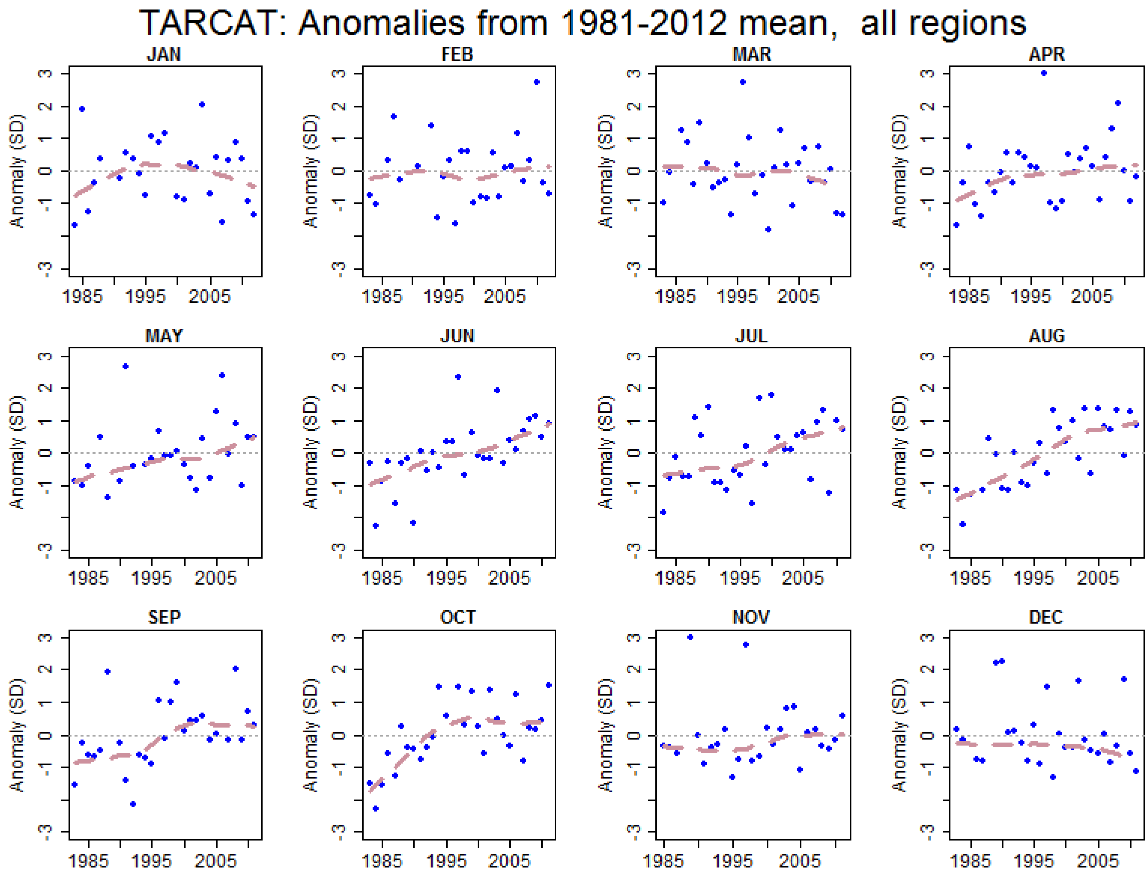


Figure 19: Anomaly from 1981-2012 JJAS mean over full TARCAT Sudan analysis region.

5.3 Concluding remarks on observed trends

Through analysis of traditional rain gauge data (GHCN) in combination with the newly released TARCAT ground-calibrated satellite data, it is evident that Sudan experienced a decline in rainfall from 1940-80; a trend which now appears to have been reversed. This reversal is accounted for by an increase in rainfall during the peak wet season months of JJAS. The TARCAT data (1981 onwards) indicates that all regions of Sudan have received increased rainfall volumes in recent years, whilst the GHCN gauge data indicates that the southern and northern regions of Sudan were particularly heavily affected by a decline in rainfall from 1940-80.

The findings presented here relate well to the available literature, particularly with respect to the decline in rainfall observed over Sudan in the early part of the 20th century. Hulme (1990), for example, noted a severe depletion in rainfall in the Sudanese Sahel, citing a 15% decline in the region from 1956-85 when compared with records from 1921-50. Zhang et al

(2011) also indicated a decline in rainfall in the Sahel region of Sudan, with a particularly rapid decline since 1960. This correlates well with the study of 1940-80 rain gauge data presented here, however no mention is made of an increase in rainfall since 1980. This may be attributed to the use of gauge data from GHCN, which has been demonstrated to be lacking in coverage in years post-1980 in Sudan, and NCEP PREC, which is known to contain some inaccuracies in its representation of historical precipitation over Africa (Diro et al. 2009).

This project aims to overcome this shortage of gauge data through use of the TARCAT dataset, with the added benefit of greater spatial coverage through use of satellite observations. Despite slightly differing analysis techniques, when the time series in the literature are compared with the time series presented in this report, similar patterns of variability are evident on the time scales in question. Having established that there has been a previously undocumented increase in rainfall over recent years in Sudan, this project will now focus on the years covered by TARCAT (1981-2012), to give consideration to the mechanisms which have caused this increase.

6 Analysis of Teleconnections and Atmospheric Dynamics

In order to establish relationships between rainfall in Sudan and meteorological and oceanographic variables elsewhere in the world, analysis was performed to compare data from TARCAT with data from the NCEP 40-year reanalysis project (Kalnay et al. 1996).

A correlation analysis was performed to determine regions of potential interest, followed by a composite analysis based on anomalously wet and dry seasons in Sudan. In addition, composite analysis was performed based on years with anomalous rainfall where ENSO was in a neutral state, in order to isolate features of interest which were not related to this dominant mode of forcing in the tropics.

6.1 Correlations

Having extracted monthly mean rainfall values from the TARCAT climatology, the NOAA correlation plotting tool (NOAA ESRL PSD 2012b) was used to draw statistical correlations between rainfall and a number of variables. The correlation plotting tool draws correlations between an index time series (drawn from the TARCAT data for all available years over the whole Sudan region as defined in section 4.2) and NCEP 40-year Reanalysis data. The following formula is applied to draw these correlations:

$$r = \frac{sum(xy)}{\sqrt{sum(x^2) \cdot y^2}}$$

Given 31 degrees of freedom, this method should return results to a 95% statistical significance level for correlation values of 0.30 or higher (NOAA ESRL PSD 2012c).

In tropical meteorology it is often noted that sea surface temperature, particularly in the Pacific Ocean, is a key driving variable of large scale weather patterns. It has also been noted in the literature that the role of Mediterranean, Indian and Atlantic Ocean SST's may be becoming increasingly important in influencing the atmospheric circulation over east Africa (i.e. Druyan & Koster 1989, Jung et al 2006, Williams & Funk 2011). Therefore, interannual correlation analysis was performed on SST throughout the tropics with JJAS precipitation in all of Sudan, as demonstrated in Figure 20.

6.1.1 Sea Surface Temperature

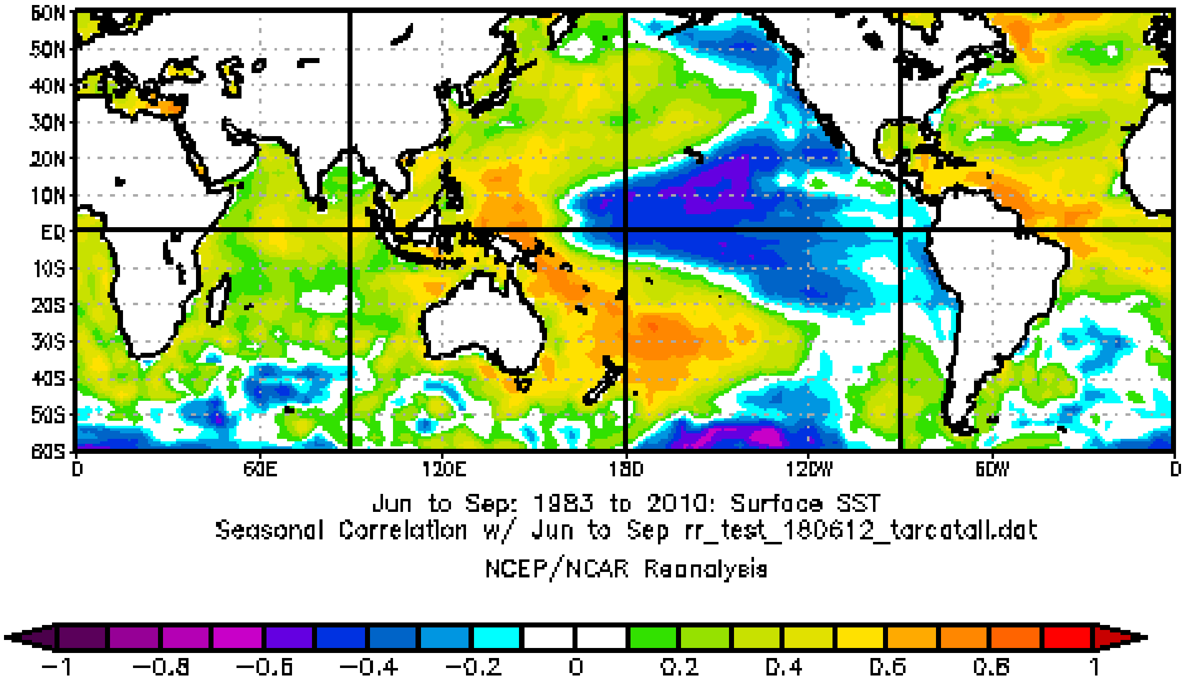


Figure 20: SST correlation against TARCAT monthly average rainfall for all Sudan during JJAS 1981-2012 (NOAA ESRL PSD 2012b)

Figure 20 demonstrates a very clear "La Niña" type correlation between the rainfall during JJAS in Sudan and tropical SST's. This is characterised by a negative correlation with SST in the Pacific Cold Tongue and a positive correlation with SST around the western Pacific and the Maritime Continent. Strong positive correlations are noted in a number of other regions, such as the central/western Atlantic and eastern Mediterranean. The same analysis was performed considering rainfall rates in the three latitude bands in Sudan discussed in previous sections, all of which returned a broadly similar pattern of La Niña correlation, although the correlation in the Mediterranean appeared to increase in intensity when considering more northerly latitudes in Sudan.

Correlations between EEA rainfall and SST in the Indian and Atlantic Oceans have been reported extensively in the literature (Janicot et al. 1996; Williams & Funk 2011), with Williams and Funk (2011) noting especially the increase in the strength of these correlations over recent years. The positive correlations in the Atlantic Ocean would appear to relate well to Janicot et al. (1996), supposing that a low Atlantic, high Indian Ocean SST dipole would increase equatorial easterly flows and induce divergence, therefore suppressing convection.

It is interesting to note the relatively low level of significance in the Indian Ocean in comparison with the Pacific during the JJAS months in Sudan, given the results of Williams & Funk (2011). Therefore, correlations for MAMJ were drawn as per Figure 21 in order to ascertain if this discrepancy is due to Sudan's more northerly latitude or due to the difference in timing of the rainy season between Sudan and EEA.

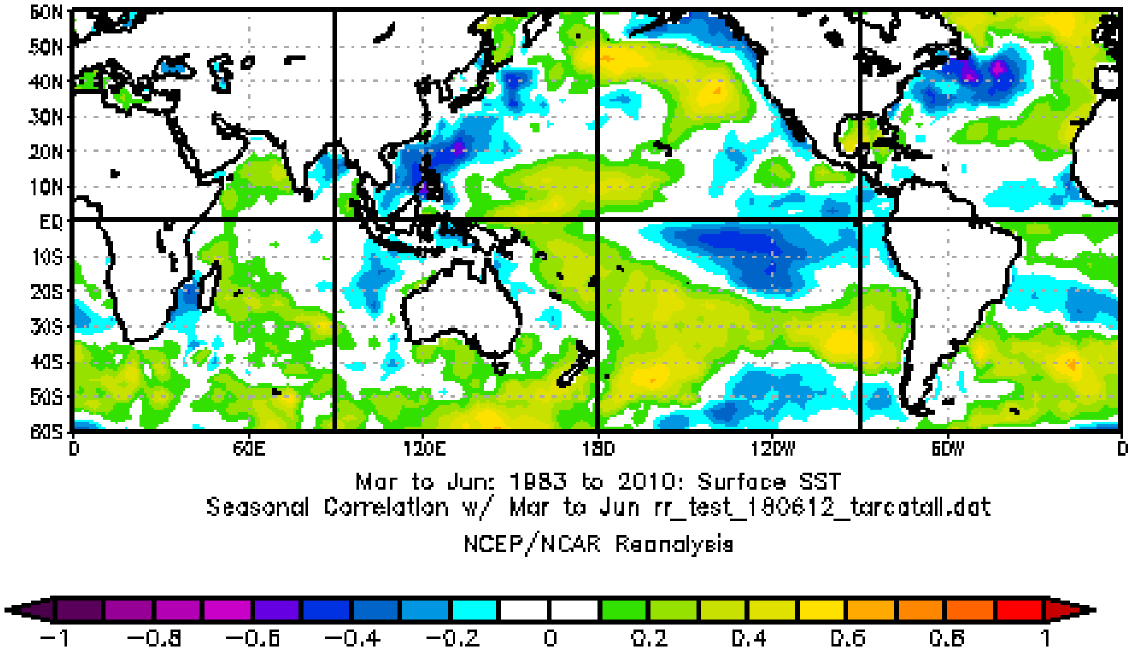


Figure 21: SST correlation against TARCAT monthly average rainfall for all Sudan during MAMJ 1981-2012 (NOAA ESRL PSD 2012a)

Figure 21 (SST correlations with MAMJ rainfall in Sudan) demonstrates much weaker correlations than Figure 20 (SST correlations with JJAS rainfall in Sudan). This is likely due to the low rainfall volumes over Sudan during these months. There appears to be particularly little correlation between Sudanese rainfall and SST in the Indian Ocean, thus suggesting that the findings of Williams and Funk (2011) are not applicable to Sudan, likely due to Sudan's northerly latitude and later rainy season than the region of EEA considered in that study. However, the negative correlation with SST in the Mozambique Channel may be associated with the assertion of Camberlin & Okoola (2003) that the onset of the rainy period is associated with wind surges through this channel.

6.1.2 Pressure and geopotential height

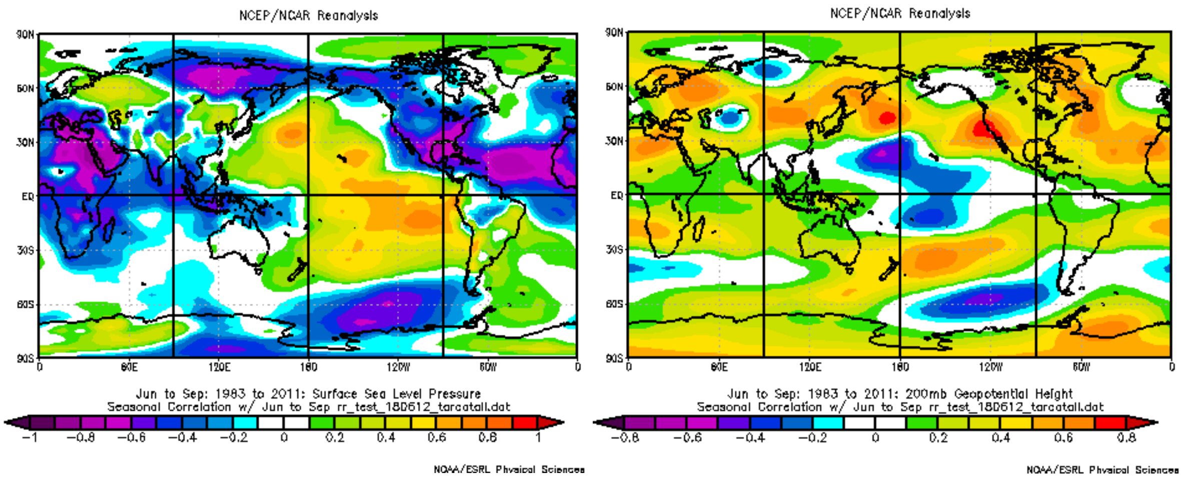


Figure 22: [Left]: Correlation between JJAS rainfall in all Sudan and JJAS MSLP. [Right]: Correlation between JJAS rainfall in all Sudan and 200 hPa geopotential height.

Figure 22 shows MSLP (left) and 200 hPa geopotential height (right), correlated against JJAS rainfall in all Sudan. These correlations appear to demonstrate a traditional “Walker” type circulation (see section 3.2.1). The low surface pressure and high upper level geopotential height correlations to the west over Africa and the Indian Ocean, and the inverse over the eastern Pacific, indicate that rainfall is statistically likely to peak where a strengthened Walker circulation exists with a descending branch over the central and eastern Pacific, reminiscent of a “La Niña” event. This would indicate a certain amount of agreement with the SST correlations shown in Figure 20. Likewise a highly significant correlation is shown with pressure and geopotential height over the Mediterranean, also in accordance with the SST correlations. Reflecting on the work of Williams & Funk (2011), who stated that a westward extension of the Walker cell due to rising Indian Ocean SSTs should dry EEA, it appears that rainfall in Sudan is actually positively correlated with an ascending branch of the Walker cell positioned toward the west. This indicates that the mechanisms affecting Sudanese and EEA rainfall may differ in some fundamental respects, and may support, and to some extent explain, the theory proposed in the IPCC AR4 report that a dipole of rain between equatorial and northern regions of East Africa may be emerging under climate change (Boko et al. 2007).

6.1.3 Zonal wind circulation

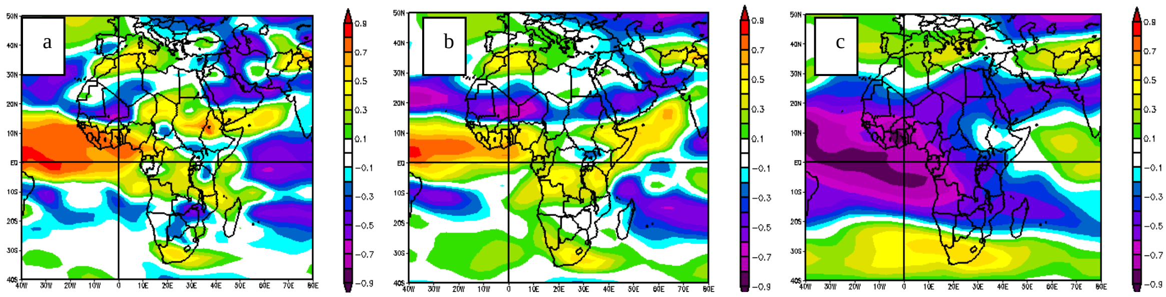


Figure 23: Zonal wind correlations against rainfall for all Sudan, 1981-2012. From left: [a] 850 hPa [b] 600 hPa [c] 200 hPa.

Following the SST and MSLP/geopotential height correlation analysis, the same analysis was performed for zonal wind at 850, 600 and 200 hPa, as shown in Figure 23. These pressure levels were chosen to detect changes in the lower, mid and upper troposphere, thus observing the effects of all of the jets and predominant circulations as described in section 3.2.2. In Figure 23[a], strong correlation is evident with westerly flow to the west of Africa and easterly flow to the east. This would be consistent with a low level convergent pattern over southern Sudan, conducive to increased convective activity. Over Sudan a westerly correlation is evident, possibly associated with atmospheric moisture transport from the Gulf of Guinea via the WAM circulation (i.e. Mattsson and Rapp 1991).

In Figure 23[b], rainfall is correlated with mid-tropospheric easterlies over the northern Sahel and Sahara, and westerlies over southern West Africa and the Horn of Africa. The correlation with the easterly flow over the northern Sahel may indicate that the strength and/or position of the AEJ is important in determining the volume of precipitation over Sudan, whilst the correlation with the equatorial westerly is likely to be a high altitude extension of the importance of the WAM circulation .

Figure 23[c] appears to indicate a strong correlation with the TEJ, with particularly strong correlations over the equatorial Atlantic. The juxtaposition of a westerly correlation at low levels with an easterly correlation in the upper troposphere over the Atlantic and northern Africa may indicate a Walker-type circulation anomaly driving interannual variability in Sudanese precipitation.

6.2 Composite analysis

Whilst the interannual correlation plots as described previously are a useful initial analysis of correlations in the overall rainfall throughout Sudan, they fail to distinguish non-linearity in the system. For example, entirely different factors may be involved in creating dry and wet conditions in Sudan, as opposed to opposite signs of the same signals (Black et al. 2003).

In order to analyse any non-linear mechanisms involved in creating rainfall anomalies over Sudan, the TARCAT dataset (entire Sudan region, all available years per section 4.2) was analysed to find samples of the five wettest and driest years (in terms of JJAS precipitation) throughout the TARCAT Sudan study area as defined in section 4.2. By taking the five most extreme years on record, a buffer of 21 "normal" years is maintained, where precipitation was in a relatively normal state of intensity. Having taken these sample years, consideration was given to the very large ENSO correlation shown in Figure 20. Due to the spatial scale and the magnitude of SST anomalies involved, ENSO is a controlling influence on many tropical systems. As such, correlations tend to appear strongly in tropical regions; however this may be a secondary influence. For example, there may be a "chain effect" whereby ENSO affects a variable which in turns affects rainfall in Sudan. It is desirable to separate these primary and secondary influences in order to determine the chain of events responsible for anomalous rainfall.

To achieve this, one year from each set was highlighted where ENSO was in its most "neutral" state, according to the NOAA MEI index (NOAA ESRL PSD 2012d). These sample years are detailed in Table 1 with the two "ENSO-neutral" case study years being highlighted in blue. Having established these reference years, anomalies in a number of meteorological variables were consider for JJAS, and statistical significance of the anomalies was determined using an unpaired, two tailed t-test. All datasets used for comparison to the TARCAT data were limited to the TARCAT temporal range of 1981-2012.

Table 1: JJAS rainfall extreme years based on TARCAT data, area prescribed in section 4 (all Sudan). Case study years of minimal ENSO MEI index are highlighted in blue (NOAA ESRL PSD 2012d)

Extreme years for JJAS rainfall, all Sudan	
Dry	**Wet**
1983	1988
1984	1998
1987	2003
1991	2008
1992	2010

6.2.1 Sea Surface Temperature

Composite analysis was performed on the SST data from the HadISST dataset to determine the relative importance of SST forcings on wet and dry periods in Sudan.

Figure 24 demonstrates SST anomalies observed in "wet" and "dry" years (per Table 1), overlaid with marks indicating statistical significance ($p < 0.05$ in black, $p < 0.10$ in grey). Wet years appear to be associated with a warming of the tropical Atlantic, northern Atlantic, Indian Ocean, eastern Mediterranean and the Red Sea, with a cool anomaly in the central Pacific. Dry years appear to indicate a cooler Atlantic, with significance in the north-west, and a cool eastern Mediterranean, Black Sea and Red Sea.

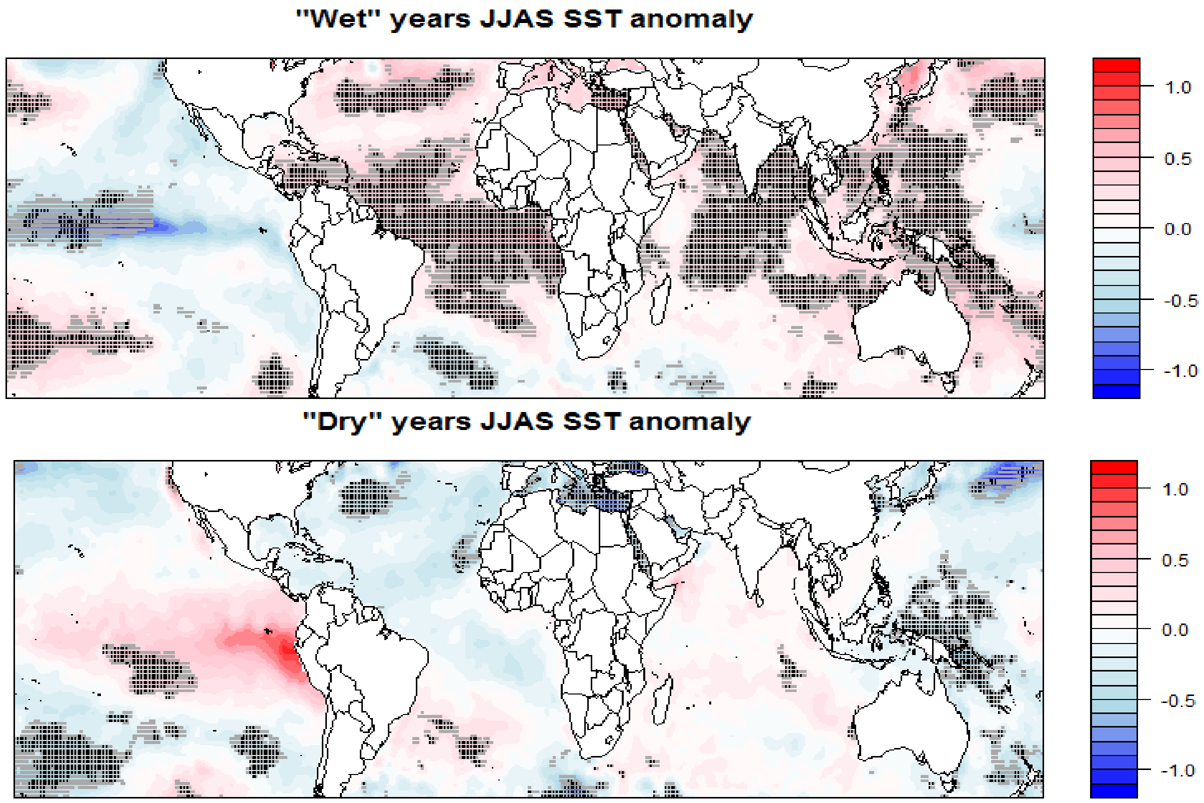


Figure 24: Sea Surface Temperature anomalies from the 1981-2012 mean for "wet" and "dry" years, per Table 1. Statistical significance marked at 95% (black) and 90% (grey). Anomalies in °C.

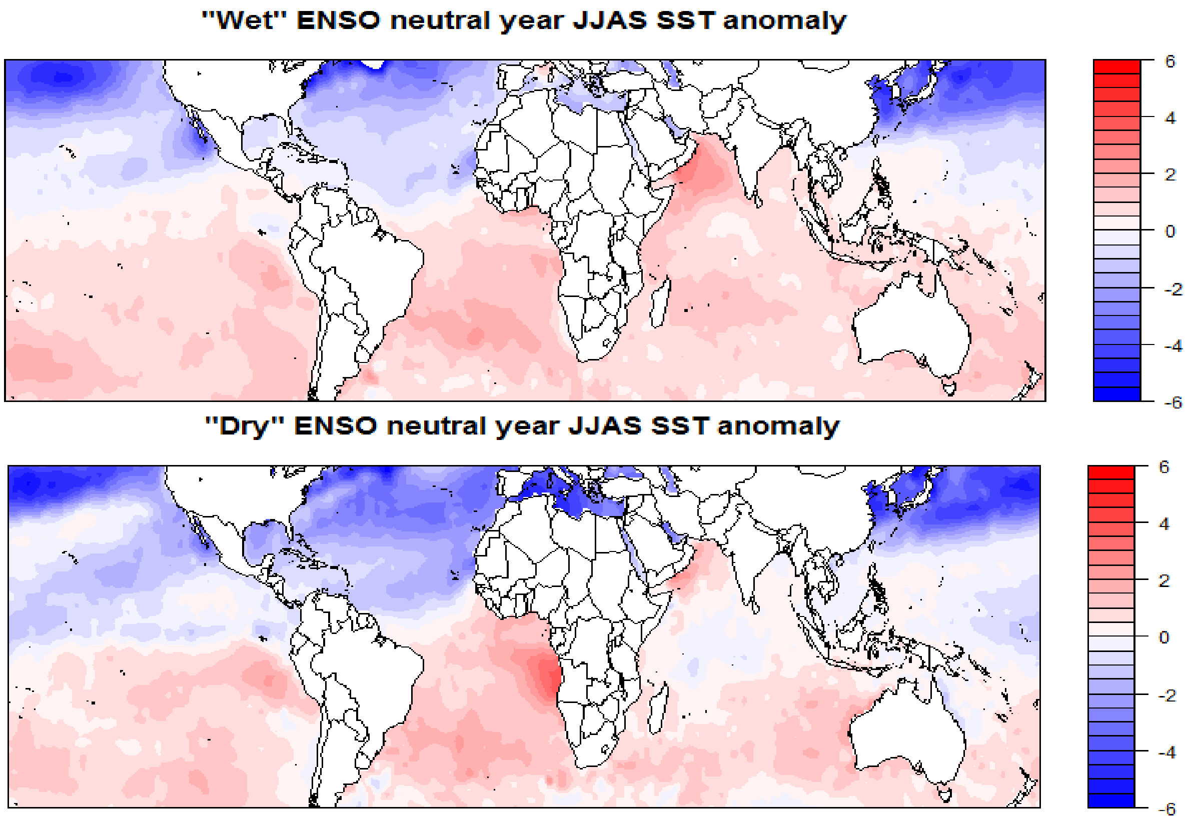


Figure 25: Sea Surface Temperature anomalies from the 1981-2012 mean for single "wet" and "dry" ENSO-neutral years (as defined in Table 1). Anomalies in °C. Significance testing unavailable for individual years.

For comparison, Figure 25 demonstrates the anomalies associated with wet and dry years in Sudan when ENSO is in a neutral state. These are single year case studies as opposed to sampled averages, precluding the use of statistical significance testing on any anomalies found. Despite this limitation, some interesting patterns emerge. Changes in the Indian/Atlantic ocean SST dipole are evident, with a slightly cooler Indian Ocean and a very warm southern/central Atlantic Ocean being noticeable in the "dry" example, with a stronger SST dipole between the warm tropical and cool northern Atlantic Ocean. Likewise, the Mediterranean shows a very strong warm anomaly in the dry year along with a zonal SST gradient; in the "wet" year the SST is cooler and more evenly distributed. It should be noted that this pattern in Indian/Atlantic SST dipole is the reverse to that proposed by Janicot et al (1996) in their study of the western Sahel; this demonstrates that Sahelian regions further to the west may be influenced by different factors to the eastern edge of the Sahel in Sudan. The presence of savannah and desert land in Sudan may also influence the rainfall totals.

6.2.2 Wind anomalies

Based on data from the NCEP 40-year reanalysis project (Kalnay et al. 1996), wind vectors local to the African continent were analysed in order to consider the mechanisms and atmospheric dynamics responsible for causing wet and dry anomalies over Sudan. Vector wind analysis was performed based on the method described in at the start of this chapter. Owing to the difficulties posed in analysing the statistical significance of wind vectors in a meaningful fashion, the vector wind analysis was supported by a statistical analysis of zonal winds. On account of the predominantly zonal character of the main jets in the region, zonal analysis is largely appropriate for capturing anomalies in the main circulations. The zonal winds were analysed over a global scale in order to consider larger scale anomalies, for example those associated with the Walker circulation. All jets and large scale circulations discussed in this section are as described in section 3.2.2.

The wind vector anomaly for dry years as demonstrated by Figure 26[b] (dry year vector and zonal anomalies) indicates a weakening of the SJ and the WAWJ. Strong easterly anomalies are evident extending across Sudan from the Arabian Sea, extending as far as Niger and interacting with the weakened westerly monsoon circulation. This indicates that the entire zonal flow across northern Africa tends to take on a more easterly component during dry years, weakening the West African Monsoon (WAM) circulation and intensifying the existing easterly flow across the northern Sahel and Sahara. A north-easterly anomaly is visible over the south of the Arabian Peninsula; this may be associated with the weakening of the south-westerly component of the Somali jet slightly to the south. This enhanced low level flow may be responsible for drawing dry air from the Arabian Desert toward the central region of Sudan. The statistical analysis of zonal winds confirms that the easterly anomaly over the Sahel and West Africa is significant to $p < 0.05$, indicating that this level of significance extends from the western Indian Ocean through to the Caribbean. This statistical testing also indicates that the weakening of the SJ is valid to within the same parameters

Conversely, Figure 26[c] demonstrates a marked strengthening in the SJ and the WAWJ during wet years in Sudan. The wet years in Sudan are marked by an absence of any notable wind vector anomalies directly over the region, whereas the major features further afield are mostly enhanced. This may indicate that wet anomalies in Sudan may be attributed to an increase in moisture transport from both the Indian Ocean (via the SJ) and the Gulf of Guinea (via the WAM westerly circulation), whilst strongly anomalous flow directly over Sudan may not be conducive to increased convective activity (for example causing increased surface level divergence in the region). The enhancement of the WAM circulation and the SJ may lead to increased surface level convergence over Sudan, encouraging convection. The statistical analysis of zonal winds for wet years, however, indicates that the anomalies are less significant in the Sudan region than in dry years. Zonal anomaly significance is restricted to the Atlantic coast of West Africa and further afield in the Pacific Ocean. The broad scale zonal analysis suggests a weakening of the Azores High cyclonic circulation, possibly suggesting a less intense high pressure and a link to the intensity of the NAO. This will be further analysed in the MSLP composite analysis (section 6.2.5).

The 600 hPa wind vectors (Figure 27) indicate anomalies in the African Easterly Jet; one of the key circulations across northern Africa. The AEJ is important for moisture transport across northern Africa, and interactions with jet systems at other pressure levels may create the convergent or divergent systems necessary for the generation or suppression of convection (Stensrud 1996). Figure 27[a] indicates the AEJ's path bisecting northern Africa from east to west, extending across central and southern Sudan. Also visible are the higher altitude reaches of the Somali jet, displaced slightly toward the equator relative to the main low altitude jet core.

Figure 27[b] indicates the mid-tropospheric wind anomalies in dry years for Sudan. The vectors appear to suggest a southward displacement of the AEJ, with the main westerly anomalies lying over the Horn of Africa, whereas the mean flow enters east Africa approximately over Djibouti/northern Ethiopia, some distance to the north. Some weakening of the Somali jet is evident here, particularly in the easterly component. This would be consistent with the 850 hPa analysis and would indicate reduced moisture transport from the southern Indian Ocean. The statistical testing on the zonal wind anomalies appears to confirm a significant displacement of the AEJ toward the south of its mean position, with the jet located over coastal West Africa.

Figure 27[c] shows wind vector anomalies to the north of the mean AEJ position, with westerly anomalies over West Africa. This would appear to indicate a northward shift in the AEJ, with a particular reduction in its influence over southern West Africa. A large increase in the influence of the SJ is visible along the coast of East Africa, again agreeing well with the observations of the SJ at 850hPa and indicating increased moisture transport from the Indian Ocean. As with the dry years, the statistical analysis indicates significance in the northerly displacement of the AEJ and strengthening in the high altitude levels of the SJ.

Analysis of the upper tropospheric (200 hPa) wind anomalies (Figure 28) highlights the role of the TEJ in Sudanese rainfall variations. The mean TEJ location is around 5-10°N over East Africa, with the jet core decaying rapidly over Sudan and diverting to a more southerly position of around 5°N over West Africa. Other circulations in the region are a westerly flow over the northern coast of Africa and the Mediterranean, and a strong westerly over the southern tip of the continent.

Figure 28[b] shows anomalies in the upper level circulation in dry years. Minimal change is evident in the area of the mean position of the TEJ over central and eastern Africa and the Indian Ocean when viewed as vector wind anomalies. The westerly over northern Africa has intensified and an anomalous westerly flow is evident to the south of the equator around the Gulf of Guinea. However, a different picture is evident when the zonal significance test is considered. This appears to show a southerly displacement of the TEJ across Sudan and strong westerly anomalies over the Atlantic and West Africa.

In wet years (Figure 28[c]) there appears to be an increase in the TEJ strength, with a displacement to more northerly latitudes across all of northern Africa. An intense easterly anomaly is seen over southern Africa and the Gulf of Guinea. Zonal significance testing appears to indicate significance in a northerly displacement and intensification of the TEJ, with easterly anomalies over the majority of the tropical Atlantic.

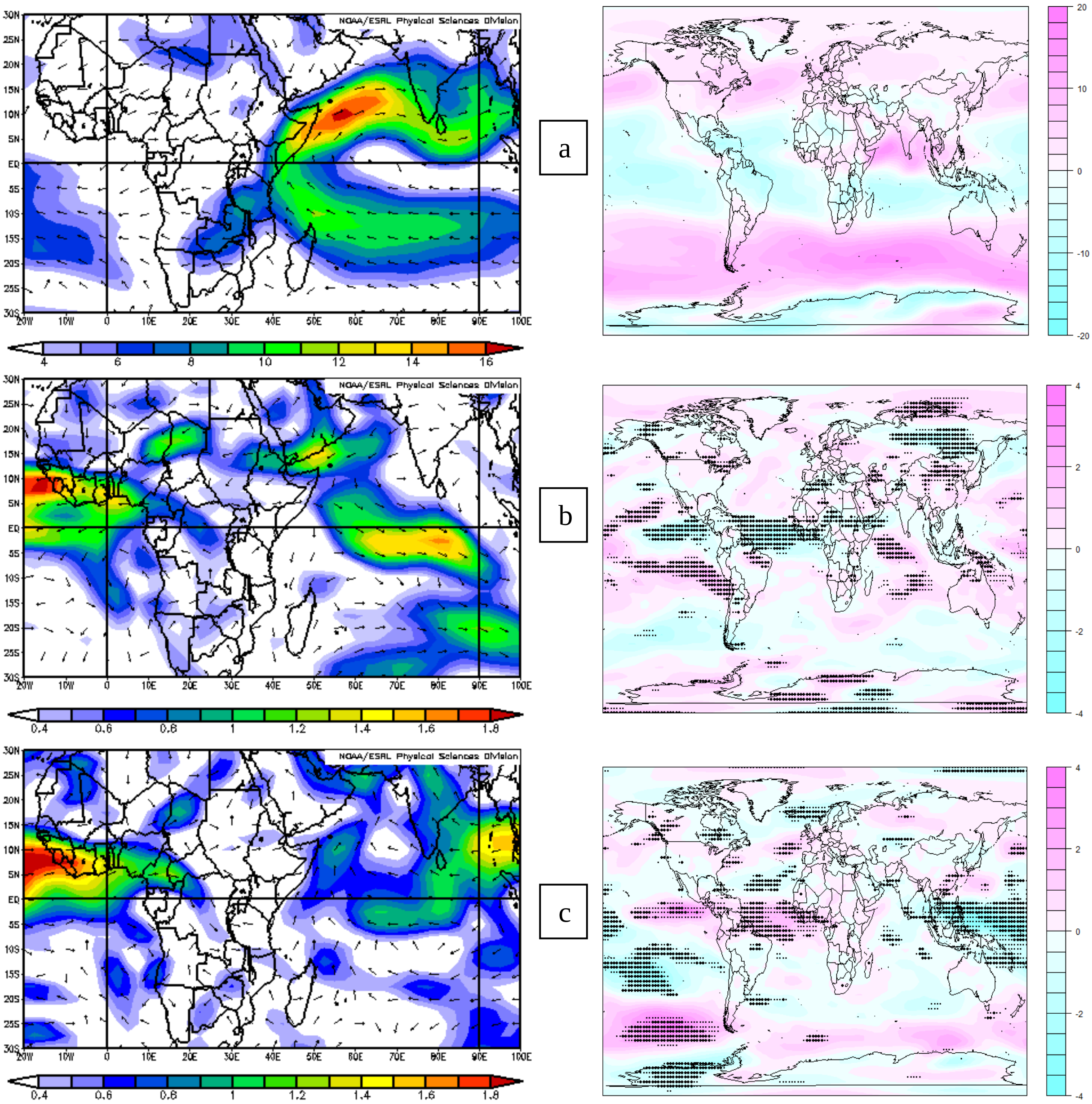


Figure 26: 850 hPa vector (left) and zonal (right) wind means and anomalies based on NCEP 40 year reanalysis. From top: [a] mean values 1981-2010; [b] dry year anomalies; [c] wet year anomalies (per Table 1). Significance marks on zonal anomalies represent significance to $p < 0.05$ (large dots) and $p < 0.10$ (small dots). Scale in ms^{-1}.

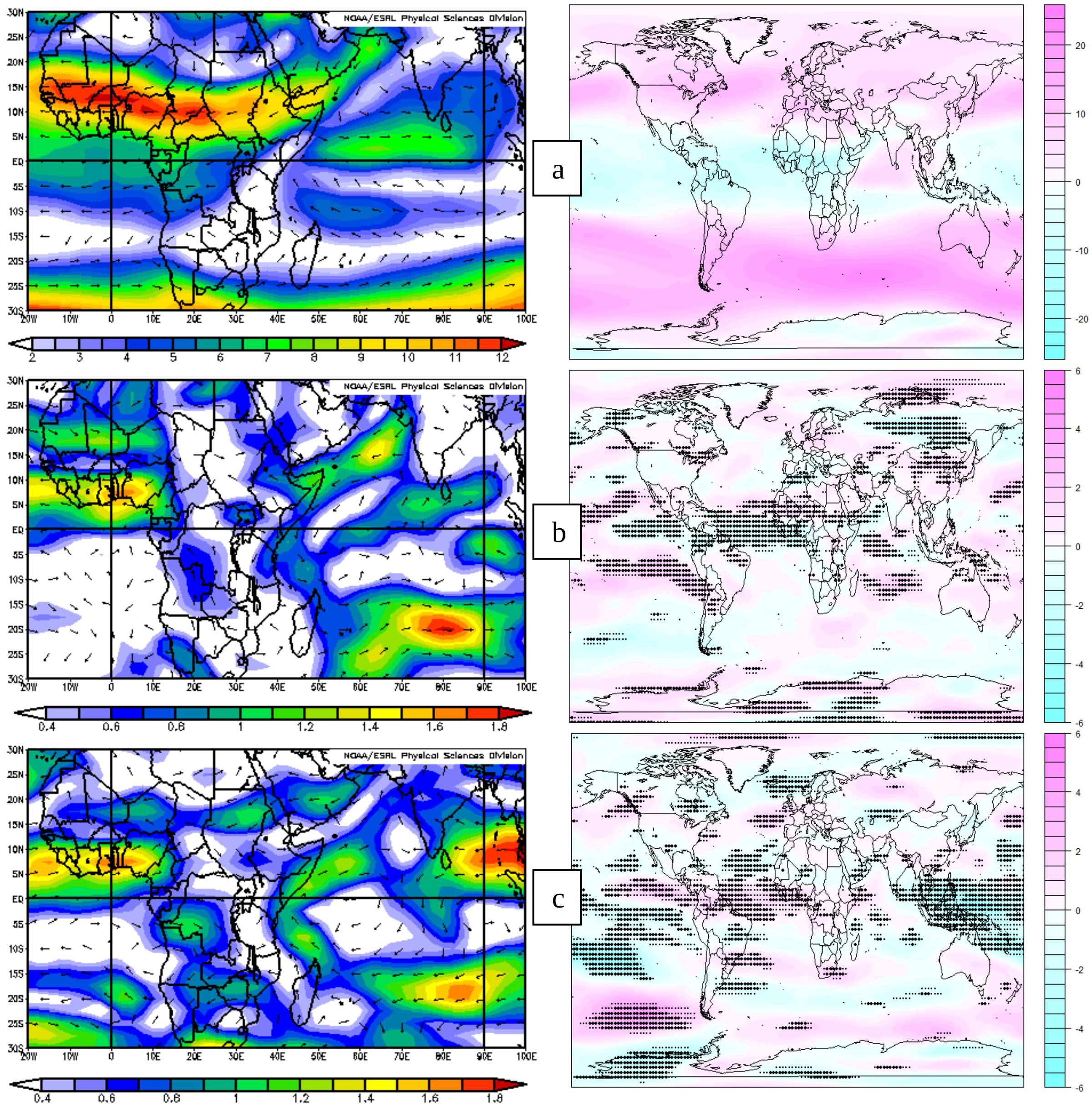


Figure 27: 600 hPa vector (left) and zonal (right) wind means and anomalies based on NCEP 40 year reanalysis. From top: [a] mean values 1981-2010; [b] dry year anomalies; [c] wet year anomalies (per Table 1). Significance marks on zonal anomalies represent significance to $p < 0.05$ (large dots) and $p < 0.10$ (small dots). Scale in ms^{-1}.

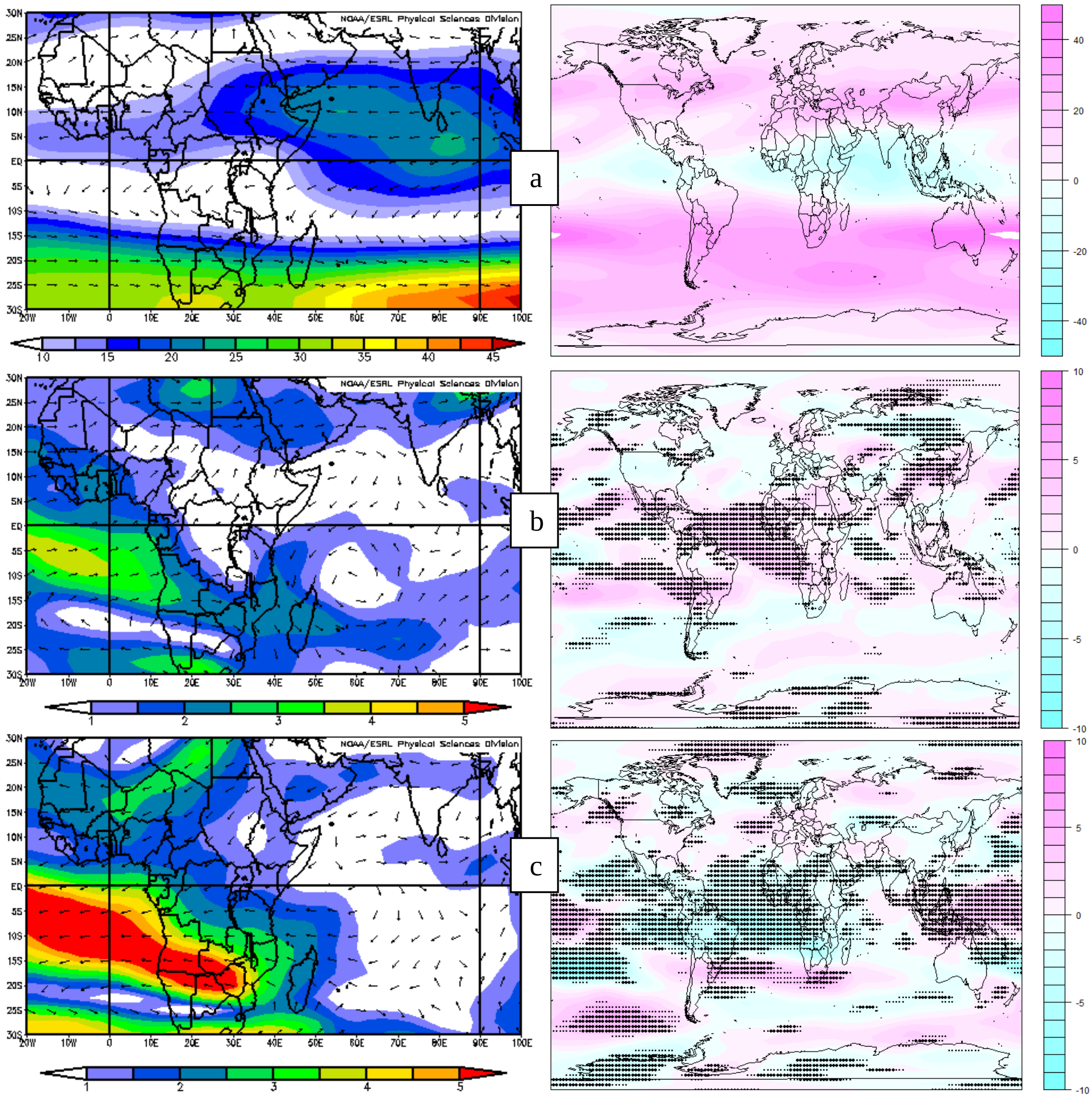


Figure 28: 200 hPa vector (left) and zonal (right) wind means and anomalies based on NCEP 40 year reanalysis. From top: [a] mean values 1981-2010; [b] dry year anomalies; [c] wet year anomalies (per Table 1). Significance marks on zonal anomalies represent significance to $p < 0.05$ (large dots) and $p < 0.10$ (small dots). Scale in ms^{-1}.

Having considered the wind anomalies over an averaged sample of wet and dry years, vector winds were considered for the two case study years where ENSO was in a neutral state, as described in section 6.2. The results are indicated in Figure 29, demonstrating anomalies for wet and dry years (left and right respectively) at pressure levels of 200, 600 and 850 hPa (top to bottom respectively). It appears that the ENSO-neutral analysis broadly conforms to the anomalies seen in the 5-year means.

At 200 hPa (Figure 29[a]) the TEJ appears to be strengthened to the north of Sudan, whilst a strong westerly anomaly is evident over the north African coast. An upper level cyclonic anomaly over central and southern Asia is evident in the dry year analysis which is not seen in the five-year sample (Figure 28).

In the mid troposphere (Figure 29[b]), anomalies are mostly consistent with the five year mean analysis (Figure 27), with strengthened westerlies over West Africa and enhanced SJ activity over the Indian Ocean during the wet year, the inverse being the case in the dry year.

At low levels (Figure 29[c]) again the ENSO-neutral analysis shows similar patterns over West Africa to the 5-year means (Figure 26), showing an enhanced WAM circulation and SJ in wet years. However, a new feature is visible hear in the form of strengthened northerly trades in the wet year. The dry year shows an anomaly drawing air from the Arabian Peninsula into central Sudan.

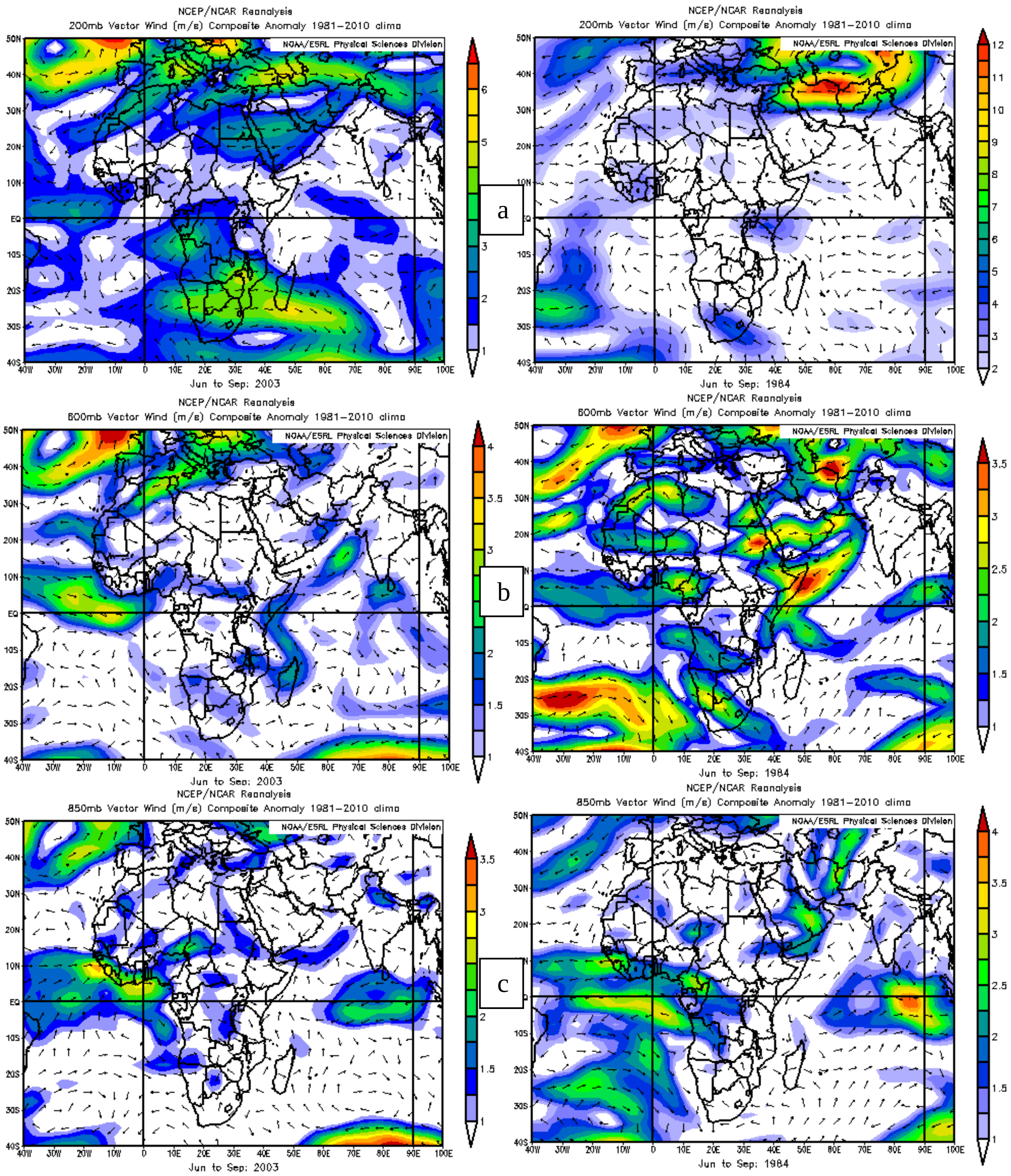
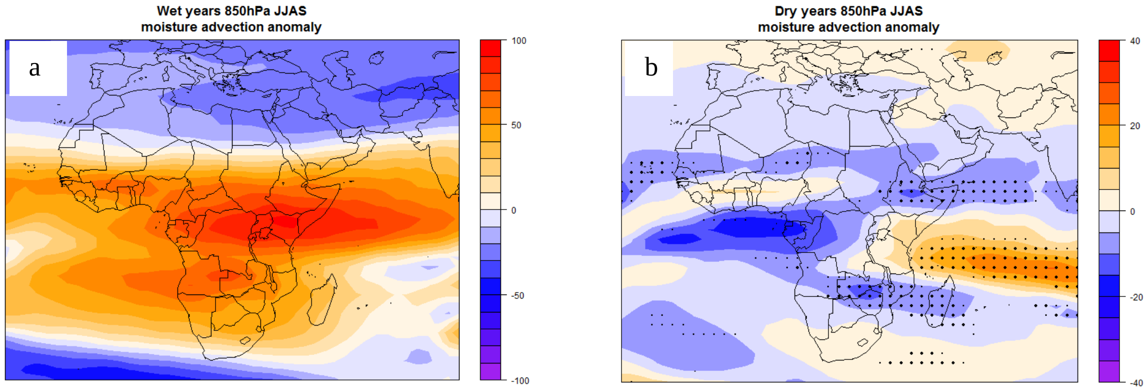


Figure 29: Vector wind anomalies for "wet" and "dry" (left and right respectively) ENSO-neutral case study years (see Table 1). From top: [a] 200 hPa [b] 600 hPa [c] 850 hPa. Scale in ms^{-1} From NCEP 40 year reanalysis data.

6.2.3 Moisture advection



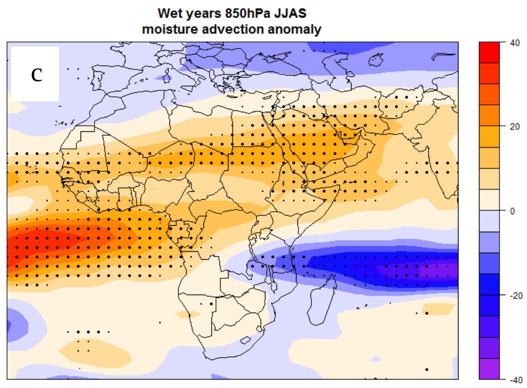


Figure 30: Moisture advection calculated as specific humidity multiplied by zonal wind. Warm colours imply westerly moisture advection. Clockwise from top left: [a] Mean [b] Anomaly in "dry" years [c] Anomaly in "wet" years. Data from NCEP 40 Year Reanalysis.

Moisture advection at low levels (i.e. 850 hPa) is one of the more important variables in generating well developed mesoscale convective systems. Determining the main sources of atmospheric moisture can assist in determining the anomalies responsible for anomalous rainfall over a region. Much research has linked the role of the low level jets to moisture advection in EEA and West Africa; however northern East Africa is less comprehensively studied.

Low level moisture advection was calculated in a simplistic fashion by making two key assumptions. Firstly, it is assumed that the majority of air flow over Africa can be represented well by its zonal component. This captures most of the strong atmospheric circulations, however it should be noted that this assumption will fail to represent any anomalies in the northerly trades, the meridional component of the Somali Jet, or any meridional fluctuations in predominantly zonal flows. The second assumption is that moisture advection can be approximated as the product of specific humidity and lateral air flow. This captures the large scale movement of atmospheric moisture, but will fail to account for factors such as vertical movement and convective mixing of atmospheric moisture.

Whilst acknowledging the limitations of this method, certain conclusions may still be drawn. Figure 30[a] shows the mean moisture transport during JJAS over Africa, which demonstrates a broadly similar pattern to the mean 850 hPa JJAS zonal wind shown in Figure 26[a]. Moisture advection appears to predominantly occur as a westerly for throughout equatorial regions, and up to the northern extent of Sudan, with easterly flow dominating further to the north. A region of particularly high advection appears to the east of the Congo rainforest, possibly indicating a role for evapotranspiration over densely forested areas for providing moisture to the atmosphere. Sudan itself appears to be on the border between the influence of the westerly flows of central Africa and the easterly flows of northern Africa.

Anomalies in the transport of moisture as demonstrated in Figure 30[b] and [c] indicate the relative importance of different systems on wet and dry years. In the wet year analysis a highly significant westerly anomaly is evident over the Gulf of Guinea, with another band of increased westerly flow evident across the entire Sahel region from the tropical Atlantic through to the Arabian Peninsula. This appears to bring increased levels of moisture to northern Sudan. Increases are also seen in moisture transport in the zonal component of the Somali Jet, although these increases are less statistically significant than the westerly anomalies. In dry years, on the other hand, moisture transport in the Somali Jet appears to be very significantly reduced. Whilst there appears to be some weakening to the westerly transport through the Sahel, this does not show nearly the same level of significance as the anomalies in wet years. This demonstrates a non-linearity in the mechanisms determining wet and dry years in Sudan due to moisture advection.

6.2.4 Vertical wind

Omega (vertical wind velocity) was analysed in order to consider if changes in rainfall could be attributed to anomalies in the ascending or descending branches of the Walker circulation. Figure 31[a] shows the mean JJAS vertical velocities averaged over 1981-2012, from the NCEP 40 year reanalysis data. This shows familiar features of the Walker circulation, for example large scale ascent to the east of the Maritime Continent with descent in the eastern Pacific. Ascent is visible over eastern Africa, as would be expected as a result of convection during Sudan's rainy season.

Statistical analysis was performed on anomalies in dry and wet years, as indicated in Figure 31 [b] and [c] respectively by the presence of contour lines. Very little significance is evident over Africa, with the largest areas of significance being over the Atlantic and western Pacific, showing ascent anomalies in the Atlantic and descent in the Pacific during dry years, and the inverse during wet years.

The lack of significance observed in the vertical wind anomalies is likely to be due to the extremely localised nature of vertical motion in the atmosphere. Whereas consistent patterns form when considering long term averages (such as Figure 31[a]), when considering sample years the anomalies are likely to be small and to vary spatially, causing low significance as observed in Figure 31[b] and [c].

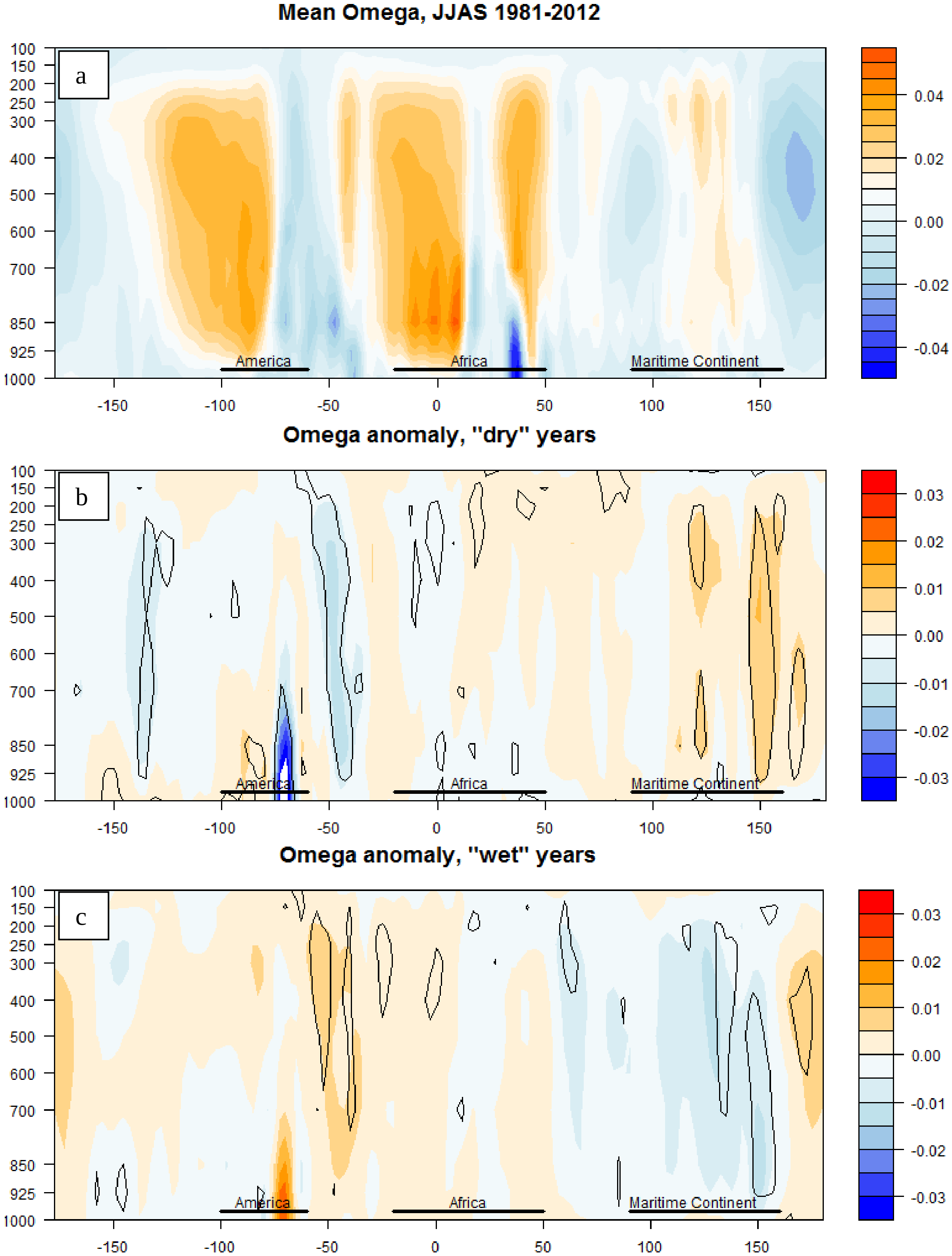


Figure 31: Omega (vertical velocity) cross sections. All longitudes, pressure 1000 - 100 hPa, averaged over latitudes 0-25°N. From top: [a] Mean values [b] Anomalies in dry years [c] Anomalies in wet years. Contour lines represent regions of significance to $p < 0.05$. From NCEP 40-year reanalysis. "Warm" colours indicate descent. Markers indicate approximate maximum longitudinal extent of continents between 0-25°N.

6.2.5 Mean Sea Level Pressure

Correlations with MSLP were demonstrated in section 6.1.2, which were linked to the possibility of changes in the Walker circulation influencing Sudanese rainfall.

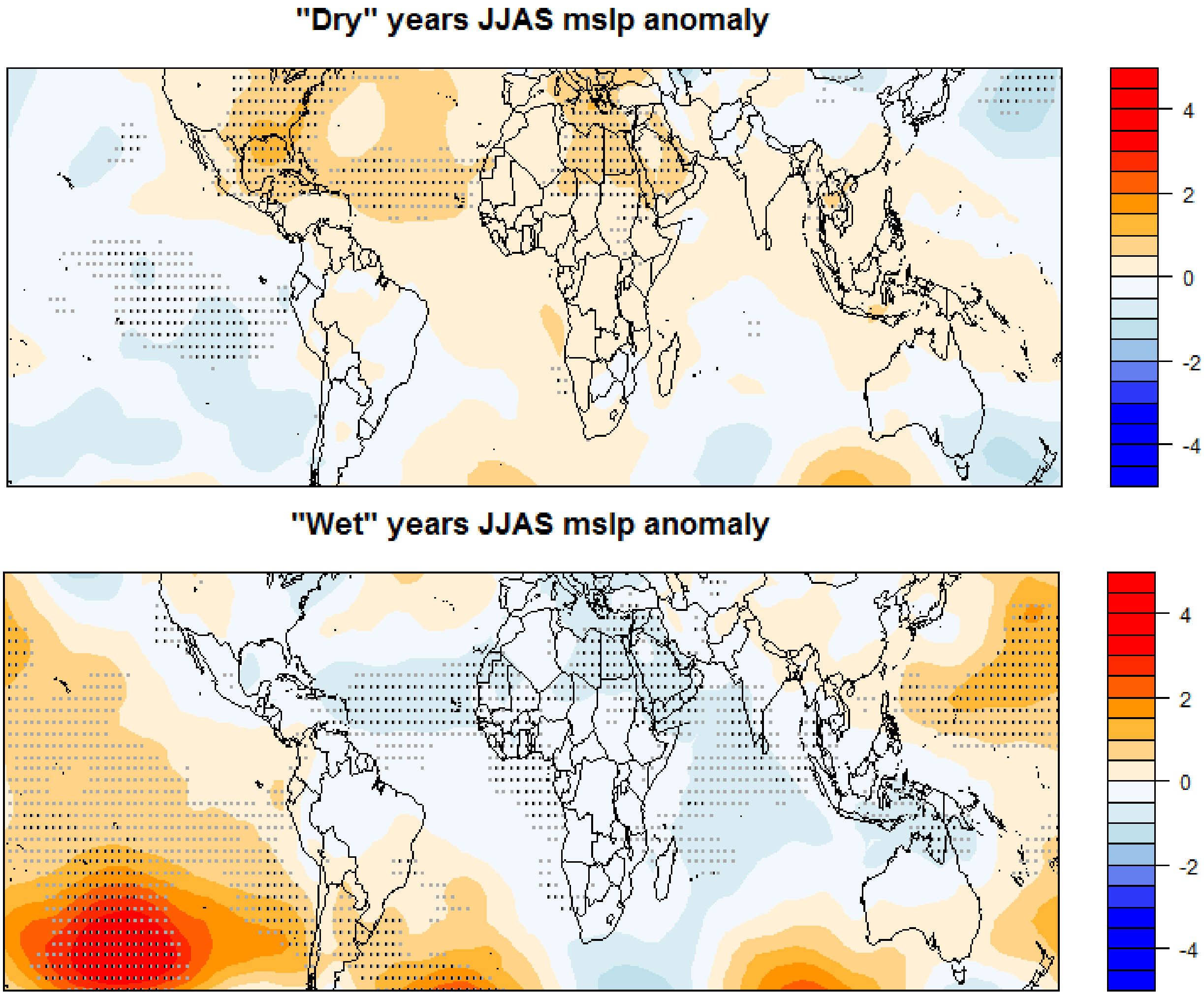


Figure 32: MSLP anomalies relative to 1981-2012 mean during JJAS. From top [a] "Dry" years in Sudan [b] "Wet" years in Sudan. Overlaid markers indicate significance to $p < 0.05$ (large markers), $p < 0.10$ (small markers). Data from NCEP 40 year reanalysis.

Figure 32 indicates high and low pressure anomalies over northern Africa for dry and wet years respectively. The dry year analysis also indicates an increase in tropical Atlantic MSLP, and a decrease in the central and eastern Pacific. This is consistent with an increase in the Azores High, and a pattern in the Pacific indicative of El Niño. The wet years analysis indicates a decrease in central Atlantic and Indian Ocean MSLP, with an increase in the central and eastern Pacific and the Gulf of Guinea.

7 Trends in variables controlling rainfall

To consider potential future changes in Sudanese rainfall, it is necessary to consider the expected changes in the variables which have been shown to be related through the correlation and composite analysis in section 6. To begin to consider the expected changes in these variables, each was correlated (using the method described in section 6.1) against a trend; in this case an ascending numerical sequence. This method results in positive correlations in variables which have been increasing during the time period under consideration, and negative correlations where they have been decreasing. The time period was kept to 1981-2012 for consistency with the previous analysis and to match with the TARCAT data used in this project.

7.1 Precipitation trend

Precipitation data from the NCEP 20th Century Reanalysis and GPCP was correlated against a trend series, in order to corroborate the trends demonstrated in section 5. NCEP precipitation is known to contain certain inaccuracies, particularly over Africa (Diro et al. 2009); however it is useful for a long time series overview of the situation over a broad area.

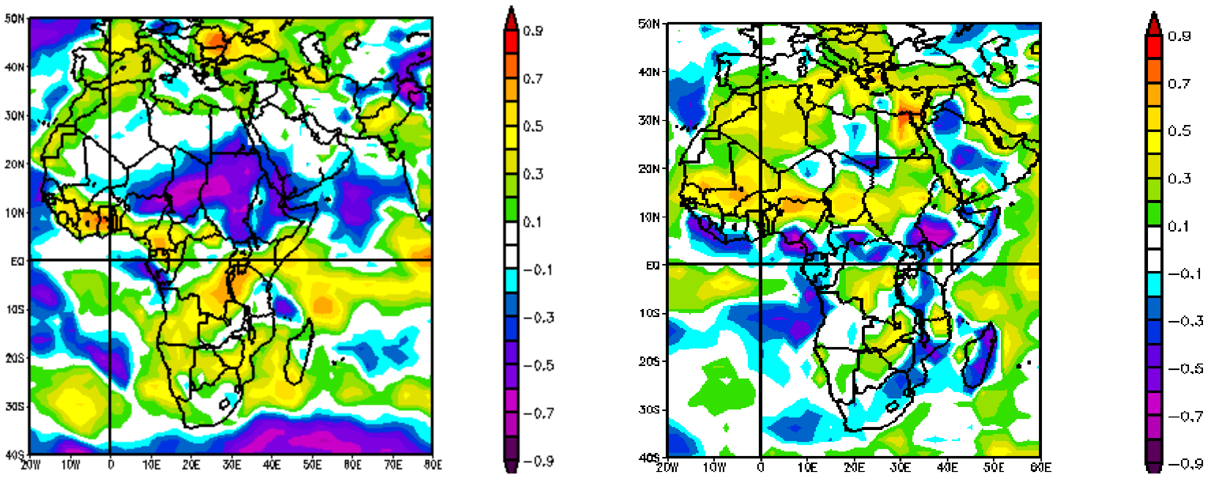


Figure 33: JJAS precipitation correlation against a trend series over Africa. [L]: 1948 – 1980 from NCEP reanalysis [R]: 1981 – 2010 from GPCP. NCEP used for historical analysis due to temporal extent of data; GPCP used for more recent analysis due to its higher levels of accuracy. NCEP demonstrates broadly similar correlations in large scale precipitation patterns over the same time period.

Figure 33 confirms the declining pattern of precipitation over Sudan prior to 1980, with an increase in rainfall during the period covered by TARCAT. This pattern is consistent with the decline in precipitation observed in the study by Lyon & DeWitt (2012), emphasising the localised precipitation regimes affecting different areas of East Africa. The contrast between the 1948-1980 trend and that of 1985-2010 explains the apparent inconsistency between the findings of this project demonstrating an increase in rainfall over Sudan and prior studies which demonstrate a decline in rainfall (i.e. Hulme 1990, Zhang 2011).

7.2 Sea Surface Temperature

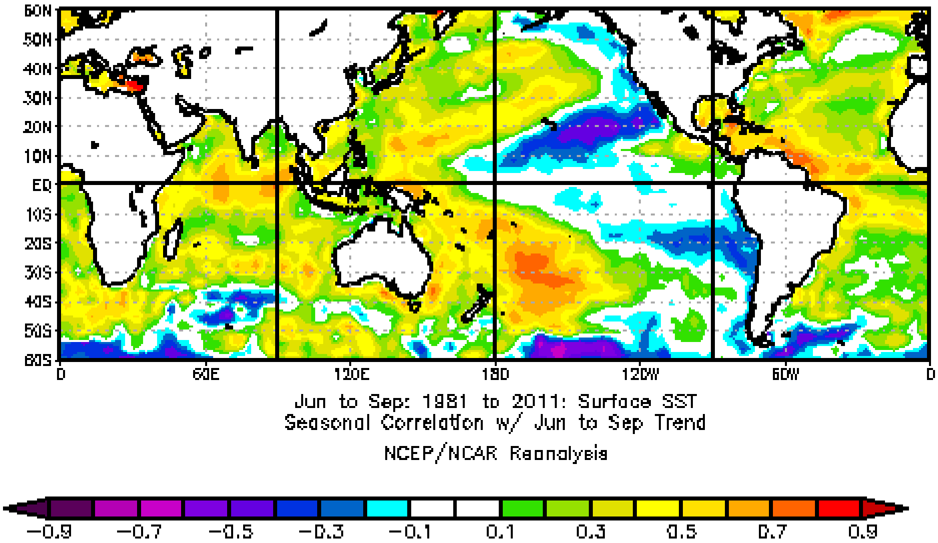


Figure 34: SST trends 1981-2012, expressed as a correlation between SST time-series and an ascending numerical sequence. From NCEP linear correlation plotting tool (NOAA ESRL PSD 2012b)

Figure 34 indicates a rise in SST during the time period analysed for most areas in the tropics, with the exception of the northern and southern edges of the Pacific Cold Tongue, where negative correlations indicate a reducing temperature. Particularly high correlations are observed in the eastern Mediterranean / Black Sea, the South Pacific and the western tropical Atlantic.

When compared with Figure 20 (correlation between TARCAT-derived rainfall data and SST during JJAS 1981-2011), a very similar pattern is evident, indicating that rainfall correlations are consistent with the observed trends presented above. This is also consistent with the "wet" years SST/rainfall anomaly composite demonstrated in Figure 24, with the trends in the Atlantic, western Pacific, Indian Ocean and eastern Mediterranean being consistent with favourable conditions for increased rainfall over Sudan.

7.3 Zonal wind

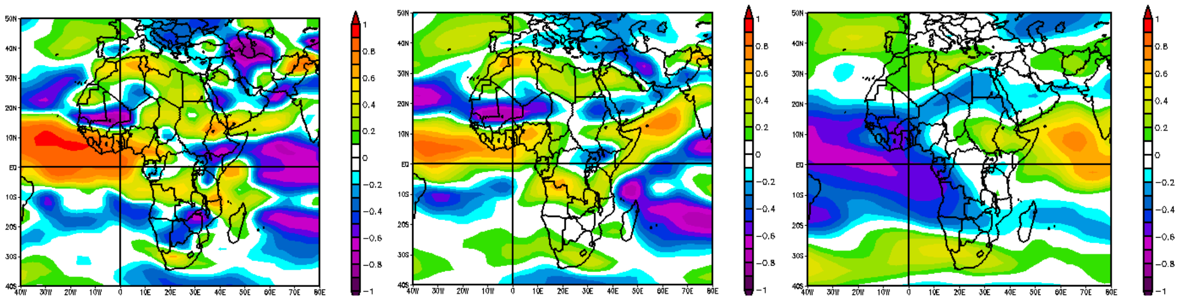


Figure 35: JJAS zonal wind trend correlations, 1981-2012. Warm colours indicate increasing westerly flow. From left [a] 850 hPa [b] 600 hPa [c] 200 hPa. From NCEP linear correlation plotting tool (NOAA ESRL PSD 2012b)

Zonal wind shows several correlations with the trend series at significant levels. At 850 hPa the zonal wind shows an increased westerly component extending from the Atlantic and Gulf of Guinea across West Africa and across Sudan. Westerly flow is also increasing over the north coast of Africa, whilst zonal wind is increasing its easterly component over the equatorial Indian Ocean, extending into EEA. This implies that convergence over the south of Sudan may be increasing, generating more favourable conditions for convection.

The trend analysis at 600 hPa shows very similar patterns to 850 hPa, albeit with a more consistent increase in easterly component across northern Africa, above the Sahel. When compared with Figure 27 (600 hPa JJAS wind vectors and zonal anomalies), it is possible that this indicates a displacement of the AEJ toward the north; however more focussed research would be required to establish if this is the case.

At 200 hPa the easterly flow appears to be increasing through time over northern Africa, extending through to West Africa and the Gulf of Guinea. An increasing westerly component is evident above the Greater Horn of Africa and the northern Indian Ocean. This indicates an increase in upper level divergence over central Africa, centred over Chad, Nigeria and the Central African Republic, increasing convective potential in this region; however it is possible that the locations of these regions of increasing convergence and divergence may be altered by a meridional component. When compared with Figure 28 (200 hPa JJAS wind vectors and zonal anomalies), this trend pattern appears to indicate a northerly movement of the TEJ.

7.4 Pressure and geopotential height

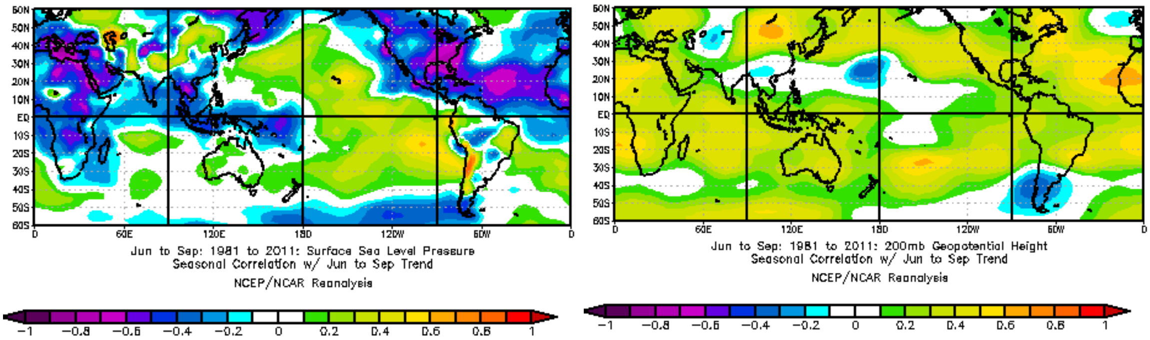


Figure 36: MSLP (left) and 200 hPa geopotential height correlations with a linear numerical sequence (trend analysis). Warm colours indicate increasing trend. From NCEP linear correlation plotting tool (NOAA ESRL PSD 2012b)

Figure 36 demonstrates recent trends in MSLP (left) and 200 hPa geopotential height (right). MSLP appears to be decreasing over the majority of the African continent, including the area around Sudan. This reducing trend is mirrored in the tropical Atlantic, equatorial Indian and western Pacific Oceans, whilst an increase in MSLP is noted in the central and western Pacific. 200 hPa geopotential height is shown to be rising across the majority of Africa, although the trend correlation is shown to be strong in the north-west with less significant trends in eastern regions. The increase is consistent in the equatorial and southern Indian Ocean, and in the tropical Atlantic. Most of the central Pacific shows no correlation with the trend series, suggesting little or no change to 200 hPa geopotential height in the area.

8 Discussion

Investigation of the observation data from GHCN and TARCAT lends support to recent studies of rainfall variability in Sudan (Hulme 1990; Zhang et al. 2011) in their findings of a reduction in rainfall volumes in the early part of the 20th century (prior to 1980). However, contrary to the Zhang et al (2011), a marked increase in rainfall was noted after 1980 in the TARCAT dataset. It is believed that this increase is observed due to the high levels of consistency found in TARCAT due to its use of long time-series satellite data. The GHCN rain gauge network in Sudan declines dramatically in number after 1980 (Figure 11), and NCEP Precipitation Reconstruction, as used by Zhang et al (2011), has known flaws over north-eastern Africa (Diro et al. 2009). This inspires confidence in TARCAT being one of the most reliable sources of rainfall climatology data in Sudan, and in the accuracy of the rainfall variability analysis produced from this data.

One particular aim of this study has been to compare the findings of Lyon & DeWitt (2012) (and closely related studies such as Williams & Funk 2011) in EEA with rainfall variability in Sudan, in order to establish to what extent variability in the EEA area and in the mechanisms affecting EEA rainfall can be expected to affect Sudan and the northern reaches of the ITCZ travel within East Africa.

It is evident from the initial analysis of variation in observed rainfall that the JJAS rainy season of Sudan has notably different characteristics to the MAMJ long rains of EEA, and as such as influenced by different factors. Williams & Funk (2011), for instance, assert that an increase in Indian Ocean SST is responsible for a drying effect in EEA. As indicated in Figure 24, a statistically significant warm anomaly is found in the Indian Ocean during wet years in Sudan, indicating an opposite response to warming in this more northerly region.

Having established that rainfall in eastern Africa is variable in its fundamental characteristics over a relatively small spatial scale, it has become necessary to determine which variables control the characteristics of rainfall in Sudan. This was found to be a somewhat under-researched area in the literature review (Section 3.1.3), so a number of variables were analysed for their correlation with a rainfall time series derived from TARCAT over the region of Sudan.

SST correlation analysis demonstrated a strong “La Niña” pattern correlation in the Atlantic. This is expected of many variables in the tropics, however this went further to demonstrate that influencing factors behind Sudanese rainfall differ greatly from those in EEA, since Williams and Funk (2011) demonstrated clearly that Indian Ocean SST is the dominant factor in the long rains variability of EEA. A number of authors have also stated that ENSO has minimal effect on the long rains of EEA (Camberlin & Philippon 2002; Camberlin & Okoola 2003; Lyon & DeWitt 2012); although most agree that ENSO has a strong influence on the intensity of the short rains (Schreck & Semazzi 2004; Sun et al. 1999).These studies also indicate that where a correlation is found with ENSO in the rainfall in EEA, it is El Niño, not La Niña, that brings about an increase in precipitation, providing another example of an opposite response to a controlling variable in rainfall in Sudan when compared to EEA.

Since a strong ENSO correlation is so regularly seen in the tropics, the weaker correlations elsewhere were analysed in more detail, since it is these regions that tend to directly influence the rainy season. Significance was found in the SST of the western tropical Atlantic and the Indian Ocean as well as the eastern Mediterranean and Black Sea. This was supported by significance testing in the composite analysis, which appeared to demonstrate that the Atlantic and Indian Oceans showed the most significant anomalies during the extreme wet years in Sudan, with positive anomalies in both bodies of water being conducive to high total rainfall. Dry years appeared to be less affected by the Atlantic and Indian Ocean, but a strong association was drawn with negative Mediterranean SST anomalies. This was further supported by the analysis of an ENSO-neutral dry year, which showed an extremely low SST anomaly in the eastern Mediterranean. SST trend correlation analysis indicates a particularly strong correlation in the eastern Mediterranean, with a warming trend shown over the entire Mediterranean and Black Sea. With respect to the composite analysis, and particularly the ENSO-neutral case study years, this appears to be favourable to rainfall in Sudan.

Investigation of wind anomalies and moisture advection gave an indication of the ways in which modifications to the mean atmospheric circulation could influence rainfall totals, with high rainfall generally being associated with increased jet and circulation activity at low levels in the troposphere, and by the intensity and positioning of upper level jets. Especially high significance in the wind analysis during wet years was placed on the intensification of the WAM westerly circulation and the SJ, with the northerly trades appearing important in the ENSO-neutral analysis. Given that these circulations converge in the region around

Sudan, the increased low level convergence may be responsible for enhancing convective activity, with the increase in moisture advection to the region enhancing this effect and increasing the available of precipitable water vapour (as per Pu & Cook 2010). In dry years it is generally shown that these circulations are weaker, reducing both convergence and moisture advection.

It is noteworthy that in the zonal moisture advection analysis, very strong significance was placed on advection eastward from the Gulf of Guinea (and to a lesser extent the tropical Atlantic), whilst an increase in advection via the zonal components of the Somali Jet was evident but less dominant. In dry years, very little association was found with advection from the Atlantic and Gulf of Guinea, whilst a high level of significance was placed on the reduction of moisture transport via the zonal components of the Somali Jet. This is indicative of a non-linearity in the system, suggesting perhaps that moisture from the Somali Jet circulation is responsible for maintaining a normal level of precipitation, whilst precipitation in peak years is enhanced by additional moisture drawn from the Gulf of Guinea. It would appear that when the westerly transport from the Gulf of Guinea is less strong, this has little effect in causing drought, whilst a reduction of moisture transport from the Indian Ocean has the potential to cause extremely dry conditions in Sudan.

Analysis of trends in zonal winds since 1981 has indicated a strong increase in westerly flow over the Gulf of Guinea, along with a more moderate enhancement of the zonal components of the SJ. Combined with an almost universal increase in SST's during the last thirty years, this should be acting to increase moisture advection in the two dominant low levels flows controlling rainfall in Sudan; this is consistent with our observations of a rainfall increase in recent years.

The vector anomalies indicate a possible increase in the northerly trade winds during the wet ENSO-neutral year. Whilst few conclusions may be drawn without considering several cases, during this case study year it is evident that the enhanced northerly trade winds provide a mechanism by which moisture is advected from the Mediterranean Sea to the north. The statistically significant SST anomalies in the eastern Mediterranean may prove to be both a source of atmospheric moisture and the initiating factor for the increased trade winds.

Considering mid-tropospheric circulation, the AEJ was shown to reduce in intensity or to flow at more northerly latitudes during particularly wet years in Sudan. This may indicate a convection suppressing effect of the AEJ, as suggested by Cook (1999) in the hypothesis that the AEJ may advect water vapour from east to west, drying the mid troposphere and reducing convective activity to the east.

At upper levels, the positioning and intensity of the TEJ was shown to be important with a more intense and northerly displaced flow being significant in wet years, and a weaker, more southerly jet being the norm in dry years. This supports evidence presented in the review of the influence of the TEJ on rainfall in Sudan produced by Hulme & Tosdevin (1989), who suggested that upper level divergence to the south of the TEJ jet exit region over Sudan could strongly enhance the level of convective activity. The trend in upper level zonal winds shows an enhancement of easterly flow to the north of the mean position of the TEJ, indicating an increasing northerly displacement. As with trends noted in many other controlling variables, this is likely to support heightened levels of rainfall across Sudan.

Considering MSLP changes allowed us to relate the SST and wind fields by considering the manner in which these circulations are driven throughout the tropics. MSLP also gave an indication of the structure of circulation patterns such as the Walker cell, since the usefulness of vertical wind anomalies are limited by their high degree of localisation.

The consideration of pressure anomalies and their influence on large scale circulation patterns brings into question the role of oscillations such as the NAO on African precipitation. The MSLP analysis in section 6.2.5 indicated anomalies in the Atlantic consistent with a strengthening of the NAO during dry years and a weakening in wet years. Whilst little reference has been made to the effects of the NAO on African rainfall in the literature to date, several authors have drawn correlations between the Atlantic-Indian Ocean pressure dipole and rainfall in Africa (Camberlin & Philippon 2002). A reduction in pressure to the north of the equator might be seen as steering the easterly jets toward the north, which has been shown to be the preferred situation for a wet summer in Sudan. The high pressure anomaly in the Gulf of Guinea seen during wet years might also be seen as instrumental in enhancing the WAM westerly circulation, which again has been shown to be strongly correlated with Sudanese rainfall.

Relating this study to future predictions, the trend correlation analysis presented in section 7 shows several strong suggestions that conditions have been becoming more favourable for wet conditions in Sudan over the last thirty years. SST in the eastern Mediterranean shows an increasing trend, and the major zonal wind circulations all appear to have been moving to a more favourable state for rain in Sudan. The major question is how the state of ENSO will change in time; the trend correlation is very weak in the Pacific Cold Tongue, however several sources including the IPCC AR4 suggest that ENSO is projected to move toward a more “El Niño” like state (Boko et al. 2007) under anthropogenic climate warming. Given the strength of the correlation shown with La Niña, this may prove to be the determining factor in the future intensity of Sudanese rainfall.

9 Conclusions and recommendations for further research

Through the use of the new TARCAT dataset, together with well-established and proven elements of the NCEP reanalysis dataset, this project has demonstrated a previously undocumented increase in the rainfall in Sudan in the past thirty years. Through correlation and composite analysis, controlling variables have been established in terms of atmospheric circulations and the sea surface temperatures which drive these circulations throughout the tropics. Recent trends in these variables are consistent with the observed increase in rainfall.

The observed trends are consistent with changes projected in publications such as the IPCC AR4 (Boko et al. 2007) where data is based on GCM modelling studies under anthropogenic climate change. The localised nature of the response of African precipitation to forcing variables has been established; when compared with previous literature (Lyon & DeWitt 2012) this study corroborates the projected dipole effect in East African precipitation as presented in the IPCC AR4. Whilst the rainfall in Sudan has been increasing in recent years, it has been noted that precipitation totals in equatorial East Africa, particularly in the long rains of boreal spring, have been declining.

Correlations have been established between Sudanese rainfall and meteorological variables in a wider area throughout the tropics, and trends in these variables are consistent both the observed response of rainfall and with projections. However, it is not possible to directly attribute the response of rainfall to changes in individual variables as a result of this study. Future detection and attribution studies would be of considerable interest in advancing the work presented here. In particular it would be useful to consider the comparison of the observed rainfall variability to modelling studies with or without the input of anthropogenic climate forcings.

The TARCAT dataset has been established through this project as a highly useful tool for analysing rainfall in Africa, where rain gauges can be poorly distributed and inconsistent, and where inconsistencies have been noted in datasets such as the NCEP Precipitation Reconstruction. This presents opportunities for wider research throughout Africa, using reliable and consistent satellite data calibrated through the use of local surface observations at sites across the continent.

Opportunities for future research have been demonstrated in a number of areas. Correlations have been demonstrated between rainfall in Sudan and a number of mechanisms usually associated with variability elsewhere in the world; for instance there is a strong possibility that the significance of surface pressure over the Atlantic Ocean on Sudanese rainfall could link rainfall variability to the North Atlantic Oscillation; more commonly associated with weather patterns in Europe and North America. Very limited research has been performed to date linking its effects with Africa, and most of this research focuses on the West African region. Likewise, a high level of significance was found in the surface temperature of the Mediterranean. Previous research in this area has mostly been limited to influences on southern Europe and the northern coast of Africa, with little suggestion of a connection with an inland African region such as Sudan.

The influence of the tropical jets has yet to be fully studied. The influence of the African Easterly Jet is usually researched downstream of its origins, in West Africa. However it is apparent that the strength and location of this jet as it forms above Sudan may be highly relevant. Likewise the Tropical Easterly Jet appears to assert an influence over Sudan, and particular focus could be applied to the effects of the jet exit region on upper level divergence, in addition to any possibility of a continued northerly displacement of the jet.

High levels of significance have been determined in the roles of the West African Monsoon circulation and the Somali Jet, which itself dominates the Indian Monsoon. Teleconnections between the intensity of these two monsoon systems and the rainy season in Sudan may be considered, and a more thorough analysis of the low level circulations would be highly relevant. In particular, it would be beneficial to study the northerly trades and the Somali Jet further, since the meridional component of these two circulations will have been overlooked by the predominantly zonal analysis presented here.

In conclusion, this report has outlined the long term variability found in the rainfall of Sudan and has proposed a number of mechanisms which may provide a controlling influence. TARCAT has been demonstrated as a useful tool in the analysis of African rainfall. Sudan's rainfall has been found to be a rich area for future research, and it is to be hoped that future detection and attribution studies will determine the response of rainfall in Sudan to changes in controlling mechanisms under anthropogenic climate change.

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