Potential causes of 2007 flooding over West Africa and the Sahel

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Abstract

The 2007 wide-spread flooding in West Africa and the Sahel regions raised a compelling argument in the scientific community as to its intensity, complexity, causes and vulnerability assessment. The paucity of observed data, lack of regional coupled models and the improper scaling of impact has aggravated the understanding of this event. However, it is generally known that these floods result from extreme rainfall of the West African Monsoon that is modulated by Sea Surface Temperatures (SSTs). Here, the influence of SST in the Gulf of Guinea (GG) along the path of the monsoon winds is examined to highlight its role on rainfall in those regions. The non-seasonal GG index and the spatial SST shows one month lead to non-seasonal cycle of rainfall. There was interannual variability of SST anomalies peaking in some years, notably summer of 2007 and that concurs well with the rainfall. The plots show stronger correlation with West Africa rainfall than with the Sahel. The SSTs lead Sahel rainfall with three months, signifying the local positioning of the Intertropical Discontinuity (ITD). The correlations are significantly higher with seasonal cycle, indicating more influence of seasonality than interannual variability akin to non-seasonal signal. When the winds weaken, the cold tongue and TIWs are damped, leading to enhanced SSTs and subsequently stronger convection and rain convergence over land. The opposite occurs when winds are stronger.

Keywords: Flood of 2007, Monsoon, SST, Rainfall, West Africa, Sahel

INTRODUCTION

Africa's Western and Sahel regions, a margin of semi-arid grassland around the southern limit of the Sahara Desert, gets most of its rainfall between June and September when the band of near-perpetual thunderstorms that hover around the equator shifts north. In 2007, the final months of the rainy season brought unusually heavy rainfall to much of the Sahel and the tropical savannas to its south, causing floods in river basins. The unusually heavy rains caused flooding in as many as 17 countries and affected more than a million people across Africa (BBC, 17 September 2007). Major countries affected across West Africa and Sahel belt are Nigeria, Ghana, Senegal, Togo, Burkina Faso and Liberia. For those areas that escaped flooding, the rains were beneficial, since farmers in the Sahel rely on rain to water their crops. This was reported by the Famine Early Warning System Network on 19 September 2007 (TRMM Science Data and Information System, 2007).

This heavy rainfall in West Africa of 2007 was ranked by the Dartmouth Flood Observatory (DFO) as one of the three most devastating flood events of the year characterised by limited access into scientific and policy debates. These heavy rains are the most common cause of floods

(Few 2003; Muhammed, 2013). The DFO data for 2007 support this, showing that 69% of a total of 244 floods worldwide were attributed to heavy rains. In the year 2007, Africa counted 2.5 million people displaced by floods (Tschakert *et al*., 2010). Tropical rains are generally heavier than in other global regions, hence any continuous rainfall that lasts more than one week tends to cause floods.

According to the Fourth Assessment Report of the IPCC (Christiansen *et al*., 2007), extremely wet seasons, high intensity rainfall events, and associated flooding in West Africa are expected to increase by 20% over the next decades. Yet, it is still predominantly droughts that occupy people's mental models of this dryland hotspot (Tschakert *et al*., 2010). The Sahel flood was predicted for the 2007 rainy season (July–September) as data showed slightly to substantially enhanced probabilities for above normal rainfall for the Western Sahel (IRI 2007; ACMAD 2007). However, people were not prepared for what resulted in the worst floods in Sahelian history. The worst day was 17 October 2007, and the UN Office of the Coordination of Humanitarian Affairs reported that more than 800,000 people were homeless in 14 countries, by 30th of October.

Samimi *et al.* (2012) observed extreme rainfall in the Sahel that lead to a catastrophic flooding, affecting most of the lower wetlands of the Sahel region leading to crises in those regions. This was corroborated by the TRMM Science Data and Information System (2007) observations using TRMM rainfall which shows that most of the southern Sahel received more rain per day than average in August and September. Their results show that places received as much as 15 millimeters more rain than average per day. The northern Sahel, by contrast, was slightly drier than average.

The West African Monsoon (WAM) is the major source of rainfall over the West, Central and the Sahel regions. Hence, precipitation patterns in these regions depend largely on the monsoonal activity. The south easterlies are the monsoon winds that convey moisture from the Gulf of Guinea onto the African subcontinent. The monsoon rainfalls are slowed by dry Hamatan airflows originating as north easterlies, the strengthening of the westerlies and the weakening of the south easterlies (Muhammed, 2013).

Historical records show fluctuations in rainfall in West Africa and Sahel regions that vary mostly north-south, and these have been attributed to changes related to oceanic, atmospheric and orographic forcing. Long-term droughts have affected the region, with total amount of precipitation reducing at interannual and interdecadal scales during the second half of the 20th century (Nicholson, 1993; Nicholson and Palao, 1993; Benson and Clay, 1998). The unreliability of rainfall in these regions has a large impact on the continental hydrological cycle, water resources, economy, health as well as food security (Le Barbé *et al*., 2002; Muhammed, 2013). Research on rainfall variability has been the preoccupation of scientists in these regions since the early 1970s.

Several hypotheses have been put forward (e.g. Grist and Nicholson, 2001; Cook and Vizy, 2006) to explain the causes of rainfall anomalies in these regions, and whether local or global sea surface temperatures (SSTs) can modulate rainfall in both the Sahel and West Africa. Strong correlation between SSTs in the tropical eastern Atlantic and rainfall variability in the West

African coastline country of Ghana has been observed (Opoku-Ankomah and Cordery, 1994).

Some studies have linked the regions rainfall anomalies to the changes in the Atlantic Meridioal Mode Index (AMMI), which is the difference between SSTs in the north central and the south central Atlantic. The AMMI is connected with the large-scale atmospheric wind patterns and the seasonal migration of the ITCZ. It involves a positive feedback mechanism between surface winds, evaporation and SST, the so-called Wind-Evaporation-SST-feedback (WES-feedback) (Vimont and Kossin, 2007), and its dynamics are connected with the Atlantic hurricane tracks (Xie *et al*., 2005; Vimont and Kossin, 2007). The positive mode means warmer north, and more rainfall over West Africa and southern Sahel, and the reverse is the case in south and over South America. This further highlights the relationship between rainfall and SST in the region through large-scale circulation and atmospheric moisture anomalies (Vizy and Cook, 2001).

This study examines the response of West Africa and Sahel rainfall with respect to Gulf of Guinea SSTs from 12 years of observed data in the region (figure 1) to determine their connection to the 2007 flood. The study is focused mainly on the influence of SST on rainfall on seasonal, non-seasonal and interannual variability. The Gulf of Guinea SST is prioritized in this study due its inherent influence on the climate of West Africa and the Sahel through the southeasterly monsoon that occur during the boreal summer.

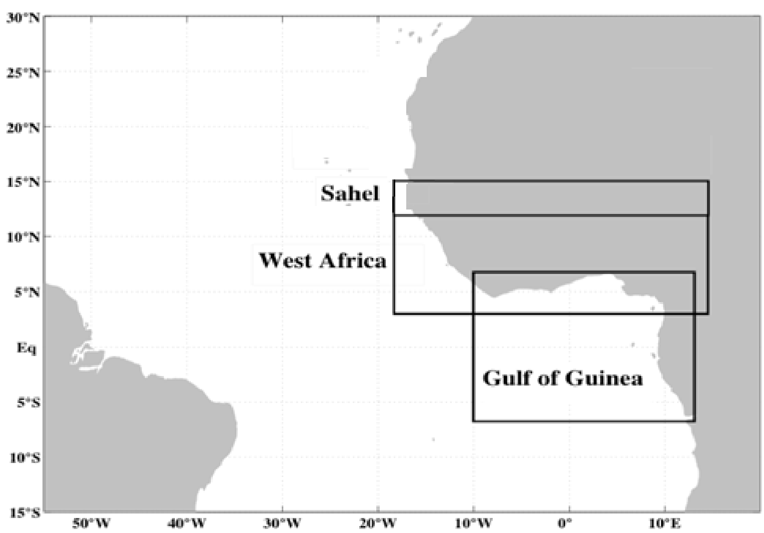


Figure 1: The boxes shown represents areas under study on this chapter. The southernmost box is the Gulf of Guinea area (7°S-7°N, 10°W-14°E), the middle is the West African climate boundary (3-12°N, 18°W-16°E) which has distinct rainfall characteristics compared with areas north or south of it, and northernmost box is the Sahel region (12-25°N, 18°W-16°E).

DATA AND METHOD

Data

For the purpose of these investigations, the Tropical Rainfall Measuring Mission (TRMM) radar precipitation and TRMM Microwave Imager (TMI) Sea Surface Temperature are used. These are corroborated with QuikScat scatterometer wind data.

TRMM Precipitation Radar

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 data cover (50°S-50°N, 180°W-180°E) (Chelton *et al*., 2000) which was achieved after altering the altitude of the satellite. 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 over West Africa and a very small overall bias of 4% was observed in the daily datasets (Nicholson *et al*., 2003). This bias is insignificant in the tropical region where precipitation is always large and storms are always high. Correlations (r) between the satellite products and the gauges on a monthly scale are also shown to be very good (approximately 0.9). These data can be accessed at the NASA′s Goddard Earth Sciences Data and Information Services Centre and detailed documentation is available at the NASA GFSC website.

TRMM Microwave Imager (TMI) SST

The Sea Surface Temperature (SST) data used is the TRMM Microwave Image (TMI) on board TRMM satellite. This TRMM radiometer provides uninterrupted record of SST signatures of the same 0.25° x 0.25° daily. The microwave instrument is very useful in addressing mesoscale variability associated with air-sea interaction. Moreover, it has the advantage of mapping through clouds than infrared sensors such as Advanced Very High Resolution Radiometer (AVHRR) that are not favourable in the tropics. The sensor only has problem with rain-bearing clouds, and this covers a small percentage of data, and that can be favourably taken care of by optimal statistical interpolation techniques. Temperature datasets are used to quantify the seasonal variation of rainfall patterns in relation to synoptic scale perturbations of the SSTs.

QuikScat winds

Wind data are from the SeaWinds scatterometer onboard the QuikScat satellite that provides estimates of the wind at 10m above water surface. Scatterometer winds are affected by rain where by it becomes difficult to differentiate signals from actual winds and those of rain. However, scatterometer processing uses contemporaneous radiometer measurements for rain flagging. Therefore, Remote Sensing Systems used four microwave radiometers (F13 SSMI, F14 SSMI, F15 SSMI and TMI) to determine if rain is present at the location of QuikScat observation and that allowed proper flagging of scatterometer observations. The daily level 3 gridded ocean wind vector data has a pixel resolution of 0.25 x 0.25 degree. QuikScat is in a sun-synchronous orbit at an altitude of 803km and a period of 101 minutes. It has a 0600 ascending equator-crossing time, and the scatterometer swath has an overall width of 1800km with no nadir gap. Daily data exist from 19 July 1999 to 19 November 2009, marking the period of existence of the mission.

Filling gaps in data

The SST data interpolation was done using Data Interpolation Empirical Orthogonal Functions (DInEOF) technique developed by Alvera-Azcárate *et al*. (2005). It is parameter free, that is all necessary parameters are derived internally from the existing data, and it is an EOF-based method for reconstruction of missing data. Lanczos strategy was employed to enhance computational speed.

After interpolating a complete dataset using DInEOF in Windows Disk Operating System (DOS), the product was not used directly because it is necessary to maximize statistical accuracy of the data. Hence, the original data was used having its gap filled by pixel from the interpolation products.

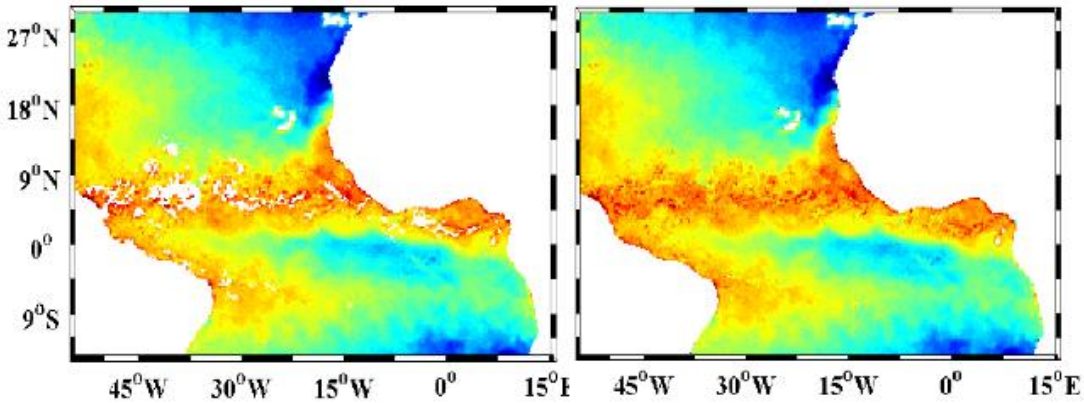


Figure 2: An example of a 3-day averaged TMI SST data: Left panel is the original data; right panel is the interpolated product. The white spaces in the left image are gaps due to rain-bearing clouds.

Method

The cloud-free SST data was processed by removing long term mean with respect to the length of data 1998-2009. Seasonal cycle was also removed to allow only extreme changes and the 3-daily data is now free of long term effect or seasonal changes. The purpose of this is to check the possibility of extreme phenomena that could cause flood. Because rainfall in West Africa and Sahel largely occur during the northern hemisphere summer (June-August), the three months were considered. The SST result is now summed to find the spatial changes of SST into one map. The same thing applies to the TRMM rainfall data over land wind data over the ocean (figure 3).

Hovmöller plots of SST across latitude 2^{o}N in the Gulf of Guinea is shown to highlight time-space variability of SST (figure 4). Indices were created using area averaged spatial data across the 12-year period for a) Gulf of Guinea SST, b) West African rainfall, c) Sahel rainfall. The result is change across time for the three datasets (figure 5).

Gulf of Guinea SST and rainfall over West Africa and the Sahel indices were correlated based on monthly lags to find the driving force of higher than normal rainfall in 2007 that lead to flood. The lead-lag correlations could explain the influence of Atlantic SSTs to flooding over the two regions. These were computed after removing mean and seasonal cycle and considered at 95% confidence level (figure 6).

The SST signal is further decomposed to highlight the presence/absence of tropical instability wave (TIWs) using a Fourier-based bandpass finite response filter (FIR). The filter allowed only signals within the period of 15-40 days and a wavelength of 500-1500km which are the characteristics of TIWs. By implication, other signals outside TIWs are filtered out.

Coherence analysis

The magnitude squared coherence (Cxy) of input signals X and Y are calculated based on Welchs averaged, modified periodogram method. The application here is based on Emery and Thomson (2001) and the mathworks implementation (mathworks.com). The magnitude squared coherence is a function of the power spectral densities between the two signals Pxx(f) and Pyy(f) of X and Y and the cross power spectral density Pxy(f) of X and Y. Coherence squared Cxy is given as

$$C_{x,y}f \quad = \frac{|P_{xy}f|^2}{P_{xx}P_{yy}f}$$

X and Y must be the same length. Coherence estimates uses Fourier analysis to determine frequencies at which the coherence is estimated. This can be determined by the sampling frequency, using periodic windowing (Hamming) to obtain eight equal sections of X and Y. The number of overlap between these sections can also be determined.

Cross Power Spectral Density

The cross power spectral density (CPSD) calculates the distribution of power per unit frequency based on Fourier analysis. It is calculated based on Welch's averaged, modified periodogram as is defined as:

$$P_{x,y}w \quad = \sum_{m=-\infty}^{\infty} R_{xy}\,(m)^{e^{jwm}}$$

The cross correlation sequence is defined as:

$$R_{xx}(m) = E[x_n + my_n^*] = E[x_n y_{n-m}^*]$$

Where,

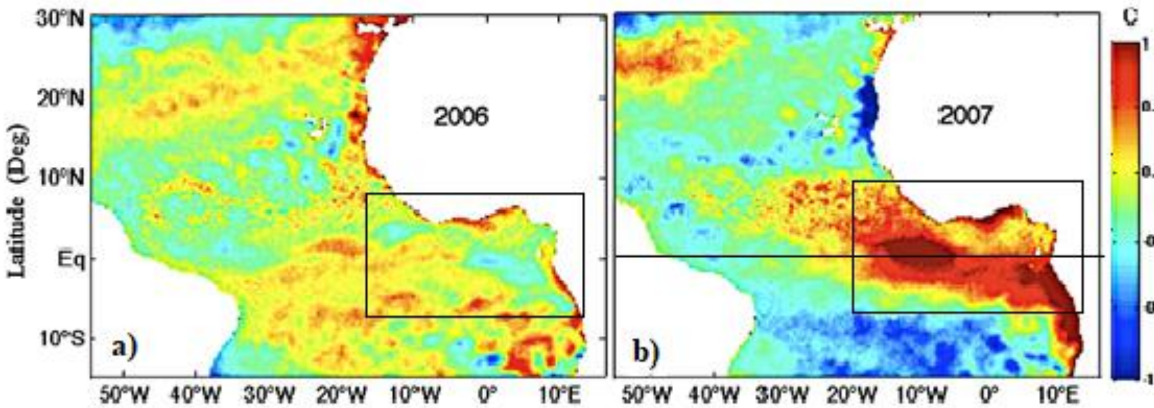
x_n and y_n are jointly stationary random processes, $-\infty < n\ \infty$, and E are the expected value operator. The CPSD uses periodic windowing (Hamming) and considers number of overlapping sections in its estimates.

RESULTS AND DISCUSSION

The Gulf of Guinea Index and Rainfall

Various studies, for example Itiveh and Bigg (2008) and (Paeth *et al*., 2010) were dedicated to finding the causes of the 2007 flood in West Africa and the Sahel. They showed that if SST might serve as explanation for the flood in West Africa, then Sahel may have been modulated by SST anomalies of the Gulf of Guinea and as well Mediterranean Sea or eastern tropical Pacific due to the wind systems emanating from these regions to the affected places (Paeth *et al*., 2010). However, the intense SST anomaly of September 2007 in the Gulf of Guinea (figure 3b) that has a magnitude of over three times that of other years (e.g 2006 – figure 3a) should not be underestimated. Besides, the anomalous signature is not just a few patches but covers the whole Gulf of Guinea region, and may potentially explain the cause of the floods. Furthering this analysis require Hovmöller plots to highlight space-time variability to compare year to year variability. Figure 3c shows wind convergence over the regions.

Hovmöller plots of long term mean and individual years were compared. The mean (figure 4a) over the 12 years shows much cooling in the Gulf of Guinea between May and October. This is the period of the intensification of the cold tongue that lowers temperatures by modulating SSTs in most of the basin. However, looking at the individual years for 2006-2009, it is clear that 2007 was the warmest with anomalous temperatures exceeding 3^{o}C. This was for the months of May-September, while year 2009 shows anomalous temperature below -2^{o}C. The spatial aspect has been shown in figure 3b where the SSTs were positively high during the June July August months of 2007. It is essential, therefore to compare the Gulf of Guinea SST with the rain data to determine the actual connection between them.



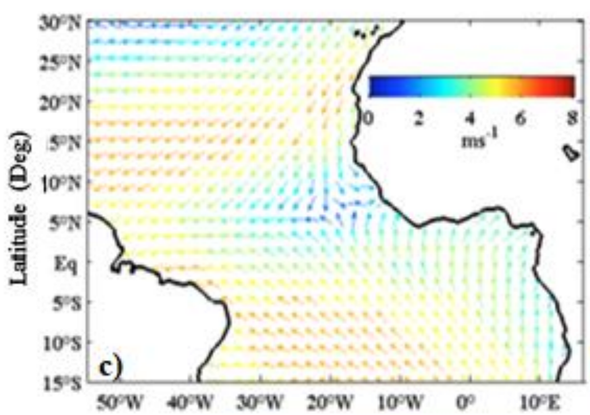


Figure 3: Non-seasonal Sea Surface Temperature anomaly for June-July-August (JJA) months to show extreme changes in the Gulf of Guinea (box). Mean and seasonal cycle has been removed based on 1998-2009 climatological mean. Note the normal temperature in 2006 (a), compared with the anomalous year 2007 (b). QuikScat wind vector for same period is shown in (c).

The comparison is based on area averaged timeseries covering West Africa and the Sahel as indicated in the boxes in figure 1. This is to show overall precipitation content monthly over the years. The rainfall over West Africa shows siginificant positive anomalies predominantly from May to September (figure 5a). Higher values are reorded in 2007 and 2008. These coincide with the period of above average rainfall record in August-September 2007 that drew the attention of media and scientists in that year (Niles, 2007; Team, 2007). Comparing this with positive SST anomalies of May to September of 2007 (figure 4c) show a good correlation between SSTs and rainfall anomalies during the boreal summer of 2007 with over 2^{o}C and 2mm/day respectively. The temperatures are warmer in August (figure 4c) compared to highest peak of rainfall in September (figure 5a), indicating a lead-lag relationship, where SST leads rainfall with one month. The SSTs need to be high for winds to develop momentum and raise convection of mositure over land within one month.

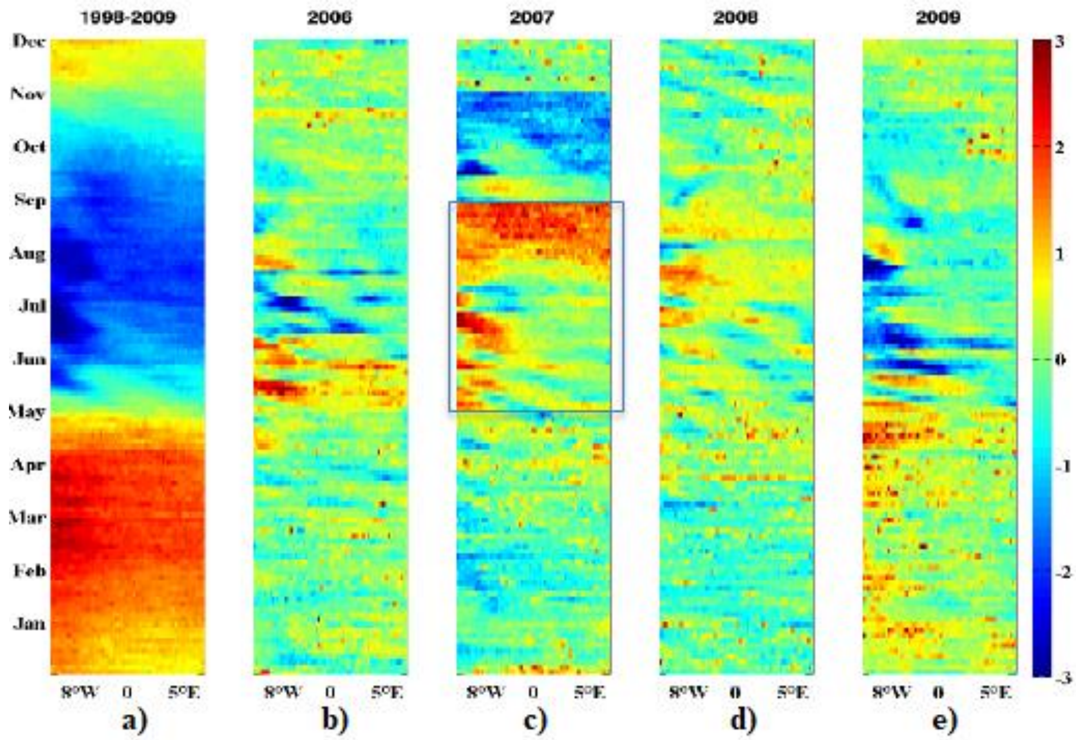


Figure 4: Hovmöller plots of 3-daily averaged TMI SST anomalies (units in ^{o}C) across 10^{o}W to 5^{o}E at the centre of the Gulf of Guinea (2^{o}N), a) averaged over the period 1998-2009, and, b-e) for various years. Mean and seasonal cycles with respect to the long-term mean (998-2009) were removed from each yearly plots on the right panel. Note the anomalous year 2007 (c) compared to other years (c, d, e).

The year 2007 shows two important peaks of rainfall in July-August and August-September in West Africa (figure 5a) with a break in rainfall in-between the two periods. Although, the flood affected almost the whole of West Africa and the Sahel, it wasn't widespread but affected some selected regions (Paeth *et al*., 2010). The peak rain rates observed in July 2007 of both West Africa (figure 5a) and the Sahel region (figure 5b) may explain the flood patterns. It was suggested that heavy rainfall fell over dry soils, which led to heavy runoff and flooding of river banks of the Niger and the Volta (Itiveh and Bigg, 2008). However from these results, the double peaks may explain that, after the dry land is saturated with rainfall in late-May to early-June due to heavy rains, it was only a matter of 3 weeks that heavier rainfall returned with the strongest downpour causing flood.

For the Sahel region (figure 5b), the heavy downpour began first in late July and early August because the ITCZ has to maintain a northernmost position before atmospheric processes (e.g. Westerly Wind Jets) comfortably act to distribute rainfall. Within an approximate period of 10 days, another heavy rainfall began in late August and persisted until mid of September. Tropical rains are generally heavier than in other global regions, hence any continuous rainfall that lasts more than one week tends to cause floods. For example, intense African Easterly Wave activity on convection, which is purely a tropical even suggests the ability of wave activity in modulating flood-producing rains.

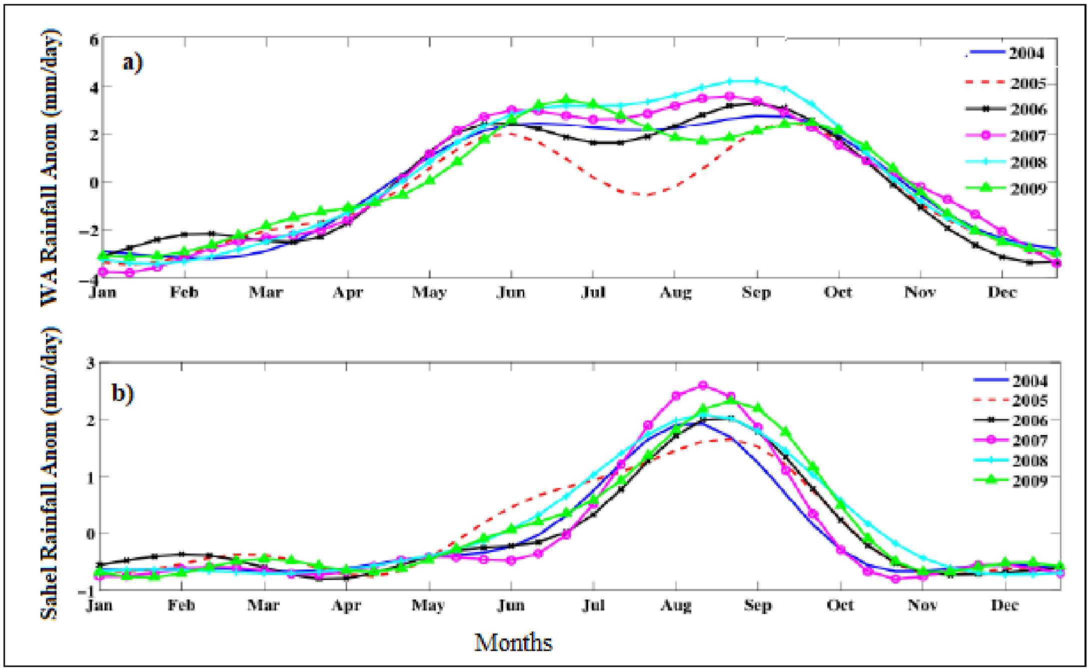


Figure 5: The seasonal cycle of rainfall over a) West Africa and, b) Sahel. Data is based on 3-daily TRMM for period of 2004 -2009 segretated annually.

Lagged Cross Correlation between SST and Rainfall

Lagged cross correlation between Gulf of Guinea SST and West Africa/Sahel Rainfall anomalies are further explored to examine whether the SSTs influence the rainfall in both regions (figure 6). Long term mean and seasonal cycle of both data were removed to allow only exceptional signals to appear. This helps to give explanations on the sensitivity of rainfall to small changes in Gulf of Guinea SSTs. The Gulf of Guinea SSTs lead West African rainfall by one month, giving a positive correlation of about 0.5. It is worth noting that correlations on tiny sensitive changes from data devoid of seasonal signal are not high but explains a lot. Direct correlations with seasonal signal was computed earlier (not shown) and gave good results ($r > 0.95$). The one month lag between SST and rainfall (figure 6a) shows that after warming of the SSTs, the process of convection took a month for winds to carry moisture that converges as rains over West Africa.

For the Sahel, the lagged correlations show SSTs lead with 3 months (figure 6b). That means moisture convergence over the Sahel comes up only about 3 months after warming of the SSTS in the Gulf of Guinea. This explains the positioning of the Intertropical Discontinuity, the land version of Intertropical Convergence Zone (ITCZ) that carries and withdraws moisture over land in West Africa and Sahel. Rainfall normally starts in the Sahel toward the end of August, and that is after the warming of the Gulf of Guinea SSTs. The correlations here are lower compared to that of West Africa. This is not a surprise because the Sahel can be modified by a number of atmospheric factors such as the African Easterly Jets (AEJ), African Easterly Waves (AEWS), dry northeasterly winds etc (e.g. Grist and Nicholson, 2001; Gu and Adler, 2004), as well as westerlies from the central Atlantic and Mediterranean SSTs. This is also an indication that Sahel rainfall is always minimal compared to West African rainfall. This weak correlation gives contrary results to previous authors (Lough, 1986; Lamd and Peppler, 1992) who observed a dipole mode in West Africa (wet) and Sahel (dry) as associated with Gulf of Guinea SST.

Connection of Rainfall with Tropical Instability Waves (TIWs)

Severe flooding over West Africa and the Sahel in 2007 has been related to the changes in Gulf of Guinea SST (e.g. Itiveh and Bigg, 2008; Paeth *et al*., 2010). Because of this reason, and because the tropical instability waves (TIWs) have been thought to warm the Gulf of Guinea, this opens an avenue to search for why the September 2007 SST in the Gulf of Guinea was warmer than other years.

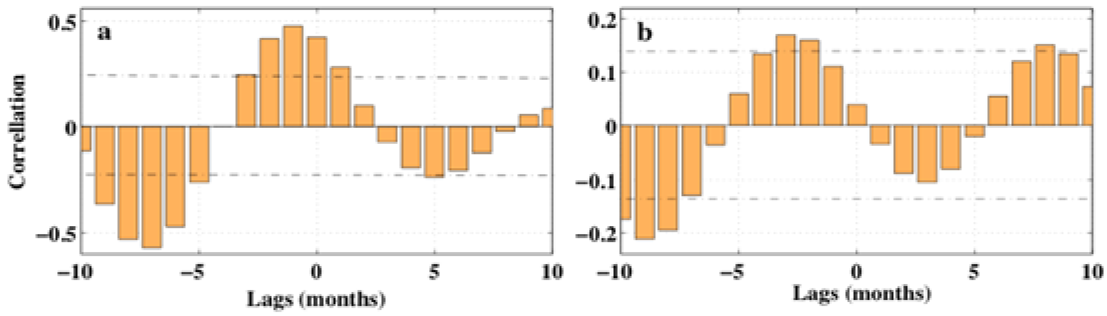


Figure 6: Lagged cross correlation between anomalies of Gulf of Guinea SST and, a) West African rainfall anomalies, b) Sahel rainfall anomalies. Lags are in months, mean and seasonal cycle was removed. Both data are based on 12 years sampling (1998 - 2009). Dash-dot lines indicate the 95% confidence level. Positive y-axis means GOGI leads.

The evolution and maintenance of the cold tongue in the tropical oceans of both Atlantic and the Pacific are dependent on processes linked to TIWs such as vertical mixing, horizontal and vertical advection as well as heat flux divergence (Peter *et al*., 2006). Because of the role these waves play in the time evolution of heat fluxes and their importance to the near-surface heat budget (Grodsky *et al*., 2005; Peter *et al*., 2006; Weisberg and Weingartner, 1988), which are necessary for convection, it is necessary investigate further their link to warming of the region in September 2007 and consequential high rainfall anomalies leading to flood.

The interannual variability of TIWs in the Gulf of Guinea centred at (2^{o}N, 10^{o}W-1^{o}E) during 2005-2008 (figure 7) is hereby determined. The bandpass filtered SST reveals TIWs that have a period of 15-40 days and a wavelength of 500-1500km. The waves are quite prominent in 2005 and 2006, but very weak in 2007. These waves are believed to be generated by the shear of zonal currents (von Schuckmann *et al*., 2008) but are predominantly excited by the southeast trade winds that intensify in spring. They affect the zonal signature on SST and weakens heat fluxes.

This analysis shows that the waves are almost non-existent in the summer of 2007 compared with other years. High-frequency south easterlies usually cause instability in the near-surface water properties leading to intensification of the cold tongue and development of the TIWs. Therefore, it could be suggested here that the weakening of the south easterly winds leads to persistent SST warming throughout the summer months of 2007. Consequentially, the warming might have a profound effect on heat fluxes and convection and hence the abnormally high rainfall events observed in September 2007.

Although, the tropical instability waves are known to warm the Gulf of Guinea SST, they are as well affected by high-frequency winds. This analysis shows that the undulating troughs and crest of the waves barely appear in summer/autumn of 2007 compared to other years. This is because high frequency winds (1-15 days) dampens the waves and allow stability in the near-surface water properties and hence the SST warming leading to convection and high rainfall.

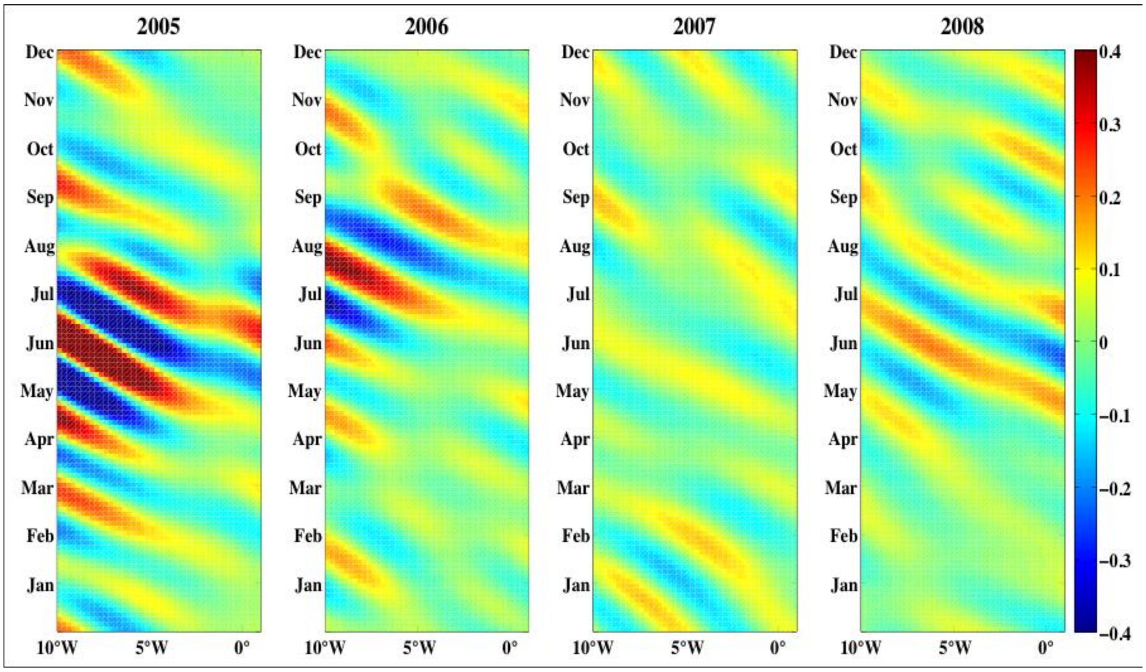


Figure 7: Hovmöller plots of 3-day averaged TMI SST (units in ^{o}C) at [2^{o}N, 10^{o}W-1^{o}E]: The long-term seasonal cycle based on 12 years of data (1998-2009) was removed. Cold tongue weakens and warming persists in 2007 unlike 2005 and 2006 when the opposite occurs.

Spectral analysis of SST and rainfall

To assess the impact of Gulf of Guinea SST to rainfall variability, coherence analysis and cross power spectral density (CPSD) based on Fourier techniques are used. This is to help identify coherent signals that connect SST and rainfall. Coherence analysis considers discrete signals and identifies patterns of correlation, while cross power spectral density identifies the energy of correlation at each frequency interval. The phase spectrum identifies the direction of relationship between the two signals. The rainfall and SST signals were decomposed with hope of finding coherent estimates in the absence of the obvious seasonality. The West African rainfall and Gulf of Guinea SST (figure 8) show strong coherence (0.7) of the SST equivalent to a semi-annual cycle of the Gulf of Guinea, having the same phase and a significant energy (CPSD). This implies that variability of SST in the Gulf of Guinea is directly associated with rainfall variability over West Africa.

While the annual cycle in the tropical Atlantic is due to the presence of the warmest SST north of the equator and the meridional march of the ITCZ that carries strongest rainfall (Li and Philander, 1997), the semi-annual cycle is controlled by upwelling and down welling which are only partially attributable to semi-annual changes in the winds (Philander and Pacanowski, 1986). Equatorial upwelling in the Gulf of Guinea is predominantly associated with the divergence of the meridional Ekman surface flow (Philander and Pacanowski, 1986). This flow is also associated with the variability of the cold tongue that helps to modulate the SSTs during the boreal summer.

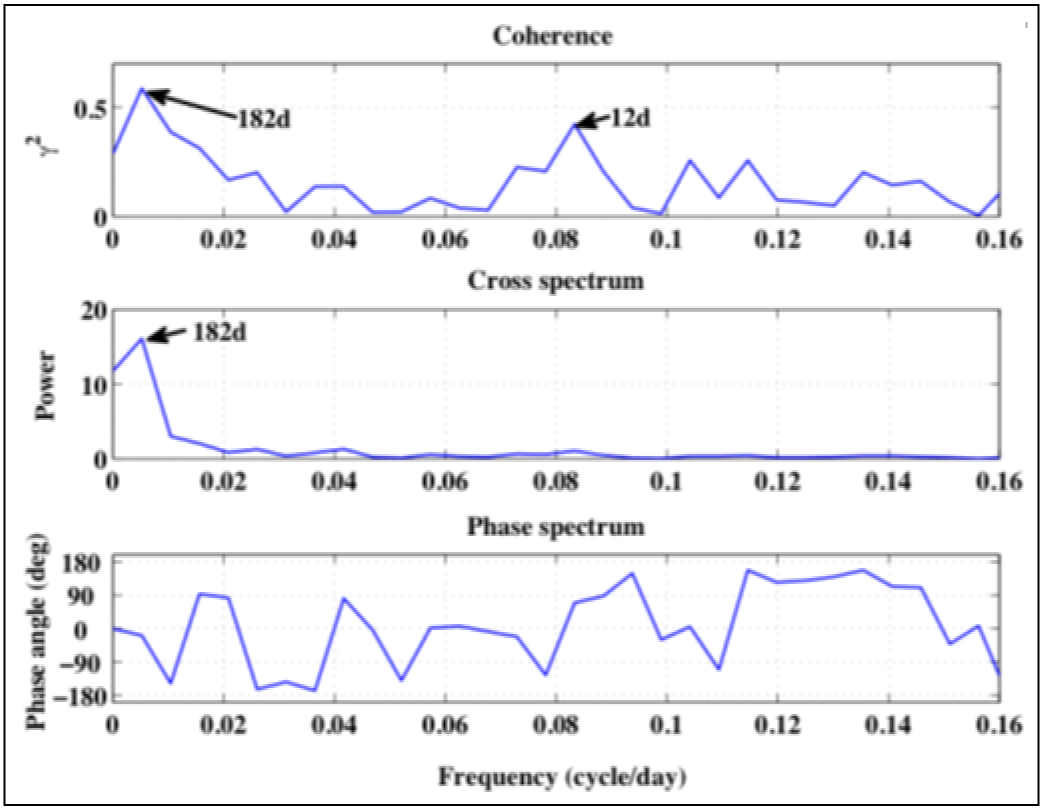


Figure 8. Coherence squared amplitude, cross power spectral density (CPSD) and Phase Spectrum of non-seasonal signal between anomalies of Gulf of Guinea SST (7^{o}S-7^{o}N, 10^{o}W-14^{o}E) and the West African rainfall (3^{o}N-12^{o}N, 18^{o}W-16^{o}E). Data is for the period (1998-2009). Both coherence and CPSD are estimated via Welch periodogram.

Although, the influence of surface winds in the western basin modifies the eastern basin through Bjerknes feedback, changes in SSTs in the eastern Gulf of Guinea is largely due to amplified southerly winds that generate the cold tongue by intense upwelling. This occurs during the onset of the summer monsoon (Mitchell and Wallace, 1992). Earlier, Busalacchi and Picaut (1983) demonstrated that the semi-annual signal in the Gulf of Guinea is driven by zonal and meridional wind stresses west of the Gulf. The 12-day peak with significant coherence, although having weaker power, is associated with high SST-rain covariability at the Guinea coast, where rainfall response quickly to a change in SST through heat fluxes.

The Sahel shows a weak coherence of about 0.3 at 182-days, having stronger power that is associated with the semi-annual cycle of the Gulf of Guinea (figure 9). However, the phase is about 180 degrees, indicating that rainfall changes in the Sahel is of opposite sign to that of SST in the Gulf of Guinea. This, by implication explains that SSTs in the Gulf of Guinea did not correspond to high rainfall in the Sahel within the seasonal cycle of 182-days. This agrees with

Itiveh and Bigg (2008) and Paeth *et al.* (2010) who suggested easterly tropical Atlantic influence on the Sahel completely. Rainfall in Sahel here may correspond to SSTs outside the Gulf of Guinea, most likely the Guinea dome, which is the turning point of the south easterlies converging on the Sahel.

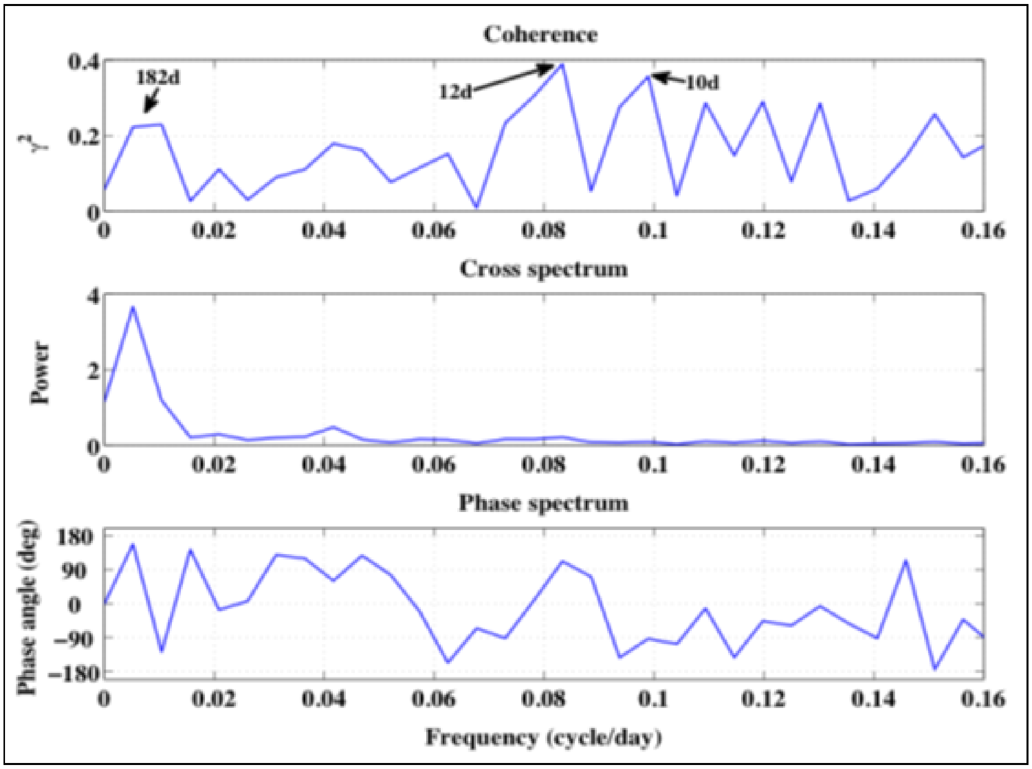


Figure 9. Coherence squared amplitude, cross power spectral density (CPSD) and Phase Spectrum of non-seasonal signal between anomalies of Gulf of Guinea SST (7°S-7°N, 10°W-14°E) and the Sahel rainfall region (12°N-25°N, 18°W-16°E). Data is for the period (1998-2009). Both coherence and CPSD are estimated via Welch periodogram.

The second and third peaks have high coherence but weaker power at 12-day and 10-day that is associated with high frequency covariability of SST-rainfall, linking Gulf of Guinea and the Sahel. At the periods when the cold tongue was absent, high SSTs in the Gulf of Guinea could correspond to high rainfall over the Sahel. The coherence estimates here is able to pick periods of strong variability within the seasonal cycle and non-seasonal cycle during the summer of 2007. This is suggestive of the importance of Gulf of Guinea SST in Sahelian rainfall, which was previously thought to be modulated predominantly by moisture-laden westerlies alone (Grist and Nicholson, 2001; Gu and Adler, 2004). In fact, the northward low-level monsoon flow that aids in moisture advection was found to penetrate far north from the Guinea coast between (5-20°N) (Cook and Vizy, 2006). Therefore, the monsoons can still modulate rainfall anomalies over the Sahel (12- 25°N). The influence of SST on Sahel rainfall was more apparent in 2007, suggesting a non-dipole year from these studies due to positive correlations, contrary to previous results of Janicot (1992), Fontaine and Janicot (1996) and Ward (1998) who showed a dipole mode.

CONCLUSION

This paper examines the impact of Gulf of Guinea SST on the West African and Sahel rainfall anomalies from observational point of view. These SSTs and rainfall over land were characterised by various statistics to highlight possible relationships. The Gulf of Guinea SST was found to influence both West Africa and Sahel rainfall anomalies but at different time lags corresponding to the meridional shifting of the ITCZ. High coherencies and stronger correlations were observed from the analysis, indicating lead/lag relationships.

The interannual variability of SST at the Gulf of Guinea was clearly apparent and was evidently found to influence rainfall anomalies over these regions. This is through the weakening of southeasterly winds that allow SSTs in the Gulf of Guinea to abnormally warm resulting in large surface heat fluxes that enhance rainfall. The consequences of these are flooding in 2007, and the opposite might have occurred in the 2005 drought (e.g. Muhammed, 2013). Further research using gauge data from the affected regions to substantiate these findings is suggested.

As a final note, both seasonal and annual signals related to the ITCZ and the Gulf of Guinea SST shows that, any forcing on West Africa and Sahel rainfalls cannot be entirely independent of the meridional shifting of the ITCZ or the influence of the local SSTs. Again, the region is better understood if we could know spatial and temporal variability of both the prevailing wind vectors and the SST. Most importantly, specific regions and time of variability, direction of propagation, connections with other large-scale processes within and outside the tropical Atlantic domain could give a better insight on rainfall anomalies and their impacts.

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