Interannual Variability of TRMM RADAR Precipitation over West Africa and the Sahel

Muhammed, I.
Department of Surveying & Geoinformatics, School of Environmental Sciences
Modibbo Adamawa University of Technology, Yola, Nigeria
Correspondence email: im@mautech.edu.ng

Abstract

Precipitation is an important part of the hydrological cycle in West Africa and the Sahel that impacts on water resources, food security and disaster management. Long term satellite observations provide an unprecedented record that helps us determine rates of change in rainfall. The Tropical Rainfall Measuring Mission (TRMM) satellite radar precipitation is important in capturing rain rates at their pixels along its footprint. Daily data has been smoothen using FIR filter to remove spurious signals due to storms. The data is averaged to 3-daily means to allow investigations at shorter time scales. Results show strong interannual spatial variability across the latitudes. Positive rain rates in West Africa corresponds with positive rain rates in the Sahel, even though climatologically the regions are different. Strong positive anomalies corresponds to period of flood, while negative to drought in both the regions. The Guinea coasts experiences rainfall year round with maximum values in June-July months. Short spells of dryness were observed across the timeseries for periods less than 2 weeks. This could be attributed to the impact of anomalous winds akin to westward African Easterly jets (AEJ) that emanates from the east and perturbs the monsoon system. The central aim is to charaterise interannual spatial changes in rainfall across the two regions, and the results herewith serves as useful background conditions to coupled ocean-atmosphere models as well in the assessment of local climate scenarios.

Keywords: TRMM, Rainfall, Interannual Variability, West Africa, Sahel

INTRODUCTION

A larger part of West African and Sahel regions are semiarid and are known for their unreliability of rainfall, which has a large impact on the continental hydrological cycle, water resources as well as food security (Le Barbé *et al*, 2001). The historical impact of dry spell that was almost conspicuous lead to famine (1972-74; 1983-84), prompting many studies to investigate possible mechanisms and events leading to these variability. In the southern humid parts of the region, shortages of rainfall affects productivity due to low water level, leading to shortage of electricity that is generated by water.

Rainfall also cools the environmental during the northern summer, so lack of it allows temperatures to plummet, further affecting health especially of the elderlies. Rainfall over these regions is majorly monsoonal, hence its greater influence is sea surface temperature – SSTs (Gu and Adler, 2004; Muhammed, 2013).

Latitudinal variability of rainfall akin to the Intertropical Convergence Zone (ITCZ) is a major determinant of southward migration of the local populace searching for pasture or livelihoods and avoiding the extreme tropical summer heat. The ITCZ on land is typically known as Intertropical Discontinuity (ITD).

The known mechanisms affecting rainfall over the two regions include forcing at: a) sub-seasonal scales e.g. equatorial waves, enhanced moisture supply, delay in the monsoon winds etc and b) seasonal to inter annual which includes Pacific El Niño due to Pacific impact on Atlantic wind stress fields, Quasi-biennial Oscillation (QBO), Madden-Julian Oscillation (MJO), strengthening of low-level moisture convergence from westerly winds, weakening of north-easterly dry winds, influence of orography etc (Muhammed, 2011).

Various studies have been dedicated to rainfall variability in the region but mainly focusing on decadal variability from atmospheric models due to the paucity of observed data (e.g Jenkins, 1997; Fontaine *et al*., 2010). Others made use of a very few station data to corroborate their findings from numerical models, while some studies employed observations that covered a brief period (e.g. Biasutti *et al*., 2003; Gu and Adler, 2004; Maloney and Shaman, 2008). Other studies show that the south Asian monsoon affects the West African monsoon through the mid- and upper tropospheric easterly jets (Chung and Ramanathan, 2006) within intraseasonal, interannual and interdecadal time scales (Webster and Fasullo, 2003; Sikka, 2003).

Seasonal variations in surface rainfall and its associated large-scale processes over the eastern tropical Atlantic and the West African region have been investigated by Gu and Adler (2004) using TRMM products NCEP-NCAR reanalysis. Their results showed two different rain bands each being modulated by a different physical process. The seasonal cycle of the eastern tropical Atlantic was found to modulate convection by means of thermal forcing and SST-related meridional gradients. This however only has an impact on rainfall from the Guinea Coast extending to 10^oN. However, the rainfall was found to be modulated within the ITCZ rain band by various processes north of 10^oN. These include moist convection, African Easterly Jets (AEJs), Tropical Easterly Jets (TEJs), Low level westerly winds and African Easterly Waves (AEWs) influences during July-September months (Muhammed, 2013).

The interannual variability of rainfall over Africa has been examined by Janowiak (1988). The year to year variability of the Atlantic cold tongue region were well correlated with West Africa and Sahel rainfall anomalies during JJAS months. From composites of rotated principal component analysis, wetter than normal conditions over West Africa ($5-10^oN$) and drier than in the Sahel (north of 10^oN) were found to be associated with positive SST anomalies in the south Atlantic. A reversed scenario occurs when SST anomalies are negative.

A dipole mode of rainfall variability has been observed between West Africa and the Sahel (Lamb and Peppler, 1992; Lough, 1986), having both dry and wet patterns. A wet (dry) Guinea coast is associated with warm (cold) Gulf of Guinea SST anomalies and a dry (wet) Sahel. The link between changes in SST in the Gulf of Guinea and rainfall across the region and the Sahel has been studied for the purpose of forecasting (Bah, 1987). The results showed that Sahel rainfall is dependent on Gulf of Guinea SST during the summer (wet) season. Positive SST anomalies correlate well with rainfall over the Gulf of Guinea and negatively correlate with Sahel rainfall.

The interannual variability of rainfall patterns across West Africa and the Sahel in relation to SST was investigated from 1950-1990 (Fontaine and Janicot, 1996). Analysis showed that, droughts over West Africa are due to a remote forcing of positive SST anomalies in the eastern Pacific and the Indian Ocean as well as negative SST anomalies in the Gulf of Guinea. In the same vein, floods over West Africa are associated with positive SST anomalies in the northern Atlantic. Sahel region was found to be highly sensitive to changes in remote (Pacific) and local (African and Indian) SSTs (Giannini *et al.*, 2003). Positive SST trend in the tropical Indian Ocean was found to be the proximate cause of negative rain events over the Sahel between the 1960s and the 1980s.

West African and Sahel rainfall are not easy to predict since it is dependent on many processes such as SSTs and soil moisture (Douville and Chauvin 2000; Douville 2002). Soil moisture cannot be neglected in the studies of West African climate. Some refinement of the statistical models for the region may however improve seasonal rainfall forecasting but not to annual or decadal level (Fontaine *et al*. 1999). The modelling approach in seasonal rainfall prediction is limited by the relatively poor representation of rainfall in the general circulation models (GCMs) as compared to large-scale dynamics. In addition, various studies have suggested a different mechanism of rainfall variability in the Sahel compared to West Africa. For example, the dipole years in which rainfall anomalies in West Africa and the Sahel (i.e. either side of about 10^{o}N) differ in sign has been clearly described (Janicot, 1992; Fontaine and Janicot, 1996; Ward, 1998). Dipole and non-dipole years for the last century have been classified (see table 4 of Ward, 1998).

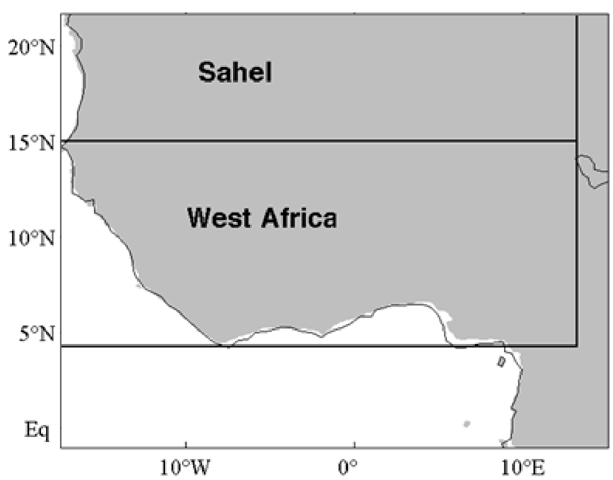

Figure 1: The boxes shown represent areas under study. The southernmost box is the West African climate boundary (3-15°N, 18°W-14°E), which has distinct rainfall characteristics, compared with areas north or east of it, and northernmost box is the Sahel region (15-22°N, 18°W-14°E).

This paper investigates Interannual variability of rainfall over West Africa and Sahel sub-regions to give insight into latitudinal variability at shorter time scales. The results may be an important background information for general circulation models that predict rains.

DATA AND METHOD

Data

To investigate Interannual rainfall patterns in these regions, Tropical Rainfall Measuring Mission zonally averaged rainfall data is used. The TRMM precipitation radar (PR) is the first space borne rain radar and the only instrument that measures vertical distribution of rain. It can achieve quantitative rainfall estimates both over ocean and land. The PR footprint is 0.25 x 0.25

horizontal resolution. Prior to February 2000, the PR data cover the span of (40°S-40°N, 180°W-180°E). After and including February 2000, the altitude of the satellite was changed, and the resulting data now cover (50°S-50°N, 180°W-180°E). The data are gridded to 0.25 x 0.25 horizontal resolution and the temporal resolution of 3-hourly is averaged to daily to give a complete spatial coverage. Daily averaged 3B42 version 6 is used in this study. The period considered is 12 years (1998-2009) to allow for analysis of interannual variability.

The TRMM products were specifically validated by Nicholson *et al*. (2003) over West Africa and a very small overall bias (4%) was observed in the daily datasets. Hence, this bias is insignificant in the tropical region where precipitation is always large as shown from the correlations (r) between the satellite products and the gauges on a monthly scale are also shown to be very good (approx. 0.9).

The TRMM microwave sensor has an advantage over the infrared sensors such as Advanced Very High Resolution Radiometer (AVHRR) because AVHRR cannot see through clouds while TRMM only fails to see through rainy cloud. These small gaps can be interpolated, unlike infrared data. These data can be accessed at the NASAs Goddard Earth Sciences Data and Information Services Centre and detailed documentation is available at the NASA GFSC website.

Method

The daily data are important because of its resolution in time and space, which allows the examination of sub-seasonal changes of rainfall over land. However, due to various storms that travel hundreds of kilometres per day in the tropics, these signals look spurious with very high/low frequency intervals. These spurious signals were removed by employing a 2-D finite response filter to capture the necessary signals at their spatial scales. All the daily data are considered with values equal or above 1-mm rainfall. This threshold was chosen because it typically marks the precision of rainfall measurements and the resolution of many rainfall datasets (Paeth *et al*., 2010). Therefore, daily data has been averaged to either 3-daily before any analysis in this study. The averaged 3-day data provide the means of quantifying changes of rainfall at high frequency and at sub-seasonal periods. Moreover, Ward (1998) provided evidence that the factors controlling rainfall variability at interannual time scale in this region differ during the wet and dry periods.

RESULTS AND DISCUSSION

The mean and standard deviation of the whole precipitation datasets spanning 12 years (1998-2009) was first calculated to determine area-wide nature and intensity (figure 2). The long-term precipitation distribution with respect to daily data of 1 January 1998 to 31 December 2009 is shown in figure 2a. Four regions stand out as having the largest mean rainfall: the north-eastern part of the Gulf of Guinea, the north-western Gulf of Guinea, the northern part of equatorial Atlantic and over South America. Areas with very low rainfall include the Atlantic Ocean south of 3°S, and also north of 15°N and the northern Sahel.

In order to quantify the magnitude and spatial distribution of non-seasonal precipitation variability, the standard deviation (σ) of precipitation is computed and plotted (figure 2b). Areas with maximum precipitation variability are similar to those described in the mean (figure 2a), with precipitation standard deviation exceeding 1.8mm/day. The maximum standard deviation observed along the West African coastline corresponds to the Cameroon highlands in the north-eastern part of Gulf of Guinea, and the Freetown peninsula mountains around 12^{o}W/7^{o}N.

Orographic forcing contributes to rainfall distribution over those regions during the boreal summer. Sultan *et al*. (2003) observed that the interaction of orography and atmospheric circulation might increase cyclonic vorticity in the heat low (a low pressure zone with hot air), which stimulates moisture convergence over the oceanic ITCZ at the western coast of West Africa. The large signal observed in the middle of the Atlantic corresponds to a quasi-stationary ITCZ position that defines the convective scheme, which largely occurs during the boreal summer around July-August.

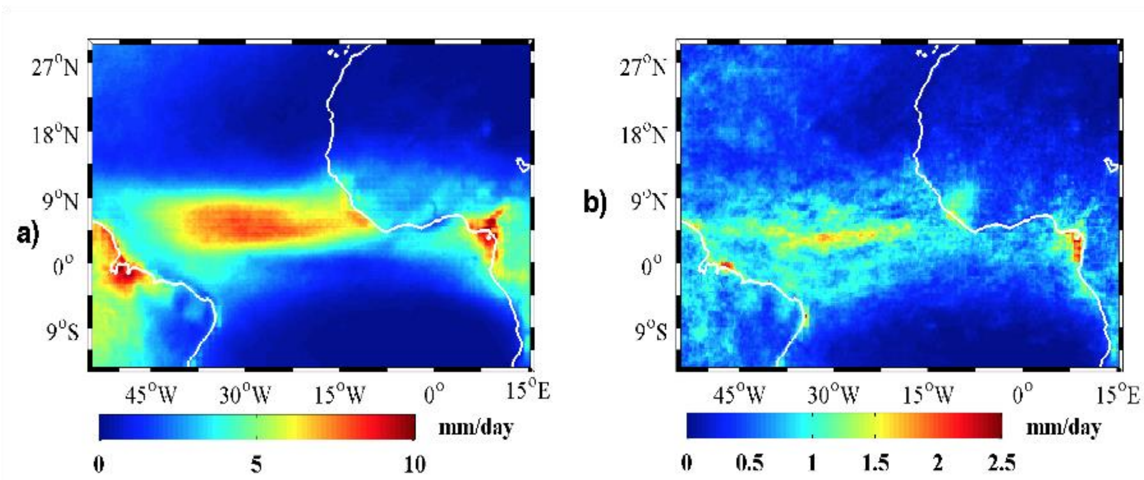

Figure 2: Long-term precipitation distribution during 1998-2009 a) mean precipitation from TRMM radar, b) standard deviation of precipitation based on the same data.

Rather than considering the Sahel separately from West Africa, TRMM precipitation rate is decomposed to highlight space/time magnitude of occurrences at interannual time scales covering both West Africa and the Sahel. A distinctly dry spell (figure 3a) with precipitation less than 1 mm/day is observed during the first 10-days of February 1998, extending from 7^{o}S to 7^{o}N within the Guinea Coast and further north in August. Although this occurs during the dry season, it is however exceptional compared with the results of the following years, which recorded between 3-4mm/day. As expected, rains of this magnitude only occur within the confines of West Africa, and do not extend into the western Sahel. A reduction in rain rate that is far less in magnitude compared to the following years occurred from June to early July.

A remarkable rainfall of magnitude of about 11mm/day is observed in June-July of 1999 (figure 3). This is followed by a dry spell in early August and a sudden northward shift of the rain band measuring about 8mm/day and lasting for 2 weeks.

Drought conditions over West Africa have been attributed to both remote forcing and negative SST anomalies in the Gulf of Guinea (Fontaine and Janicot, 1996). This scenario however seems to occur either due to difference in time lag between SST forcing and rainfall, or connected to other forcing mechanisms rather than the Gulf of Guinea SST. The year 2000 clearly highlights a

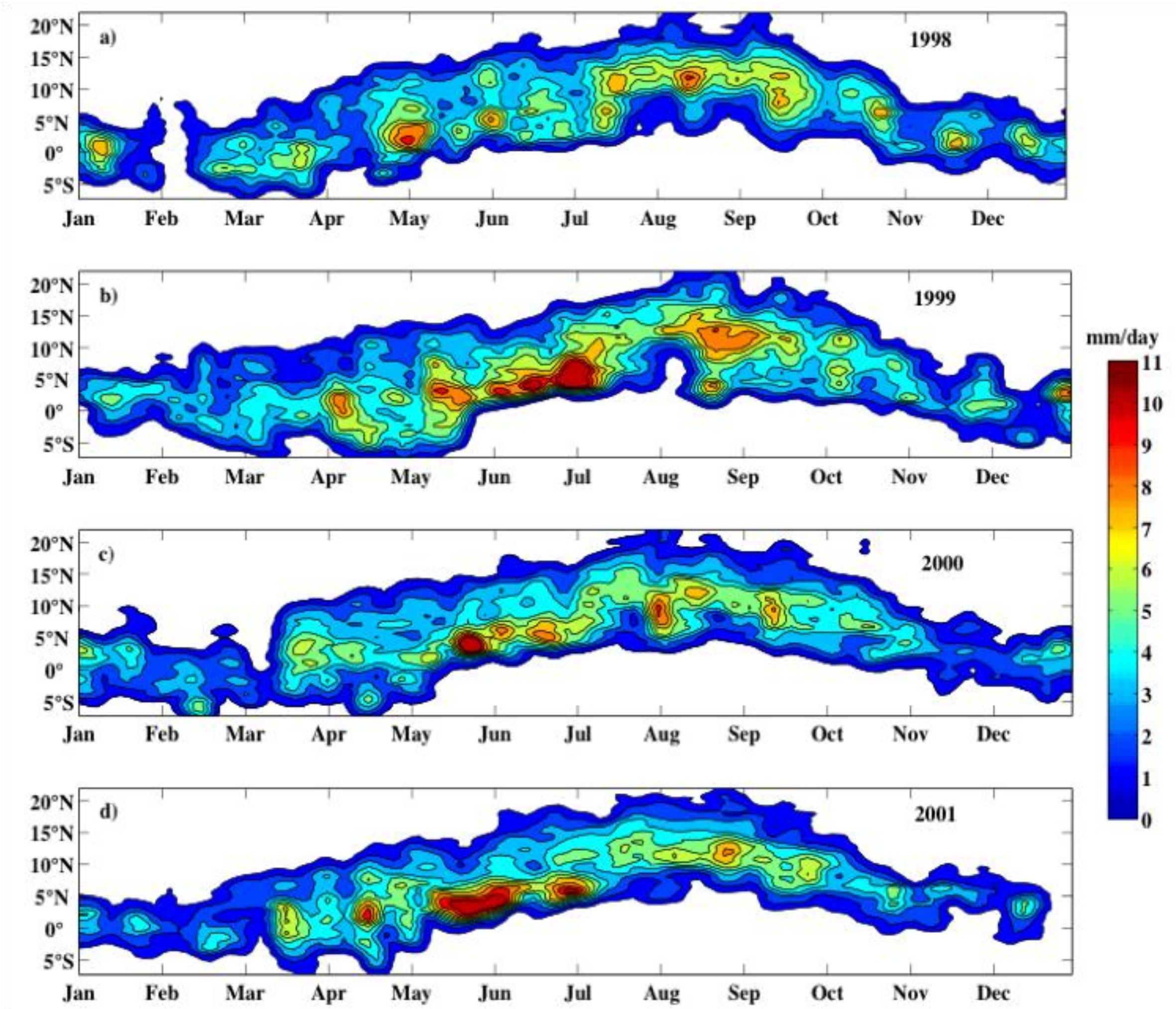

Figure 3: Variability of zonally averaged rainfall over West Africa and the Sahel (18°W to 16°E) from TRMM Precipitation radar based on 3-day running mean. Precipitation estimates between 0 and 1 are not shown. Data were filtered by a 2-d Finite Response filter to remove spurious signals. Cotour interval is 1mm/day. Maximum rate rates are observed at the Guinea Coast in late June 1999, late May 2000 and mid-May to mid-June 2001.

weaker magnitude and spreading of rains, with strong rains only lasting a week or two in May and July. Short spell of dryness in August 1999 that lasted around two weeks might be as a result of interruption by the westward African Easterly Jets (AEJs). Guinea coast experiences strong rainfall in May-June 2001 (figure 3d) as the summer monsoon strengthens and the ITCZ moved northward. A drop in rain magnitude is seen further north until another high magnitude appears at 11°N in August. This is the maximum northward position of the ITCZ that controls convection over the region.

In 2002, peak rain rates occurred only in the second quarter of the year (April-June), after which a reduced rainfall persisted until the end of the year. These rains remained within the realms of the Guinea coast as was previously noted by Gu and Adler (2004). June and August stands out in 2003 with high rainfall of about 11mm/day. Contrary to the previous years (2001 and 2002), years 2003 and 2004 exhibit just an average rainfall in both the Guinea coast and north of it almost all the year. A strong week long rain pattern in April is observed in 2005 (figure 4d).

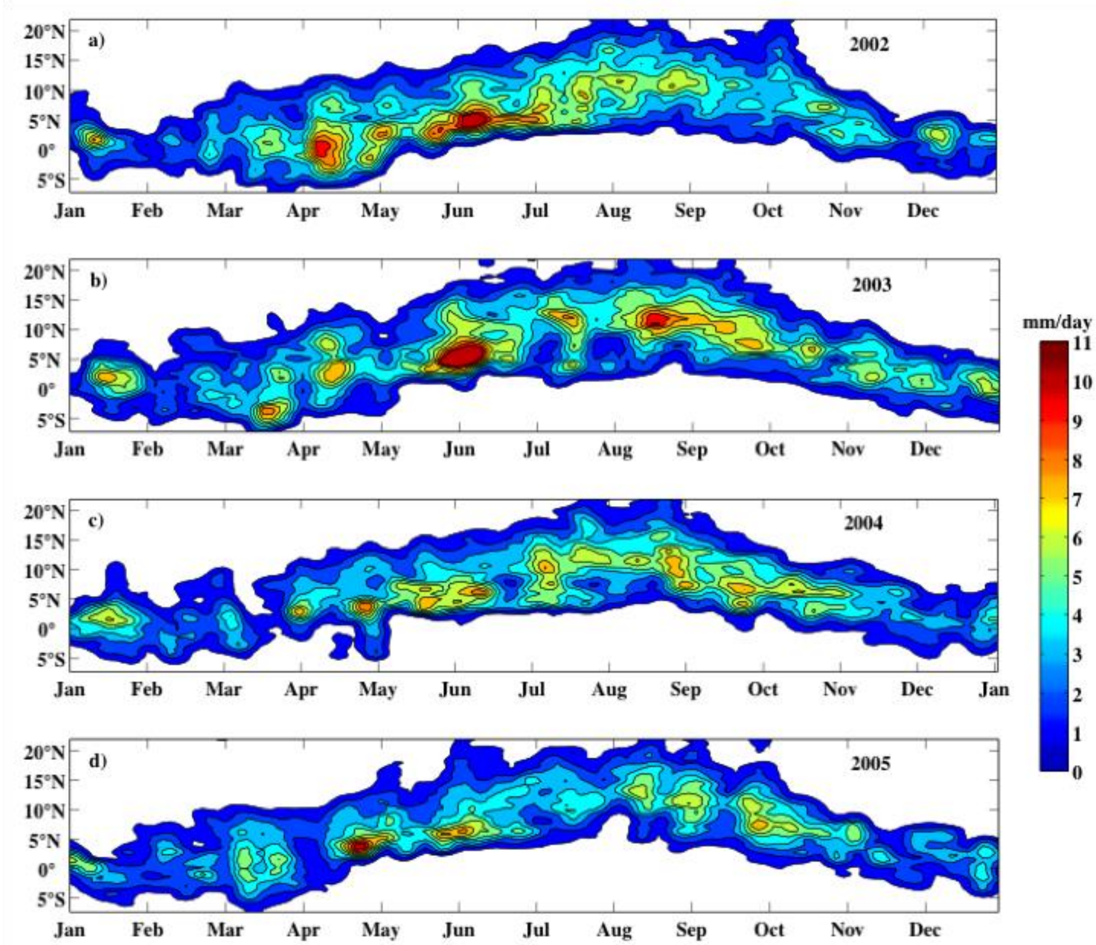

Figure 4: Variability of zonally averaged rainfall over West Africa and the Sahel from TRMM precipitation radar. Cotour interval is 1mm/day. Data were filtered as in figure 3.

A break in rainfall is further observed in the Gulf of Guinea (south of 3°N) in February and early April of 2006, and later a high magnitude rain band become largely visible from late April to early May. This heavy rainfall pattern corresponds to the weakening of the equatorial winds and an increase in temperatures. In spring, the sun is directly overhead and the incident solar radiation raises SSTs to above 27°C from 8°S-5°N (Xie and Carton, 2004). This supports convection, especially at the Guinea coast and further north. As time goes on, southerly winds begin to strengthen, and the thermocline uplifting leads to cooling of SSTs. Since SSTs must reach a certain threshold (at least 26°C, e.g. Gu and Adler (2004) for convection to initiate, the cooling effect due to the cold tongue would suspend the impact of SSTs on convection. This might explain the brake in rains and dry spells observed during the years. The peak rain pattern observed in year 2006 (figure 5a) seems to shift in time the year after. Maximum rain rates are generally in May-June at the Guinea Coast.

In late-August to early-September 2007, there is a peak in rainfall pattern that lasts about 1 month. This is repeated in the following year (2008) with almost the same phase at the same latitude of 5-12^{o}N. In 2009, only a half of this magnitude is observed with rainfall of about 6mm/day. This raises a question as to why this large difference occurs in such a small area.

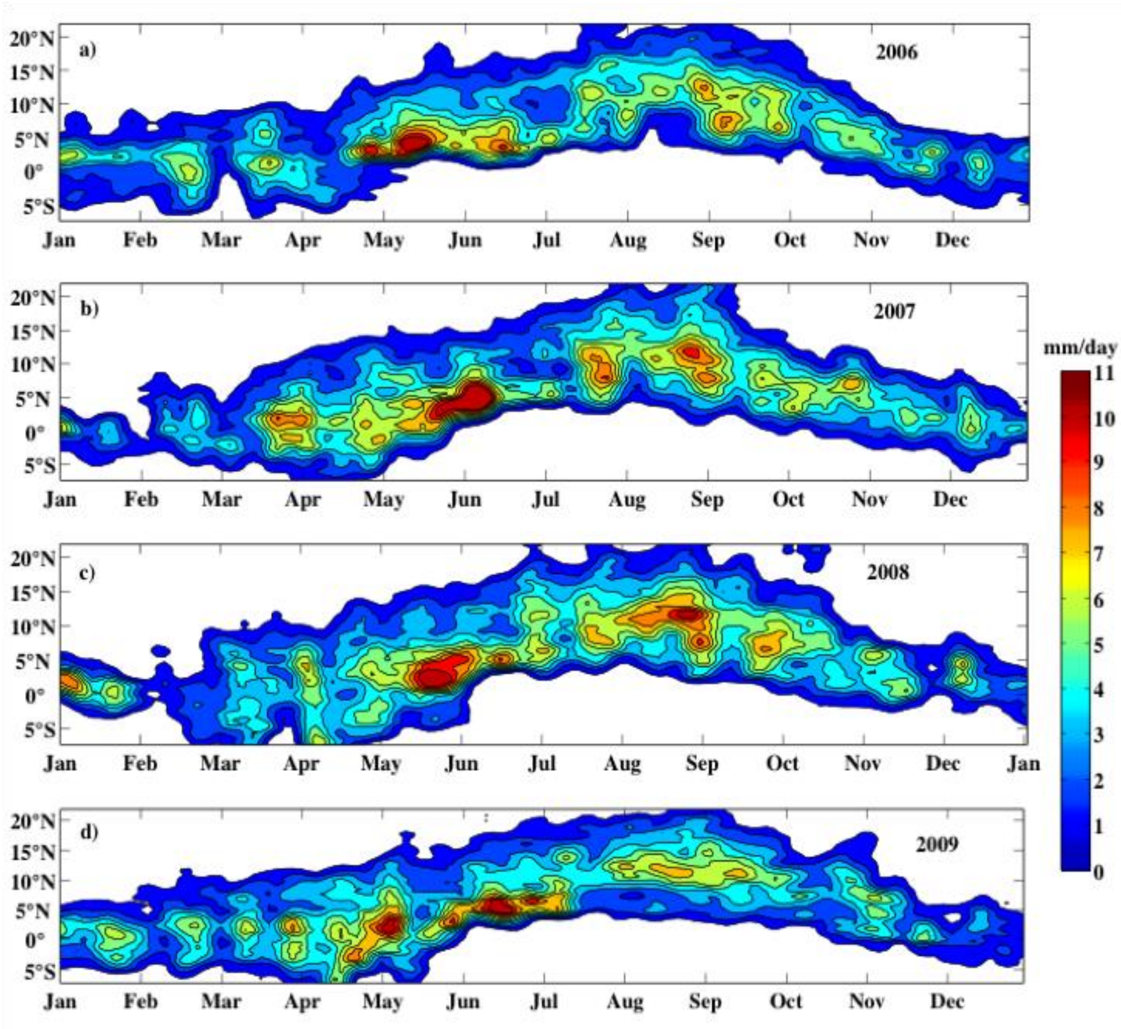

Figure 5: Variability of zonally averaged rainfall over West Africa and the Sahel from TRMM precipitation radar. Cotour interval is 1mm/day. Data were filtered as in figure 3.

Seasonal variability in West Africa

Based on the description of rainfall shown above, it is possible to separate clearly the rainfall occurrences between the wetter West Africa and drier Sahel. We have chosen the boundary at 12^{o}N based on the observed magnitude of rainfall shown in figures 3-5 so as to characterise each region separately to further our analysis. Janicot (1992) has shown that distinguishing the region north and south of 10^{o}N would give a better description of interannual variability of rainfall over West Africa and the Sahel.

The year 1999 recorded peak rain rate anomaly in June-July and September-October compared to other 5 years (figure 6a). In 2001, rain rates were low in July-September months. The period

November to April marks the dry season. The strengthening of northeasterly dry Hamatan winds during this period north of the equator significantly weakens rain-bearing southeasterly monsoon winds, thereby inhibiting moisture convergence over West Africa and the Sahel regions.

Year 2005 (figure 6b) however, recorded the lowest rain rate compared to the 12 years during the summer. This low precipitation rates perhaps is connected to the monsoon system. A possible explanation of this is that the monsoons winds were exceptionally strong during 2005 due to associated large-scale atmospheric circulation. An intensification of the monsoon shallows the cold tongue that allows a significant cooling to persist between June-August months. In the tropical Atlantic Ocean, the cold tongue develops around mid-May in response to the intensification of the southeasterly winds. This strengthens upwelling of cold subsurface waters and consequentially weakens the air-sea processes, hence moisture convergence over land. This explains the drought conditions that occurred in that year (Muhammed, 2013).

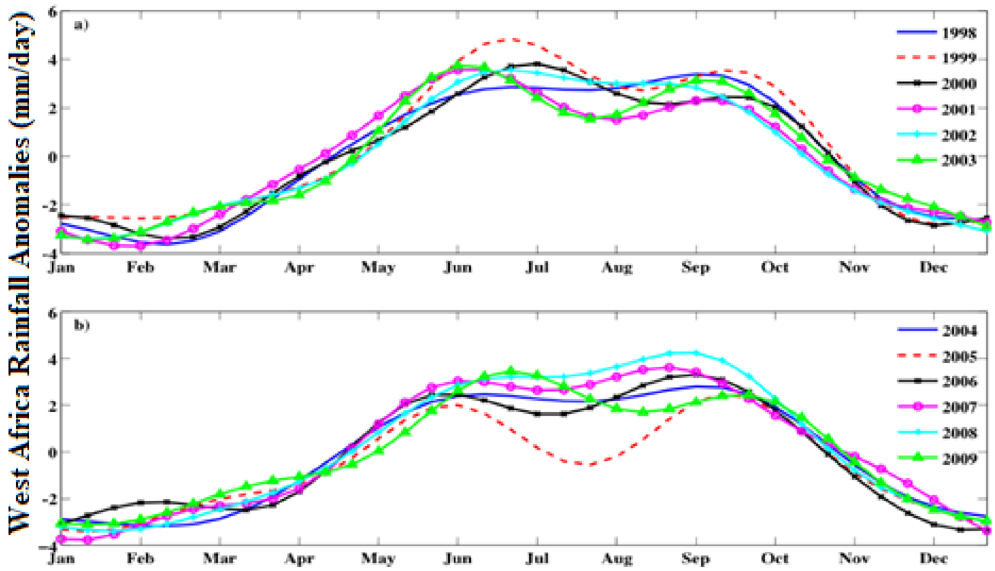

Figure 6: The seasonal cycle of rainfall over West Africa averaged between [3N-12N, 10W- 16E] for a) 1998-2003, b) 2004-2009.

Seasonal variability in the Sahel

Anomalous positive rain rate events in the Sahel occur between June and October (figure 7). Even so, rain rates are low compared to West Africa. Variations from year to year can be observed. For example, 1999 and 2007 recorded higher rain rates while 2002 and 2005 recorded lowest. These are associated with flood and drought in the Sahel in those years respectively (Muhammed, 2013). However, it should be noted that these changes may not repeat their spatial areas from year to year as shown in previous images (figure 3-5).

Non-seasonal variability in West Africa

The years 1998, 1999, 2003, 2005, 2006, 2007 show a marked difference of rain rates from May-October months with about +/- 5mm/day (figure 8). This is contrary to the preceding years, and the presumption on further strengthening of the monsoons is probable.

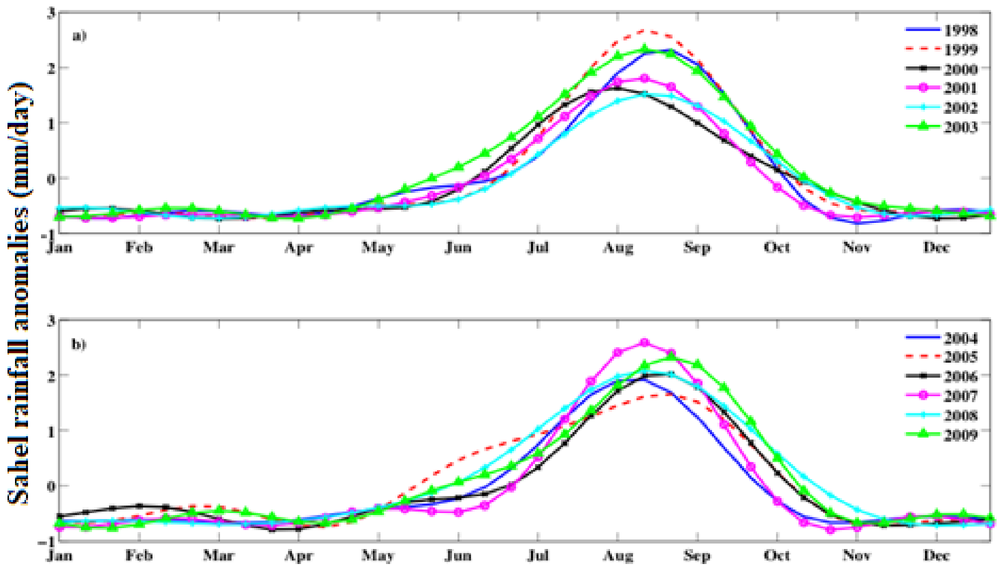

Figure 7: The seasonal cycle of rainfall over Sahel averaged between (12^{o}N-25^{o}N, 10^{o}W-16^{o}E) for a) 1998-2003, b) 2004-2009. Positive anomalies occur from May-October.

Significant interannual variability as positive peaks in June 1999, May 2003and July 2003. These signifies the warmer years. The years 2001, 2005 and 2006 recorded considerably negative rain rate anomalies during the summer (May-August) signifying cooler years. Warmer years with high SST in the gulf of guinea corresponds to times of flood, and cooler years with low SST corresponds to times of drought (Muhammed, 2013).

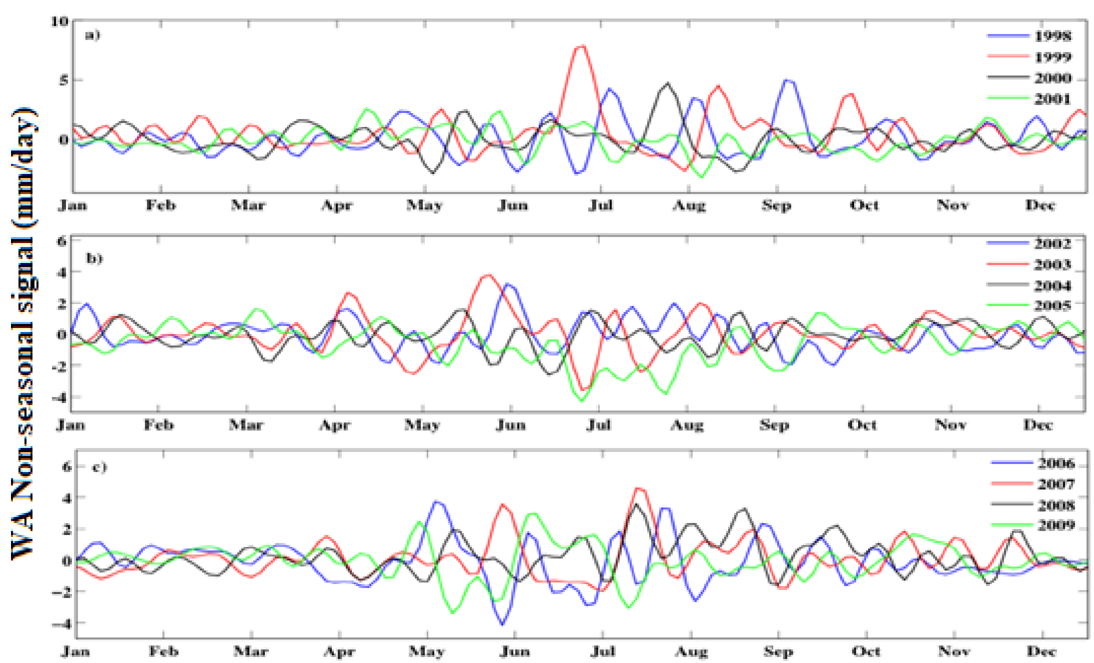

Figure 8. The interannual variability of rainfall over West Africa aver- aged between [3^{o}N-12^{o}N, 10^{o}W-16^{o}E] for a) 1998-2001, b) 2002-2005 and c) 2006-2009. The long-term seasonal cycle based on the 12 years data were removed.

Interestingly, the June 1999 rainfall is approximately out of phase with rainfall of 1998. This area averaged timeseries could signify spatial pattern variability of rainfall over the region, with some areas having high rain in one year and run to deficit in the next. This is quite connected with the condition of the Gulf of Guinea SST and the cold tongue. Although, development of the cold tongue is based on the impact of trade winds that increases currents, which then shoals the thermocline (Houghton, 1989), seasonal evolution and maintenance of the cold tongue depends on dynamical processes. These processes include heat flux divergence, vertical and horizontal advection and vertical mixing due to tropical instability waves (Peter *et al*., 2006), which are common to both Atlantic and the Pacific oceans.

Non-seasonal variability in the Sahel

The years 1998, 1999, 2003, 2007 and 2009 showed significant positive peaks during the Sahel summer contrary to 2001, 2005 and 2008 that showed negative peaks (figure 9). There is also a conspicuous raining from June-September for all the datasets. This is a direct replica of the rainfall over West Africa shown in figure 8.

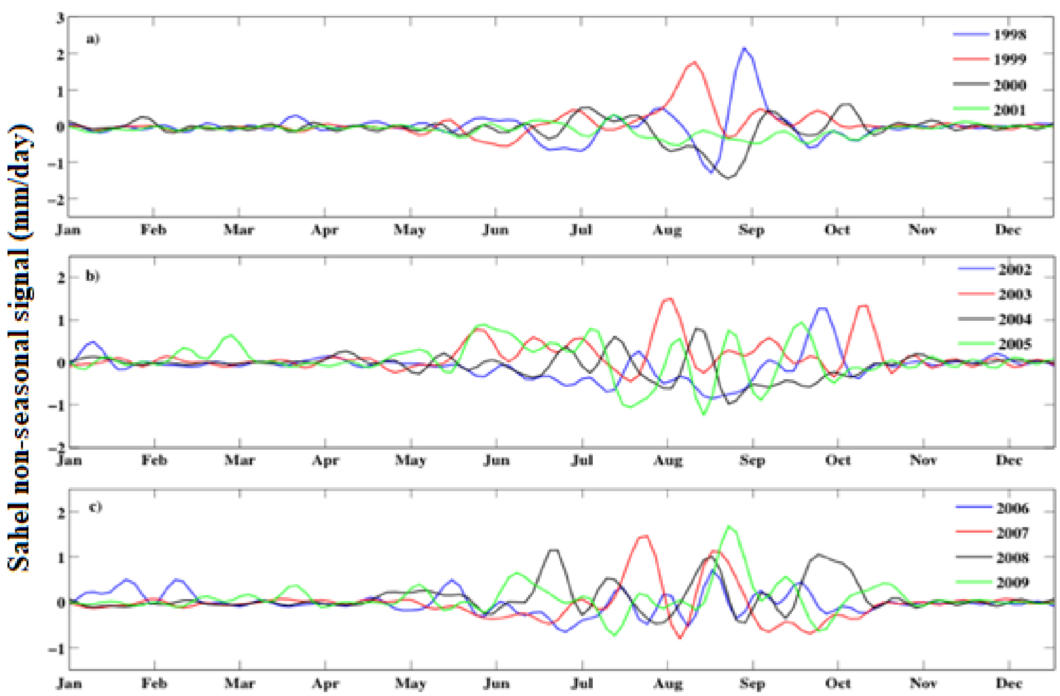

Figure 9: The interannual variability of rainfall over the Sahel averaged between [12N-25N, 10W-16E] for a) 1998-2001, b) 2002-2005 and c) 2006-2009. The long-term seasonal cycle based on the 12 years data were removed.

The West Africa rainfall (figure 8) also seems to have a connection with the Sahel rainfall (figure 9) by replicating peaks and troughs. Although, strong rainfall areas south of 12°N was charaterised and categorised the Sahel north of this boundary, the influence of Guinea Gulf SST still persists further north. The influence of westerly winds to carry precipitation to land wasn't much because even at the Guinea Dome located to the westernmost of the Sahel, convergence of Gulf of Guinea moisture over land is the most significant (see Muhammed, 2013). This influence is rather prominent in August-September months when the ITCZ is farthest north carrying the rain band, compared to when it was at the south in previous months. However, while rainfall in 1999 showed an approximate positive peak only in August figure 9a), the previous year (1998) recorded a negative peak in the same month, but with positive peak of an equal magnitude in September. This concurs well with previous studies on the summer season rainfall in West Africa (Levinson and Lawrimore, 2008; NIMET, 2008; Thomson, 2007).

CONCLUSION

The West Africa and the Sahel have difference climatological settings, hence characterising them separately is highly significant. Spatial pattern variability of rainfall is apparent across the whole latitudinal bands and time. At the Guinea Coast, rain rates are usually higher around May/June and persists throughout the year. Years with higher than normal rainfall corroborates with times of flood, and low rainfall to drought when compared with previous studies. Sea Surface Temperature in the Gulf of Guinea influences higher rainfall (high SST) and lower rainfall (low SST), with stronger impact on West Africa and the Sahel.

The Sahel is north of 15^oN, and rain rates that builds up in any year has being characterised by late August-October, and a magnitude of not more than 5mm/day for all years.

This obvious rain rate anomaly can be further investigated to assess possible implication to local climate scenarios. For example, rainfall and Atlantic Meridional Mode Index (AMMI), wind system around the Guinea Dome centred at $15^oN/15^oW$ to assess moisture convergence emanating from western West Africa and western Sahel. Atlantic Niño 1 and 2 can also be explored for further studies and El Nino Southern Oscillation (ENSO) can be studied to examine their influence on rainfall over the region.

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