INVESTIGATION OF THE UPWELLING MECHANISM IN THE GULF OF GUINEA

Chaire Internationale en Physique Mathématique et Applications
(CIPMA - Chaire UNESCO)

Master of Science en Océanographie Physique et Applications

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ABSTRACT

Several mechanisms have been proposed to explain the occurrence of the seasonal upwelling in the Gulf of Guinea, yet do not adequately explain the phenomenon. The main mechanisms, proposed over three decades ago, include Ekman transport induced by the south-west prevailing winds during the season induced current along the coast; induced upwelling as a result of interaction between the flow of the Guinea current and afar field remote forcing mechanism from off Brazil. This study seeks to provide a better understanding of the upwelling using current data from various oceanographic programs. A time series of remotely sensed sea surface temperature (SST) data with high spatial resolution from NOAA-AVHRR between the period of January 1985-December 2007 and wind stress data from NOAA-QuikSCAT from January 1988- December 2006 was used. An analysis of sea-surface temperature (SST) and surface winds in selected areas of the tropical Atlantic indicates that the nonseasonal variability of SST in the Gulf of Guinea is highly correlated (with a coefficient of 0.5401) with the nonseasonal variability of the zonal wind stress in the western equatorial Atlantic and weakly correlated (with a coefficient of 0.2217) with the local winds (resultant (T)) of the Gulf of Guinea. A negative (positive) anomaly of the zonal wind stress near the Brazilian coast is followed by a positive (negative) SST anomaly in the Gulf of Guinea about one month (38 days) later. Moreover, analysis of sea surface temperature in the Gulf of Guinea during the minor (January-March) and major (July-September) upwelling seasons over the period indicated that the intensity of the minor upwelling is reducing at a faster rate of 0.027 for every 15 yrs compared to the 0.017 rate of reduction in strength of the major upwelling, hence indicating that the winter months are warming at a faster rate as compared to the summer months due to Global warming. Furthermore, a time lag of 20 days (time taken by Kelvin wave with 2 m/s speed to travel from the Central Eastern Equatorial Atlantic to the Gulf of Guinea coast) was observed between the onset of the Equatorial upwelling of the Central Eastern Atlantic and the Gulf of Guinea coastal upwelling. Also a strong positive correlation of 0.8329 was observed between the Equatorial upwelling of the Central Eastern Atlantic Ocean and the Gulf of Guinea coastal upwelling. Finally, varying sea surface temperature observed in the coast of Nigeria in January (27°C), May (above 29°C) and September (25°C) proved of the presence of a feeble upwelling in this region. Two upwelling seasons the major upwelling occurring in July-September and the minor upwelling in January was observed in the Nigerian coast. Also, a strong correlation of 0.5210 was observed between the West Atlantic zonal wind stress and the SST in the Southern coast of Nigeria. These preliminary results indicate that remote forcing in the western equatorial Atlantic Ocean and local process are important mechanisms affecting the eastern equatorial Atlantic sea-surface temperature with the remote forcing being the dominant mechanism. The results further proved that the intensities of both the major and minor upwelling in the Gulf of Guinea has been reducing over the last 20 yrs. Moreover, a link of the onset of the equatorial upwelling in the Central Eastern Atlantic and the Gulf of
Guinea coastal upwelling was investigated. Finally, the results from the theses further proved the existence of another upwelling phenomenon though feeble in the Gulf of Guinea of the Nigerian Coast as reported by the on-going Guinea Current Large Marine Ecosystem Project and was also proved to be dominated by remote forcing.
Chapter 1

1.0. Introduction

The frictional stress of equator ward wind on the ocean's surface, in concert with the effect of the earth's rotation, causes water in the surface layer to move away from the western coast of continental land masses (Sverdrup et al. 1942). This offshore moving water is replaced by water which upwells, or flows toward the surface from depths of 50 to 100 meters and more. Upwelling is an oceanographic phenomenon that often involves wind-driven motion of dense, cooler and usually nutrient-rich water towards the ocean surface, replacing the warmer nutrient-depleted surface water. Upwelled water is cooler and saltier than the original surface water, and typically has much greater concentrations of nutrients such as nitrates, phosphates and silicates that are key to sustaining biological production (Kosro et al. 1991).

Generally there are two main types of upwelling; the coastal and equatorial upwelling, with the coastal upwelling being the dominant type in the Gulf of Guinea region. The link between the onset of the Gulf of Guinea upwelling and the Equatorial upwelling was investigated, which forms part of the main objectives of this theses.

Coastal upwelling

Coastal upwelling is the best known type of upwelling, and the most closely related to human activities as it supports some of the most productive fisheries in the world. Wind-driven currents are diverted to the right of the winds in the Northern Hemisphere and to the left in the Southern Hemisphere due to Coriolis Effect. The result is a net movement of surface water at right angles to the direction of the wind, known as the Ekman transport (Ekman, 1890). When Ekman transport is occurring away from the coast, surface water moving away are replaced by deeper, colder and denser water. These deep waters rich in nutrients including nitrate and phosphate is brought to the surface, these nutrients are utilized by phytoplankton, along with dissolved CO₂ (carbon dioxide) and light energy from the sun, to produce organic compounds, through the process of photosynthesis.

Figure 1.0. coastal upwelling; source: http://www.coastalwiki.org/coastalwiki/Ocean_circulation&usg.
Seasonal coastal upwelling occurs along the central Gulf of Guinea coast between Cape Palmas (Coˆte d’Ivoire) and Cotonou (Benin), driving the biology of the system. Upwelling tends to occur on the concave coasts to the east of Cape Palmas and Cape Three Points (Ghana). There are two periods of upwelling each year in the Gulf of Guinea making the upwelling in this ecosystem different and interesting to study. The major upwelling occurs between July and September, whereas the minor upwelling normally only lasts for about 3 weeks during January and February, although it has been known to occur any time between December and March (Roy 1995, Koranteng 1998). Investigation of the trend in strength of both the major and minor upwelling over the period forms part of the goals of this theses. The upwelling in the Gulf of Guinea has a significant effect on the abundance of fish (Bakun, 1978) and on the rainfall distribution along the western African coast and the sub-Saharan countries (Lamb, 1978). For this reason, understanding the ocean dynamics of this region is of great interest to both meteorologists and oceanographers.

**Equatorial upwelling**

Upwelling at the equator is associated with the Intertropical Convergence Zone (ITCZ) which actually moves, and consequently, is often located north or south of the equator. Easterly (westward) winds blowing along the ITCZ in both the Pacific and Atlantic Basins drive water to the right (northwards) in the Northern Hemisphere and to the left (southwards) in the Southern Hemisphere. If the ITCZ is displaced above the equator, the wind south of it becomes a southwesterly wind which drives water to its right or southeasterly, away from the ITCZ. Whatever its location, this results in a divergence, with denser, nutrient-rich water being upwelled from below.

![Equatorial upwelling](http://oceanmotion.org/images/upwelling-and-downwelling)

**Figure 1.1:** equatorial upwelling. Source: [http://oceanmotion.org/images/upwelling-and-downwelling](http://oceanmotion.org/images/upwelling-and-downwelling).

Several ideas have recently been proposed to explain the mechanisms of the upwelling. Philander (1978, 1981) argues that the local wind forcing may account for this variability. Moore et al. (1978) suggested that remote forcing by winds in the western Atlantic may provide an alternate explanation. Therefore, investigating the upwelling mechanism in this
region is of great importance. Also, in this study, evidence, based on historical SST and wind data, which investigate these mechanisms and other questions was presented.

Worldwide, there are five major coastal currents associated with upwelling areas: the Canary Current (off Northwest Africa), the Benguela Current (off Southern Africa), the California Current (off California and Oregon), the Humboldt Current (off Peru and Chile), and the Somali Current (off Western India). All of these currents support major fisheries.

Figure 1.2: Major upwelling regions of the world (mostly found in the west coast of the continents located with red). Source: http://en.wikipedia.org/wiki/Upwelling.

1.1. Objectives

The main goal of this research work was to investigate the upwelling mechanism in the Gulf of Guinea and to better understand the mechanism of the seasonal upwelling phenomenon using combination of data from NOAA-AVHRR/QuikSCAT and satellite imageries. The research sought to address the following issues:

- Is the upwelling governed by local process or remote forcing?
- Is there an intensification of the minor upwelling in relation to a reduction in the strength of the major upwelling?
- Is there a link between the Gulf of Guinea upwelling and the equatorial upwelling of the Central Eastern Atlantic Ocean?
- Is there another upwelling phenomenon in the Gulf of Guinea?

1.2. Structure of the document

This document is organized as follows: Chapter 1 presents an introduction and the main objectives of the research. Chapter 2 presents background knowledge of the Coast of the Gulf of Guinea with special attention to the mechanisms of the upwelling in this area (Literature review). A description of the data and analytical methods used in this work is presented in Chapter 3. Chapter 4 presents the results of analyses and a complete analysis from investigations. Finally, Chapter 5 presents a general discussion. And Lastly, Chapter 6 gives the conclusions and suggestions for future work.
Chapter 2

2.0 Literature Review

2.1. Introduction

The Gulf of Guinea ecosystem particularly is located between 20°W and 10°E at low latitude. The East-West orientation of the Coast is a singular characteristic of this tropical upwelling ecosystem. However, the eastward flow of the Guinea current and the westward undercurrent make the structure of the surface and subsurface circulation quite similar to the other upwelling area such as the Benguela, California and Peru/Chile upwelling (Roy 1995). Aman and Fofana (1995, 1998) used Meteosat SST data to identify the location of upwelling and study seasonal variability along the coastal area of the Gulf of Guinea. They identified the periods of the major and minor upwelling season. The minor event occurred between January and March whereas the major event occurs from July to September.

2.2. What Causes The Upwelling?

A lot has been studied about the seasonal upwelling system in the coast of the Gulf of Guinea by Authors such as: Bakun, Philander, Houghton and Collin, Moore, Servain etc. but the main mechanism responsible for the occurrence of the seasonal upwelling in this ecosystem still remains unclear. There are still some questions that remain open about the main mechanism responsible for this upwelling. For example along the coast of the Gulf of Guinea the local winds are favorable for upwelling throughout the year. They blow parallel to the shore and causes an offshore Ekman drift which, between the Greenwich meridian and 8°W, has practically no seasonal variability (Bakun, 1978). Yet low sea surface temperatures occur seasonally along this coast only between July and September. Also, the magnitude of the wind seems to be lower than previously thought, especially in the offshore area; there is also an absence of a pronounced seasonal cycle of the wind which seems also to question the importance of the local wind to the upwelling process. The SST difference between an offshore area and a coastal area off e.g. Côte d’Ivoire is positively correlated with the offshore component of the Ekman transport. This result suggests that the local wind may also be an important contributor to the upwelling off the Gulf of Guinea as proposed by Philander.
Remote forcing is also thought to play an important role in the dynamics of this upwelling (Moore et al. 1978): an increase of the easterly wind in the western equatorial Atlantic creates an internal upwelling Kelvin wave that propagates eastward along the equator; when reaching the African coast, this wave reflects as coastal Kelvin waves that moves along the coast. Picaut (1983) showed that the phase lag observed in the SST signal from several coastal stations along the Coast is in agreement with the idea of a westward propagation of the upwelling signal. Servain et al. (1982) found a correlation between the zonal wind stress in the western Atlantic and the SST in the Gulf of Guinea. The Remote forcing hypothesis is well documented and is supported by some numerical models and data analyses but the offshore scale of the thermocline oscillations along the coast suggests that local processes have to be considered.

Therefore this document is aimed:
- Is the upwelling in this ecosystem governed by a local process or remote forcing?
- Is there a link between the Gulf of Guinea coastal upwelling and the equatorial upwelling of the Central Eastern Atlantic Ocean?

Also, Hingham (1970) proposed the idea of a current induced upwelling along the Coast of the Gulf of Guinea. The Guinea Current, in geostrophic balance, is associated with an upward slope of the thermocline toward the Coast. The shoaling of the thermocline is consistent with geostrophic adjustment of the north-south slope of isotherms when the Guinea Current intensifies in summer, a phenomenon which is enhanced off Cape Three Points. This idea was tested using a numerical model.
(Philander, 1979) but insignificant coastal upwelling is produced because all subsurface isotherms are undisplaced at the Coast.

![Figure 2.2: A schematic diagram of a current induced coastal upwelling by the eastward flow of the Guinea Current. Source: Roy, 1995.](image)

Furthermore, Marchal and Picaut (1977) proposed another type of current induced upwelling. The dynamic interactions between the flow of the Guinea Current and Cape Palmas /Cape Three Points can induce a shallowing of the thermocline downstream of the two capes and an accumulation of water upstream. This would be enhanced on the wide and shallow shelf east of Cape Three Points.

![Figure 2.3: A schematic diagram of a current induced (cape effect) coastal upwelling. Source: Roy, 1995.](image)

Moreover, the minor (winter upwelling) has received less attention than the major (summer upwelling). The intensity of this minor upwelling is maximum in the surrounding of Cape Palmas and sharply decreases toward the east to become almost unnoticeable on the SST signal of the Ghana coastal stations (Arfi et al., 1991). The local wind and the Guinea current are important contributors to the upwelling in the Gulf of Guinea. The intensification of the Guinea current and the local wind stress in January and February is thought to contribute to the upward movement of the thermocline associated with this minor upwelling (Moliere, 1970). Using data from ships and coastal stations, Pezennec and Bard (1992) provided evidence of an intensification of the minor upwelling over the past. In verifying the above hypotheses, the work has been guided also by the objective:

Is there an intensification of the minor upwelling in relation to a reduction in the strength of the major upwelling?

Finally, the on-going Guinea current Large Marine Ecosystem Project has also reported of the possibility of another upwelling phenomenon off Nigeria which forms part of the objectives of this document.
Chapter 3

3.0 Methodology

To achieve the requirements to investigate the upwelling mechanisms in the Gulf of Guinea, complementary datasets available from NOAA-AVHRR/QuikSCAT in combination with satellite imageries was used. This work was based on observational data covering January 1985 to December 2007, and this chapter will make a complete description of these datasets and the methods of analysis.

3.1. Description of Study Area

The study area covered the entire Equatorial Atlantic Region (West Equatorial Atlantic (A), Central Eastern Equatorial Atlantic (B), and the Gulf of Guinea (C)) with particular emphasis on the Gulf of Guinea (figure3.0). The Gulf of Guinea is situated in the north-eastern equatorial Atlantic. This is a critical position for Atlantic ocean dynamics (Hardman-Mountford 2000), which are less well understood than those in the Pacific (Enfield and Mayer 1997), despite the importance of the equatorial ocean in influencing global climate (Kerr 1999). Since the early 1960s the Gulf of Guinea has been studied intensively. A few large multinational experiments like EQUALANT, GATE and FGGE have taken place in the region (Picaut, 1982).

The Gulf of Guinea region has a humid tropical climate with almost constant Monthly temperatures and a relatively large amount of precipitation (Allersma and Tilmans 1993). Winds vary seasonally from a persistent south-westerly monsoon to north-easterly trade winds, modified by land and sea breezes in the coastal area. The Inter-Tropical Convergence Zone (ITCZ) migrates latitudinal over the region (Binet and Marchal 1993) and is a major influence on the local climate. The region can be divided into three subsystems based on differing oceanographic and biological characteristics: The Sierra-Leone Guinea Plateau (SLGP) subsystem, The Central West African Upwelling (CWAU) subsystem and the Eastern Gulf of Guinea (EGOG) subsystem (Hardman-Mountford et al 2000).

Oceanographic conditions in the region are dominated by the Guinea Current, Guinea Undercurrent, coastal upwelling and the presence of warm, low salinity ‘Guinean’ waters. The Guinea Current is an eastward, shallow, surface flow, fed by the North Equatorial Counter Current (NECC) off the Liberian coast. Its average depth is 15m near the coast and 25m offshore (Binet and Marchal 1993) and it mostly flows offshore, only approaching the coast near promontories (Allersma and Tilmans 1993).
Sea surface temperature (SST) in the Gulf of Guinea varies between 27°C and 29°C outside of the upwelling seasons (Allersma and Tilmans 1993), but can drop to below 22°C at the coast during the major upwelling (Longhurst 1962). The depth of the tropical thermocline can vary seasonally between 10 and 60m in the Gulf of Guinea (Longhurst 1962, Koranteng 1998).

Figure 3.0: Map of the Gulf of Guinea region. Data for analysis was obtained from regions enclosed by thick lines (A, B, C). A (Western Equatorial Atlantic), B (Central Eastern Equatorial Atlantic), C (Gulf of Guinea).

### 3.2. Dataset

#### 3.2.1. Satellite data

<table>
<thead>
<tr>
<th>Type of Data</th>
<th>Source</th>
<th>Period</th>
</tr>
</thead>
<tbody>
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<td>SST</td>
<td>NOAA-AVHRR (<a href="http://www.nodc.noaa.gov">www.nodc.noaa.gov</a>)</td>
<td>1985-2007</td>
</tr>
<tr>
<td>Wind Stress</td>
<td>NOAA-QuikSCAT (<a href="http://www.manati.orbit.nesdis.noaa.gov">www.manati.orbit.nesdis.noaa.gov</a>)</td>
<td>1988-2006</td>
</tr>
</tbody>
</table>

Table 3.0: Data type, source and period used for the investigation from NOAA.

The satellite data used, NOAA-AVHRR and NOAA/NESDIS-QuikSCAT datasets were produced by the National Oceanic and Atmospheric Administration (NOAA) (www.nodc.noaa.gov). The Advanced Very High Resolution Radiometer (AVHRR) is a cross-track scanning system with five spectral bands having a resolution of 1.1 km and a frequency of earth scans twice per day (0230 and 1430 local solar time). AVHRR data are also used to retrieve various geophysical parameters such as sea surface temperatures and energy budget data. AVHRR data processing includes calibration, navigation (georeference adjustments), atmospheric correction, cloud detection, remapping, and sea surface temperature (SST) computation.

The QuikSCAT (Quick Scatterometer) is an earth-observing satellite that provides wind speed and direction information over oceans to NOAA. It is in a sun-synchronous low-earth orbit.
The NOAA-AVHRR and QuikSCAT datasets have been used in many studies of marine surface variables and has proven to provide reliable estimates of temperature, salinity, wind and wind stress data from a high spatial resolution of 1.1km and 12.5km respectively.

In this study, the AVHRR thermal infrared SST data sets, obtained during the period January 1985–December 2007 was used. The main reason for choosing AVHRR SST data for this study is because of its high spatial resolution of 1.1km as compared to microwave sensors with spatial resolution of about 50km, and also has low sensitivity to sea-surface roughness, unlike microwave retrievals. Also The QuikSCAT products of ocean surface winds at 10m height, as processed by NOAA/NESDIS, retrieved using observation data from NASA/JPL’s SeaWinds Scatterometer aboard the QuikSCAT obtained during the period of January 1988 to December 2006 was used.

The data obtained from the NOAA-AVHRR/QuikSCAT was used in this work to investigate the four main objectives.

3.3. Methods of Analysis

This work explores processes that are nonstationary. This section describes the methods used for the data analysis.

The first step of the methodology was to locate the selected areas of relevance to the study: a Central Eastern Atlantic region 1°N-1°S, 5-10°W, a Gulf of Guinea region 5°N-4°N, 0-6°W and a Western Equatorial Atlantic region 6-4°N, 35-38°W. These regions were chosen to test, in the simplest way, the effect of remote or local wind forcing on the sea surface temperature in the Gulf of Guinea and the other objectives of the work with data described previously.

To investigate whether the upwelling in the Gulf of Guinea is governed by local process or remote forcing, a temporal distribution of the wind stress and SST data was observed in the Gulf of Guinea and the West Atlantic area and the analysis was limited to this time period. Because of the strength of the annual cycle of the data sets, it was expected to have a high correlation between all the variables. Furthermore, a time series analysis was conducted between the zonal wind stress in the West Atlantic equatorial, the Gulf of Guinea and the sea surface temperature in the Gulf of Guinea.

According to the qualitative model of Cromwell (1995), variations in the northward and westward wind stress near the equator should induce local temperature fluctuations there. Furthermore, according to Philander (1978) the northward equatorial wind can affect SST along the northern coast of the Gulf of Guinea. So, following these authors, a good correlation between $T^X$ and $T^Y$ anomalies and SST might be expected. For local forcing, a positive (negative) peak in $T^X$ is expected to correspond to a positive (negative) peak in SST anomaly and a positive (negative) peak in $T^Y$ was expected to
correspond to a positive (negative) peak in SST anomaly. Also, according to the remote forcing idea of Moore et al. (1978), variations in the westward wind stress, $T_X$ in the western equatorial Atlantic should induce temperature fluctuations in the eastern equatorial Atlantic. Hence with the described method above, the question “is the upwelling governed by local process or remote forcing” was investigated.

Additionally, the Students Statistics Test (Hypotheses test) was further used to verify the authenticity of the correlation between the SST and wind stress data in the Gulf of Guinea and the West Atlantic.

### 3.3.1. Upwelling Index

The frictional stress of equatorward wind on the ocean's surface, in concert with the effect of the earth's rotation, causes water in the surface layer to move away from the western coast of continental land masses. A natural hypothesis is that interyear variability in upwelling intensity may be the cause of variability in the biotic components of the ecosystems. Wooster and Reid (1963) demonstrated that the offshore directed surface Ekman transport constitutes an 'index of upwelling' that satisfactorily explains the seasonal variation in the near-coastal cooling attributed to upwelling. According to PFEL (Pacific Fisheries Environmental Laboratory), coastal upwelling indices are calculated based upon Ekman's theory of mass transport due to wind stress. Ekman mass transport is defined as the wind stress divided by the Coriolis parameter (a function of the earth's rotation and latitude).

Thus, this work also estimated the usefulness of identifying the intensities of the interannual minor and major upwelling by using the upwelling index technique, that is: Interannual variability in the intensities of the major and minor upwelling along the coast of the Gulf of Guinea was assessed quantitatively by calculating measures of upwelling intensity for both the major (July–September) and minor (January–March) upwelling seasons. The Upwelling intensity ($I$) was calculated for each box by subtracting the mean SST value for each box ($SST$) from an SST of $25\degree C$.

$$I = 25.0 - SST$$

The value of $25\degree C$ was chosen as this was the contour used to define the upwelling by Bakun (1978).

Also the strength of the minor upwelling (January-March) in relation to that of the major upwelling (July-September) was investigated by computing the means of the sea surface temperature during the two upwelling seasons in the Gulf of Guinea from 1985 to 2007.

Finally, the interannual variability of SST along the coast of the Gulf of Guinea was compared to the interannual variability along the equatorial Central Eastern Atlantic to
investigate whether there is a link between the Gulf of Guinea upwelling and the equatorial upwelling of the Central Eastern Atlantic Ocean.

Is there another upwelling phenomenon in the Gulf of Guinea?
Areas of upwelling are highly productive of primary organic matter and support most of the world’s richest fisheries. Such areas are also known to have economic deposits of Petroleum, glauconite, phosphorite and barite among others. Evidence inferred from the occurrence of petroleum source beds, glauconite and phosphorite in offshore Nigeria (Ibe 1982; Ibe et al 1983) as well as limited hydrographic data pertinent to the area (Anon, 1953, 1954, 1960; Berrit, 1959, 1961, 1962a, b, c) suggested that some upwelling, even if feeble, may be occurring in the inshore waters of Nigeria. Coastal upwelling usually manifests itself as a depression in the SST often times bringing them to thermocline levels. Other evidence of coastal upwelling includes the occurrence of more saline water containing less dissolved oxygen. But as Ingham (1970) pointed out, the salinity criterion becomes ambiguous if the water is upwelled from a depth beyond which the salinity maximum occurs. The concentration of oxygen is also not a firm indicator of upwelling at or near the ocean surface because of its susceptibility to rapid modification by biological process. Because of this, the monthly variation of SST data along the Nigerian coast was plotted and analyzed in this research work. Also the wind data in the region was examined to investigate whether the supposed upwelling in the region is governed by local process or remote forcing.
Chapter 4

4.0 Results

4.1. Seasonal and spatial variability in SST

4.1.1 The Gulf of Guinea Coast

Generally, SST variations in the Gulf of Guinea for most periods did not exceed 32°C and ranged between 22-30°C. Sea Surface temperature in this region manifested less intense drops in values between 26-27°C in the period from January to March known as the minor/winter upwelling. The minor upwelling season appeared to commence in January along the coasts of Ghana and Côte d’Ivoire. The upwelling appeared over the continental shelf from Cape Palmas to the Volta delta, with the largest area over the wide shelf to the east of Cape Three Points (figure 4.0a and b). In February, upwelling was absent from the area to the east of Cape Three Points, although it was present around this headland. The intensity of the minor/winter upwelling reduced in March with slightly increased SST values of about 27°C observed around Cape Palmas. SST values further increased from April to May to about 29-30°C and decreased drastically from July to September between 22-25°C, known as the major/summer upwelling season (figure 4.0b and c). The major coastal upwelling season appeared to start in July and upwelling in this month was greater at the capes and to the east of Cape Three Points. In July, there was a large drop in SST and strong upwelling occurred along the entire coast from Cotonou (Benin) to Cape Palmas. The upwelling was greatest to the east of Cape Three Points. The most intense upwelling occurred in August along the entire coast from Cape Palmas to Cotonou (figure 4.0c). The upwelled water extended well beyond the continental shelf edge, with SSTs reduced from the coast to the equator (equatorial upwelling). In September, upwelling was weaker than in August but still extended beyond the shelf edge. In October, upwelling was greatly reduced in both spatial extent and intensity. The main upwelling area was seen on the Ivorian coast to the east of Cape Palmas, although some cold water was still visible around Cape Three Points. In November and December, warm waters covered the whole coastal area with values of SST observed between 29-31°C.

4.1.2 Central Eastern Equatorial Atlantic (0-20°W)

Bounded by land to the north (at 5°N) and to the east (at 10-12°E) the Central Eastern equatorial Atlantic, is open to the South Atlantic Ocean. In January (figure 4.0a), SST value was quite low around 26°C between 0-20°W with a slight increase further west...
at the equator. In February, SST values increased slightly to about 27°C and increased to about 28°C further west in the west equatorial Atlantic (figure 4.0a). The sea surface temperature recorded in the region during this period was observed to be similar to that experienced during the minor coastal upwelling in the h Coast of the Gulf of Guinea. A slight increase in SST and a reduction in upwelling intensity were observed in March in both areas (figure 4.0b). The existence of a direct relation observed between SST values in the Coast of the Gulf of Guinea and the Central Eastern Equatorial Atlantic from January to March was observed. April recorded an increased SST value of about 29°C over the entire equatorial region from East to West. The onset of the equatorial upwelling in the region was noticed in May between longitudes 0-20°W and extended further East (figure 4.0b). June recorded an increase in the intensity of the equatorial upwelling with a sharp decrease in SST to about 24°C between 0-20°W. SST values increased slightly to about 26°C from 20-30°W and increased further west. It was seen that, the Central Eastern equatorial upwelling appeared to precede the summer coastal upwelling in the Coast of the Gulf of Guinea, that is, whiles the Central Eastern equatorial upwelling commences in June, the summer upwelling in the Coast of the Gulf of Guinea starts in July (figure 4.0b). July recorded a further decrease in SST value of about 23°C with an intensified upwelling progressing further west. In August the entire Gulf of Guinea was occupied by anomalously cold water. The low SST extended westward and reached its most westerly position on the equator at about 40°W (figure 4.0c). The upwelling intensity increased rapidly in this period marking the month of maximum upwelling. The upwelling intensity as well as the spatial extent of the equatorial upwelling decreased slightly in September with an observed increase in SST to about 23°C. The spatial extent of the equatorial upwelling further decreased from October to December (figure 4.0c). A westward propagation of the upwelling in these region was observed from May with a maximum westward spatial extend noticed in August. The spatial extent then decreased gradually from September till it became almost unnoticeable in April (figure 4.0b and c).

Figure 4.0. Monthly mean SST with NOAA-AVHRR data calculated from January 1995 to December 2006. (a) January-February.
Figure 4.0. (b) March-July
Figure 4.0 (c) August-September
4.2. Seasonal and spatial variability in Wind stress

4.2.1. The Gulf of Guinea Coast

Southeasterly trade winds, which prevail over the south of the equator, become southerly near the equator and southwesterly as they approach the African continent. In the Gulf of Guinea coast, the wind is not purely zonal oriented with an eastward component at its easternmost part due to a low pressure system over the African continent. The maximum zonal wind stress magnitude in this area was observed in March and April with values of 0.0338 and 0.0238 N/m² recorded respectively (figure 4.1). Also, the maximum meridional wind stress magnitude in this region was recorded to be 0.0552N/m² and 0.0647N/m² in May and June respectively. Spatially, the zonal wind stress exhibited very weak magnitudes in wind stress as compared to the meridional wind stress in the region with an average mean of 0.0156 N/m² and 0.0351N/m² respectively. March, April, and June experienced high zonal wind stress magnitudes above the mean value with all the other months recording values below the mean stress. The zonal wind stress in the Gulf of Guinea showed an alternating increase and decrease in the wind stress magnitude with a rapid increase from January-March, a drastic decrease from March-May, a slight increment in June, and a long stream of weak magnitudes observed from July-December (figure 4.1). However, the meridional wind stress exhibited strong strengths in wind stress magnitudes showing a gradual rise in magnitude from January to June (where its maximum was recorded) and a gradual fall from June to December (figure 4.1). Thus the winds could, in principle, induce a coastal upwelling in the region. However, in spite of the northward migration of the ITCZ during summertime, and the wind field intensification over the equatorial Gulf, winds remain quite weak along the region as compared to other regions.

Figure 4.1. Monthly mean of zonal (top) and meridional (down) wind stress for January to December with NOAA-QuikSCAT data from January 1995 to December 2006 in the Gulf of Guinea.
4.2.2. Western Equatorial Tropical Atlantic

In the western part of the tropical Atlantic basin, the wind is mainly zonal and westward. The maximum zonal wind stress above a mean of 0.0590N/m² in this region was observed from January-April and November-December with magnitudes between 0.0987 and 0.0641 N/m² (figure 4.2). The low zonal wind stress magnitudes below the mean were observed from June to October similar to the period of summer upwelling in the Eastern Atlantic (Gulf of Guinea). The very low wind stress amplitude recorded from July-September also corresponds to the highly intense upwelling observed during this period in the Gulf of Guinea. Comparing statistically the absolute maximum and minimum wind stress values of figures 4.1 and 4.2, it was concluded that the Western Equatorial Atlantic region experienced strong annual zonal wind stress variation with a mean of 0.06117 N/m² as compared to the weak zonal and meridional wind stress variation in the Eastern Atlantic (Gulf of Guinea) with a mean of 0.0156 and 0.0351 N/m² respectively.

![Figure 4.2](image)

**Figure 4.2.** Monthly mean zonal wind stress in N/m² (West Atlantic) from January to December with NOAA-QuikSCAT data from January 1995 to December 2006 in the Western Equatorial Atlantic.

4.3. Is the upwelling governed by local process or remote forcing?

A time series of the interannual anomalies of SST along the gulf of guinea from 1995 to 2006 showed a strong seasonal variation of SST in the region, with a seasonal anomaly between -3.5 and 3 (figure 4.3). Thus, the SST anomaly had a spatial extent affecting the whole eastern equatorial basin and a characteristic of this region. The image identified the large-scale pattern of the interannual variability of SST in the region.

![Figure 4.3](image)

**Figure 4.3.** Annual SST anomaly from 1985-2007 in the Gulf of Guinea. Source: NOAA-AVHRR data.
4.3.1. Local Process

A very low positive correlation of 0.0872 was computed between the SST and the zonal wind stress data in the Gulf of Guinea. This weak correlation explained the poor relationship between the zonal wind stress and the sea surface temperature in the region. A poor visual agreement existed between the zonal wind stress and SST in the Gulf of Guinea showing alternating positive and negative trends in the wind stress and SST with no perfect correlation between them (figure 4.4).

**Figure 4.4.** Time series of the annual anomalies of SST (black) and zonal wind stress (blue) from 1995-2006 in the Gulf of Guinea: Source: NOAA-AVHRR/QuikSCAT data.

The magnitude of the zonal wind stress from the mean monthly bar plot (figure 4.5) was multiplied by a scale factor of 1000.

A poor visualization in the zonal wind stress and SST trend in the Gulf of Guinea during the upwelling and even the non-upwelling season was observed. April, May and December were known to be non-upwelling seasons but recorded varying wind stress amplitudes exhibiting values above and below the mean wind stress. Moreover, the maximum and minimum periods of SST and wind stress did not correspond, that is to say, the maximum SST neither corresponded to a minimum nor a maximum wind stress and vice versa (figure 4.5). Furthermore, low magnitudes of wind stress below a mean value of 15.58N/m² was observed throughout the whole period except in March, April and June and corresponded to varying values of SST. For example, August recorded the lowest SST value but neither experienced the maximum nor the minimum wind stress value. Also, August, noted to be an upwelling month with low SST, recorded a wind stress value of 12.0553N/m² greater than that in May (non-upwelling month) and lower than that in July (upwelling month).

**Figure 4.5.** Bar plot of the monthly mean of SST (blue) and zonal wind stress * 1000 (red) from 1995-2006 in the Gulf of Guinea: Source: NOAA-AVHRR/QuikSCAT data.
However, the wind in the Gulf of Guinea coast is not purely zonal, hence investigating the influence of the meridional portion of the wind stress to the SST variation in the region is also important.

Also, a poor positive correlation coefficient of 0.0215 was computed between the meridional wind stress and the SST in the Gulf of Guinea (figure 4.6). Moreover, the poor visualization between these two quantities was also observed when the monthly mean of the wind stress and SST was plotted in the bar plot (figure 4.7). The poor link existing between both the zonal and the meridional component of the wind stress and the SST fluctuations in the Gulf of Guinea concluded that the local winds have very little or no influence on the SST fluctuations in the Gulf of Guinea.

![Figure 4.6](image)

**Figure 4.6.** Time series of the annual anomalies of SST (black) and meridional wind stress (blue) from 1995-2006 in the Gulf of Guinea: Source: NOAA-AVHRR/QuikSCAT data.

![Figure 4.7](image)

**Figure 4.7.** Bar plot of the monthly mean of SST (blue) and meridional wind stress *1000 (red) from 1995-2006 in the Gulf of Guinea. Source: NOAA-AVHRR/QuikSCAT data.

Furthermore, since the wind along the coast of the Gulf of Guinea is neither fully zonal (T\textsuperscript{x}) nor meridional (T\textsuperscript{y}), the resultant T was calculated and verified from the relation $T = \sqrt{(T^x)^2 + (T^y)^2}$. The resultant wind stress (T) was computed and a time series plotted with the SST in the Gulf of Guinea (figure 4.8). The time series also exhibited a weak correlation coefficient of 0.2217 (but stronger than that of the zonal and meridional), with the SST in the Gulf of Guinea (figure 4.8). The resultant wind stress (T) also showed intense wind stress magnitudes greater than that of the zonal and meridional wind stress making it favorable to influence temperature variations in the region.

Moreover, the monthly mean bar plot did not give a clear visual agreement between the trends of the resultant local wind stress (T) and the SST in the Gulf of Guinea. For
example, July (upwelling season) recorded a maximum wind stress value of 56.7593 N/m$^2$ as well as September (also an upwelling season) recorded a minimum stress value of 33.0009 N/m$^2$ (figure4.9).

**Figure 4.8.** Time series of the annual anomalies of SST (black) and the wind stress magnitude (blue) from 1995-2006 in the Gulf of Guinea: Source: NOAA-AVHRR/QuikSCAT data.

**Figure 4.9.** Bar plot of the monthly mean of SST (blue) and the Resultant wind stress * 1000(red) from 1995-2006 in the Gulf of Guinea. Source: NOAA-AVHRR/QuikSCAT data.

### 4.3.1.1. Hypothesis Test

However, for further investigation and proof of the authenticity and existence of the observed correlation between the various components of the Local wind stress (Zonal ($T^X$), Meridional ($T^Y$) and the Resultant ($T$)) and the SST in the Gulf of Guinea, the Student t-test (Hypotheses Testing) was employed.

The hypothesis testing is simply the use of statistics to determine the probability that a given hypothesis is true.

So in this paper, the correlations 0.0872, 0.0215, and 0.2217 observed between the Zonal ($T^X$), Meridional ($T^Y$), and their Resultant component ($T$) of the local wind stress with the SST in the Gulf of Guinea respectively was tested using the students t-test from the relation

$$t = r \sqrt{\frac{n-2}{1-r^2}}$$

to further proof if the correlation existing between the local wind stress components and SST in the Gulf of Guinea is sufficient enough to influence temperature variations in the Gulf of Guinea region.
From the relation, \( t \) is the time, \( n \) is the number of degrees of freedom which is equal to the length of the time series (144), \( t_\infty \) is the critical value (1.96), and \( r \) is the calculated correlation coefficient (0.0872, 0.0215, and 0.2217)

From calculations not shown here, it was observed that there existed no correlation between the zonal and meridional wind stress and SST in the Gulf of Guinea with \( t = 1.04 \) and 0.26 respectively less than the critical value of 1.96, hence falling inside the confidence interval and accepting the null hypothesis of no correlation. Moreover, the authenticity of a weak correlation existing between the Resultant component of the local wind stress and SST in the Gulf of Guinea was verified with \( t = 2.71 > 1.96 \). By looking at the correlation between SST and alongshore local wind stress in the Gulf of Guinea, it can be concluded that there is a little apparent relationship of about 22% between the interannual variability of the local wind and the intensity of the summer cooling. That is to say, the local wind stress mainly the Resultant component, influences about 22% of the temperature fluctuations in the Gulf of Guinea region.

4.3.2. Remote Forcing

According to the remote forcing idea of Moore et al (1978), variations in the westward wind stress in the western equatorial Atlantic would provoke the depth of the thermocline in the eastern equatorial Atlantic (Gulf of Guinea) thereby inducing temperature fluctuations in the region. So, a good correlation between the zonal wind stress anomaly in the West Atlantic and the SST anomaly in the Gulf of Guinea was expected. A positive (negative) peak in the zonal wind stress anomaly of the West Atlantic region corresponded to a positive (negative) in SST anomaly of the Gulf of Guinea (figure 4.10) which obeyed the remote forcing theoretical hypotheses proposed by Servain, (1982).

A maximum positive correlation coefficient of 0.5401 was calculated between the zonal wind stress anomalies in the western Atlantic and the SST anomalies in the Gulf of Guinea (figure 4.10). Nevertheless, a vivid look at the time series indicated that a peak wind stress anomalies within the West equatorial Atlantic precede a peak SST anomaly in the Gulf of Guinea.

![Figure 4.10](image-url) Time series of the annual anomalies of SST (black) in the Gulf of Guinea and zonal wind stress (blue) in the Western Atlantic from 1995-2006. Source: NOAA-AVHRR/QuikSCAT data.
A strong positive relationship was also observed between the west Atlantic zonal wind stress and the sea surface temperature in the Gulf of Guinea when a bar plot of the monthly means was plotted (figure 4.11).

**Figure 4.11.** Bar plot of the mean monthly SST (blue) in the Gulf of Guinea and zonal wind stress * 1000 (red) in the Western Atlantic from 1995-2006. Source: NOAA-AVHRR/QuikSCAT data.

A clear influence of the West Atlantic zonal wind stress on the SST fluctuations during the summer upwelling in the Gulf of Guinea was noticed (figure 4.11). It was observed that, a change in the strength of the magnitude of the western Atlantic zonal wind stress was mainly associated with anomalous conditions in SST during the summer upwelling period between July and September. The maximum zonal wind stress value in the West Atlantic region was experienced in January and December, with a slight decrement observed from February to April. A rapid relaxation in the wind stress strength below the mean value of 61.66 N/m² commenced in June, and decreased further from July to September.

It was noticed from the plot that, a rapid change in the magnitude of the zonal wind stress of the West Atlantic in June corresponded to a drastic change of SST in July in the Gulf of Guinea. But it was observed that the change in the zonal wind stress is not fully responsible for the overall temperature variations in the Gulf of Guinea but has a 54% chance of influencing fluctuations in temperature mainly during the summer upwelling season in the region.

Due to the rapid change in the West Atlantic zonal wind stress in June, one could have also expected the onset of the summer upwelling in June but rather it started in July. This explains a month lag existing between the change in strength of the zonal wind stress amplitude in the western Atlantic and the onset of the summer upwelling in the Gulf of Guinea.

So the wind stress fluctuations in the Western Equatorial Atlantic in July excited equatorially trapped Kelvin waves which propagated eastward along the equator and caused shoaling of the thermocline that in turn induced a remotely forced response in the Gulf of Guinea with a one month lag between the zonal component of the wind stress off the Western Equatorial Atlantic and SST in the Gulf of Guinea. The one month lag is the time required for an equatorial Kelvin wave, with a phase speed of 2 m/s
Where appropriate the significance of the results above was estimated using the standard two-sided Students t-test, assuming a null hypothesis of no correlation.

4.3.2.1. Hypothesis Test

However, the significance of the correlation of 0.5401 existing between the zonal wind stress of the West Atlantic region and the SST in the Gulf of Guinea estimated using the students t-test, further proved the authenticity of the relationship between the West Atlantic zonal wind stress and the Gulf of Guinea SST with \( t = 7.65 > 1.96 \) (critical value). The strong existing relation between the two quantities further proves that the upwelling in the Gulf of Guinea is dominated by the remote forcing mechanism with a 54% influence on the SST variations in the region but not solely influenced by remote forcing.

These results support the hypotheses that the upwelling in the Gulf of Guinea is dominated by the remote forcing mechanism but slightly influenced by the local winds with the remote forcing and local process forming about 54% and 22% respectively of the mechanisms responsible for inducing temperature fluctuations in the Gulf of Guinea.

Furthermore, winds inducing upwelling around the equator have to be strong and persistent, because of the diminished Coriolis Effect around the equator. The weak local wind stress in the gulf of guinea compared to the zonal wind stress of the western equatorial Atlantic, also explained the fact that the West Atlantic easterlies dominate.

4.4. Is there an intensification of the minor upwelling in relation to a reduction in the strength of the major upwelling?

Upwelling intensity may be the cause of variability in the biotic components of the ecosystems. Observations of upwelling rate are not available. Indications of coastal upwelling in the sea temperature distributions are qualitatively obvious but very difficult to quantify, particularly on longer time scales.

Bakum hypothesis states that global greenhouse warming should lead to intensification of the continental thermal lows adjacent to upwelling regions. This intensification would be reflected in increase onshore-offshore atmospheric pressure gradient, intensified alongshore winds, and accelerated coastal upwelling circulation. It is believed that coastal upwelling intensity has increased globally because of raising greenhouse gas concentrations in the atmosphere and an associated increase of the land-sea pressure gradient. Upwelling variability clearly confounds both sampling and data interpretation.
4.4.1. Minor Upwelling

The minor/winter upwelling has received less attention than the major/summer upwelling (Roy, 1995). The maximum intensity of this minor upwelling was observed in the surrounding of Cape Palmas and sharply decreased toward the east to become almost unnoticeable on the SST signal of the Ghana coastal stations.

A trend of alternating warm and cool intensities in the minor upwelling for the period of 23yrs from 1985 to 2007 was shown (figure 4.12). 1997, 1985, 1986, and 1990 recorded the maximum upwelling intensities in ascending order, with low SST values ranging from 26.37 to 26.78 respectively. The minimum upwelling intensities were observed in 1999, 1998, 1996 and 1991 with very high SST values ranging from 28.15-27.96°C. A rapid reduction in the upwelling intensity was observed in 1998 and 1999. A reduction in the upwelling intensity corresponded to an increase in the sea surface temperature. Fluctuations of upwelling intensities were observed over the last decade from 1997-2007. The computed mean of the upwelling intensities from 1985-1996 and that from 1997-2007 was -2.2553 and -2.4303 respectively with the mean intensity of the last decade being lesser than that of the first decade corresponding to a reduction in the strength of the minor upwelling over the last decade. Furthermore, the regression line of best fit with -2.15 intercept gave the trend of the minor upwelling intensity over the period with a continuous reduction of the minor upwelling intensity from 1985 to 2007.

This contradicts the hypothesis proposed by several authors such as (Morlière, 1970), which states that "the intensification of the Guinea current in January and February is thought to contribute to the upward movement of the thermocline associated with this Minor upwelling".

![Minor Upwelling Intensity in the Gulf of Guinea](image)

Figure 4.12. Mean SST between January and March from 1985 to 2007. Source: NOAA-AVHRR data.

4.4.2. Major Upwelling

The major upwelling season appeared to start in July with its maximum intensity observed in August along the entire coast from Cape Palmas to Cotonou. The major upwelling also known as the summer upwelling has been investigated to be influenced by local, remote forcing and other uninvestigated mechanisms in this paper but dominated by remote forcing, that is variations in the West Atlantic zonal wind stress.
The upwelling intensity strongly induces temperature variations in the Gulf of Guinea during the summer upwelling. The combined upwelling intensity for the major season showed strong and weak upwelling in 1991-1992 and 1987/1989 respectively, with an extended period of weak upwelling from 1993 to 1999. The minor upwelling showed a similar pattern from 1985 to 1989 but then diverged with a continued weakening of the upwelling from 1990 to 1991 (figure 4.13). An alternating trend of strong and weak intensities was observed between 2000 and 2004 followed by a drastic reduction in the strength of the upwelling from 2005 to 2007.

The mean upwelling intensity computed for the first decade from 1985-1996 and that of the last decade from 1997-2007 was -0.5375 and -0.7148 respectively. The mean intensities for both the first and last decade indicated the reduction in the strength of the major upwelling over the last decade from 1997-2007. The trend of the regression line of best fit with an intercept -0.4 showed a reduction in strength of the major upwelling intensity over the 23 yr period from 1985-2007.

The decomposition trend in SST during the minor and major upwelling revealed gradual warming of surface waters due to the existing climate change.

![Figure 4.13. Mean SST between July and September from 1985 to 2007. Source: NOAA-AVHRR data.](image)

However, it was observed that the strength of the minor upwelling is decreasing at a faster rate as compared that of the major upwelling due to the gradual intensification of the West Atlantic zonal wind stress (figure 4.14) which has been proved to be an influential factor of the temperature variations in the Gulf of Guinea mainly during the summer upwelling hereby reducing the rate at which the major upwelling is reducing. The regression line of best fit drawn showed a gradual increase of the West Atlantic zonal wind stress over the period due to global warming.

![Figure 4.14. Mean West Atlantic zonal wind stress between May and October from 1985 to 2007.](image)
4.5. Is there a link between the Gulf of Guinea coastal upwelling and the equatorial upwelling of the Central Eastern Atlantic Ocean?

Clearly looking at figure 4.15, a strong existing relationship between the mean annual sea surface temperature of the Central Eastern Atlantic Equatorial upwelling and the coastal upwelling of the Gulf of Guinea was noticed. A positive (negative) peak in the SST anomaly of the Central Eastern Atlantic Equatorial upwelling region corresponded to a positive (negative) peak in the SST anomaly in the coastal upwelling region of the Gulf of Guinea. Therefore the two curves were in phase (figure 4.15).

The strong visual agreement between these curves was confirmed by the bar plot in figure 4.16. However, a maximum correlation coefficient of 0.8329 existed between the sea surface temperature plots in both regions. The time series plot also showed that a (positive or negative) peak in the SST anomaly of the Central Eastern Atlantic region preceded a positive or negative peak in the SST anomaly of the Gulf of Guinea. Moreover, both plots showed the existence of a maximum and a minimum peak of SST anomaly in each year.

Figure 4.15. Time series of the annual anomalies of SST (black) in the Gulf of Guinea and (blue) in the Central Eastern Equatorial Atlantic from 1955-2007.

From the computed monthly mean plotted (figure 4.16), a clear visual agreement in the corresponding trend of SST from January to December between the Central Eastern Atlantic Equatorial upwelling and the Gulf of Guinea coastal upwelling was noticed. This observed correspondence contradicted the hypothesis made by (Houghton and Colin, 1987) that, there is no apparent relationship between onset of the equatorial upwelling and the onset the coastal upwelling.

The minor upwelling period in the Gulf of Guinea coastal upwelling as already known occurred between January-March, also the figure exhibited the existence of cold sea surface temperature in the Central Eastern Equatorial Atlantic region during the same period, relatively colder than that observed in the Gulf of Guinea during the coastal minor upwelling (figure 4.0a and b).

However, a slight increase in sea surface temperature in both regions from January to April with warm SST values recorded in April was observed (figure 4.0b). SST values decreased rapidly in June in the Central Eastern Equatorial Atlantic region marking the onset of the
equatorial upwelling whiles the SST in the Gulf of Guinea reduced slightly in the same period but did not commence the major coastal upwelling in the region. June, marking the onset of the equatorial upwelling recorded SST value below the mean SST of 25.73 computed over the region. The onset of the major/summer coastal upwelling in the Coast of the Gulf of Guinea was observed in July with a recorded SST below the computed mean SST of 26.92 over the region. This clearly proved the existence of a month lag between the onset of the equatorial upwelling of the Central Eastern Atlantic Ocean and the onset of the Gulf of Guinea summer coastal upwelling.

After the commencement of both upwelling, SST values decreased with increasing upwelling intensities in both regions from July to September with the intense upwelling observed in August extending over the entire Gulf of Guinea ecosystem (figure 4.0b). Colder sea surface temperature was still observed in the Central Eastern Equatorial Atlantic region in November and December whiles very warm sst values were recorded during the same period in the Coast of the Gulf of Guinea. This observation concluded that the equatorial upwelling is experienced all year round in the Central Eastern Atlantic Ocean except during April and a very minor one in March.

As investigated, the upwelling in the Gulf of Guinea, both the coastal and equatorial upwelling is dominated by remote forcing, that, a change in strength of the easterly wind in the western equatorial Atlantic creates an internal upwelling Kelvin wave that propagates eastward along the equator at a speed of 2m/s; when reaching the African continent, this wave reflects as coastal Kelvin waves and Rossby waves, the coastal Kelvin waves are trapped along the Coast and propagate poleward, the Rossby waves propagate westward on both sides of the equator.

A rapid change in intensity of the easterly wind in the western equatorial Atlantic in June as already observed, excites an internal upwelling wave travelling at a speed of 2m/s (http:en.wikipedia.org/wiki/Kelvin_wave) that induced an equatorial upwelling in the central eastern Atlantic in June and a coastal upwelling in the Coast of the Gulf of Guinea in July. Hence the actual time that existed between the onsets of each of the upwelling was computed from the relation

\[ \text{Time} = \frac{\text{Distance}}{\text{Speed}} \]
Where speed (phase speed of the Kelvin wave 2m/s), distance (distance the wave travelled from the West Atlantic (35-38°W) to the central eastern equatorial Atlantic between (5-10°W) and also the coast of the Gulf of Guinea (1-6°W and 4-5°N)), and time was the time the wave took to get to the region.

<table>
<thead>
<tr>
<th>Latitude</th>
<th>Surface distance per 1° change in latitude</th>
<th>Surface distance per 1° change in longitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>110.574km</td>
<td>111.320km</td>
</tr>
<tr>
<td>15°</td>
<td>110.649km</td>
<td>107.551km</td>
</tr>
<tr>
<td>30°</td>
<td>110.852km</td>
<td>96.486km</td>
</tr>
<tr>
<td>45°</td>
<td>111.132km</td>
<td>78.847km</td>
</tr>
<tr>
<td>60°</td>
<td>111.412km</td>
<td>55.800km</td>
</tr>
<tr>
<td>75°</td>
<td>111.618km</td>
<td>28.902km</td>
</tr>
<tr>
<td>90°</td>
<td>111.694km</td>
<td>0.000km</td>
</tr>
</tbody>
</table>

Table 4.0: An appropriate calculator for any latitude as provided by the U.S. government’s National Geospatial-Intelligence Agency (NGA).

The average longitudinal span between the western equatorial Atlantic and the central eastern equatorial Atlantic is 29°.

distance between the West equatorial Atlantic and central eastern equatorial Atlantic region at latitude 0° is:

\[
1° \text{ longitude} = 111.320\text{km} \\
29° \text{ longitude} = 29 \times 111.320 \\
= 3,228,280\text{meters.}
\]

From the previous relation #

\[
\text{Time} = \frac{3,228,280}{2} \\
= 1,614,140 \text{ sec.} \\
= 18\text{ days and 16hrs}
\]

Hence it took 18days and 16hrs for the Kelvin wave with a speed of 2m/s to travel from the West equatorial Atlantic to the central eastern equatorial Atlantic region to induce SST variation (shallowing the thermocline) leading to the onset of the Equatorial upwelling.

Total distance travelled by Kelvin wave from the west equatorial Atlantic to the coast of the Gulf of Guinea:

- Average distance from west to eastern boundary of the Atlantic i.e. from 31.5°W-10°E 
  \[= 41.5 \times 111.320\text{km} \]
  \[= 4,619,780\text{meters.}\]

- Average distance of the wave along the African coast from 0-4.5°N 
  \[= 4.5 \times 110.574\text{km} \]
  \[= 497,583\text{meters.}\]

- Average distance from 10°E to 3°W along the north Gulf of Guinea coast 
  \[= 13 \times 111.320\text{km} \]
  \[= 1,447,160\text{meters}\]
Total distance travelled = 6,564,523 meters

\[
\text{Time} = \frac{6,564,523}{2} = 3,282,261.5 \text{sec} = 38 \text{ days}
\]

From the above calculations, it was noticed that a change in strength of the easterly wind in the western equatorial Atlantic in June creates an internal upwelling Kelvin wave that propagated eastward along the equator at a speed of 2m/s which took 18 days to reach the central eastern equatorial Atlantic enhancing the onset of the equatorial upwelling still in June. After it propagated eastwards, upon reaching the African continent, this wave reflected as coastal Kelvin waves and Rossby waves, the coastal Kelvin waves were trapped along the Coast and propagated poleward along the African continent to induce the onset of the coastal upwelling in the Gulf of Guinea coast (0-6°W) 20 days after the onset of the equatorial upwelling which was July marking the onset of the coastal upwelling in the region.

This therefore proved the lag existed between the onset of equatorial upwelling of the Central Eastern Atlantic and the onset of the coastal upwelling in the coast of the Gulf of Guinea obtained to be about 20 days. Also, it proved a 38 day lag between the relaxation of the zonal wind stress in the west equatorial Atlantic and the commencing of the coastal upwelling.

### 4.6. Is there another upwelling phenomenon in the Gulf of Guinea?

Areas of upwelling are highly productive of primary organic matter and support most of the world’s richest fisheries. Such areas are also known to have economic deposits of Petroleum, glauconite, phosphorite and barite among others. Evidence inferred from the occurrence of petroleum source beds, glauconite and phosphorite in offshore Nigeria (Ibe 1982; Ibe et al 1983) as well as limited hydrographic data pertinent to the area (Anon, 1953, 1954, 1960; Berrit, 1959, 1961, 1962a, b, c) suggest that some upwelling, even if feeble, may be occurring in the inshore waters of Nigeria. Coastal upwelling usually manifests itself as a depression in the SST often times bringing them to thermocline levels.

The Nigerian coast with a coastline of about 853km has been observed to exhibit seasonal annual variations in sea surface temperature. Figure 4.0a, b and c showed a spatial distribution of monthly sea surface temperature of the Nigeria coast (lying between latitude 4-6°N and longitude 3-10°E). Variations in SST in the south Nigeria coastline showed a similar trend in SST variations in the Cote d’Ivoire-Ghana ecosystem but with lower SST values. Two upwelling periods (periods with lower SST values below the mean of 27.71) with lower upwelling intensities compared to other upwelling areas were observed in this ecosystem with the minor upwelling occurring in January and the major commencing in July through to September (figure 4.17).
The rapid fall in sea surface water temperature to near thermocline levels between July-September suggested that upwelling occurred about this period. August recorded the maximum upwelling intensity with temperatures as low as 25°C observed in the South Nigeria Coast.

From figure 4.0b and c, along longitude 6°E the almost perennial warming at the Niger Delta was evident except in July-August when the impact of the coastal upwelling off Cote D’Ivoire-Ghana broke this trend. From the spatial distribution of sea surface temperature, another upwelling phenomenon in the Gulf of Guinea was observed of the south Nigerian Coast with less intense upwelling intensity as compared to other upwelling areas of the region.

The Hovmuller plot (Figure 4.18) further showed the magnitude of the hydrographic seasons in the Nigeria coast, with certain areas showing varying time span. The plot exhibited three different temperature variations for three different observed months: January, May and September. Between January, May and September, there were two very brief moderately warm and colder periods (May and September respectively) and a slightly cold period (January)(minor upwelling) (Figure 4.18).

Along latitude 4.5°N the strong presence of cold water that possibly emanated from the subsurface lasted from July to September.

The fall in the sea surface temperature to near thermocline level in September suggested that upwelling occurred about this period. The plot gave a clear visualization of the SST variations with alternatively cold and warm temperatures observed in the south Nigeria Coast convincing one on the occurrence of another upwelling phenomenon in the Gulf of Guinea.
Figure 4.18. Spatially averaged latitudinal (4.5°N) monthly SST of the South Nigerian Coast. White patches are regions with no data due to cloud contamination or land cover.

Chapter 5

5.0 Discussion

5.1. General Discussion

The intention of the study reported in this thesis was to contribute towards a better understanding of the mechanisms of the upwelling phenomenon in the Gulf of Guinea. In addition, it was to characterize, 1) whether the upwelling in the Gulf of Guinea is governed by remote forcing or by local process, 2) whether there is an intensification of the minor upwelling in relation to a reduction in the strength of the major upwelling, 3) whether there is a link between the Gulf of Guinea coastal upwelling and the Central Easterns Atlantic equatorial upwelling, and 4) whether there is another upwelling phenomenon in the Gulf of Guinea. The combination of NOAA-AVHRR/QuikSCAT (SST and Wind stress) datasets sought to exploit their qualities of complementarities.

Globally, it has become pertinent for continuous investigation of the mechanisms responsible for the upwelling in the Gulf of Guinea and other upwelling areas at large. As an example, Hingham (2001), Philander (1979), Servain et al (1982), all investigated several mechanisms responsible for the Gulf of Guinea upwelling. The present work made the first contribution in characterizing all the earlier mentioned abjectives.

Satellite observations provided means of repeated coverage of ocean features including ocean surface temperature to help understand the seasonal variations of the sea surface temperature over the period. The 23yrs of gridded SST and 13yrs of wind stress resulting from the objective analysis provided an opportunity to jointly analyze and investigate the upwelling mechanisms in the Gulf of Guinea for the regions discussed earlier. Myriad of processes emanating from solar heating and wind stress (Daly and Smith, 1993) results in upwelling.

The spatial distribution patterns in the sea surface temperature followed unique physical conditions of the subsystems of the gulf of guinea (figures 4.0a, b and c). From the spatial distribution, upwelling was seasonal especially in the Gulf of Guinea where there were two periods of coastal upwelling: the major upwelling between July and September and been
characterized by very low SST values between 22-25°C investigated to be dominated by remote forcing, and a minor upwelling from January-March, strongest in January but also visible in February and March exhibiting sea surface temperature values ranging from 25-27°C. Both upwelling periods commenced to the east of Cape Three point and this was also the area of greatest upwelling strength. The upwelling then shifted westward towards Cape Palmas. The position of the major upwelling celled to the east of the capes. This effect was also seen to a lesser degree around the mouth of the Volta Delta. The observed westward shift in dominance from Cape Three Points to Cape Palmas was consistent with the results of Picaut (1983) who observed a westward propagation of the upwelling, counter to the dominant surface flow.

Moreover, an equatorial upwelling in this region commenced in June, increased rapidly in August and decreased slowly, both spatially and in intensity till it became almost unnoticeable in March.

**5.2. Is the upwelling governed by local process or remote forcing?**

According to the qualitative model of Cromwell (1995), variations in the northward and westward wind stress near the equator should induce local temperature fluctuations there. Furthermore, according to Philander (1978) the northward equatorial wind can affect SST along the northern coast of the Gulf of Guinea.

For local forcing, a positive (negative) peak in $T^x$ was expected to correspond to a positive (negative) SST anomaly and a positive (negative) peak in $T^y$ was expected to correspond to a positive (negative) SST anomaly in the Gulf of Guinea. That is to say, a positive (negative) SST anomaly implies an increase (decrease) SST value relative to the mean SST value. Also, according to the remote forcing idea of Moore et al. (1978), variations in the westward wind stress, $T^x$ in the western equatorial Atlantic should induce temperature fluctuations in the eastern equatorial Atlantic.

The analysis showed that, the SST anomaly in the eastern equatorial Atlantic (Gulf of Guinea) is influenced by both the local forcing (resultant wind stress) and the remote forcing by 22% and 54% respectively with the remote zonal wind forcing of the west equatorial Atlantic being the dominant mechanism. The nonseasonal variability of SST in the Gulf of Guinea was weakly correlated with correlation coefficients of 0.0872, 0.0215 and 0.2217 to the nonseasonal zonal, meridional and the resultant(T) (zonal and meridional) local wind forcing respectively, and highly correlated with a coefficient of 0.5401to the nonseasonal variability of the zonal wind forcing off the West Equatorial Atlantic region.

Furthermore, a time lag of roughly one month (38days) existed between the change in strength of the West Atlantic zonal winds leading to the generation of the equatorial Kelvin
waves and its response in the Gulf of Guinea, that is, the onset of the major upwelling along the coast of the Gulf of Guinea lags the zonal wind stress fluctuations of the equatorial west Atlantic region by a month, which was the time the Kelvin wave travelled from the forcing area to the Gulf of Guinea.

Moore et al (1978) proposed a simple remote forcing mechanism to account for the Gulf of Guinea upwelling. According to this hypothesis, a change in strength of the easterly wind in the western equatorial Atlantic excites an internal upwelling equatorial Kelvin wave that propagates into the eastern equatorial Atlantic. When this disturbance reaches the eastern boundary it splits into Kelvin waves propagating poleward along the coasts in both hemispheres and a large number of westward propagating equatorial Rossby waves. Thus, the lag between the response in the Gulf of Guinea and the winds off the west equatorial region was simply related to the speed of Kelvin waves. This result was the main feature of the remote forcing mechanism proposed by Moore et al (1978) and illustrated by the linear model of O’Brien et al (1978).

However, comparison of the predominantly annual signals depicted in figures 4.4, 4.6 and 4.8 respectively bared this out. A mismatch of periodicities in the monthly mean SST and the overlying zonal and meridional local wind stress of the Gulf of Guinea were observed. The strong correlation coefficient existing between the West Atlantic zonal wind stress and the SST in the Gulf of Guinea increased when the wind stress averaging area reduced and centered further west. Furthermore, a correlation analysis (hypotheses testing) tested, revealed the authenticity of the strong correlation existing between the anomalies of the west Atlantic zonal wind stress and the SST in the Gulf of Guinea and a weak correlation obtained between the local winds and the SST in the Gulf of Guinea. The existing correlation of 0.2217, even if weak between the local winds and the SST in the Gulf of Guinea proved that the local wind has an influence of about 22% even if feeble on the SST variations in the region, hence the local winds contributes to the onset of the summer/major upwelling in the Gulf of Guinea although proved to be dominated by the remote forcing mechanism with 54% influence.

Consider the following scenario: A wind anomaly appears first in the Gulf of Guinea, but apparently affect the ocean there slightly. Sometime later, a similar wind anomaly appears in the western equatorial Atlantic. Only after a delay of one month, the ocean surface temperature in the Gulf of Guinea drops rapidly. This is due to the influence of remote forcing. The result of the study indicated that, the annual wind-driven response within an idealized Gulf of Guinea region was dominated by equatorial wind stress fluctuations remote from the Gulf.

Finally, it should be pointed out that there is a similarity between the temperature variability of the eastern equatorial Atlantic (Gulf of Guinea) and Pacific Oceans.

In the Pacific Ocean, Wyrtki (1975) suggested that the El-Nino event was caused by the relaxation of the Southeast trades in the Central and Western Pacific which in turn results
in eastward propagation of energy along the equator. Numerical and analytical models by McCreary (1976) and Hurlburt et al, (1976) simulated the excitation of an equatorially trapped internal Kelvin wave and its reflection on the eastern boundary. Busalachi and O’Brien (1981) with a linear model forced by monthly estimates of the observed surface wind over the tropical Pacific for 1961-1978, were able to explain a significant amount of the variability of sea level at the eastern boundary as being caused by remotely forced equatorial waves.

5.3. Is there an intensification of the minor upwelling in relation to a reduction in the strength of the major upwelling?

A mechanism exists whereby the global greenhouse warming could by intensifying the alongshore wind stress lead to acceleration of the coastal upwelling. Evidence from several different regions suggests that the major coastal upwelling systems of the world have been growing in upwelling intensity as greenhouse gases have accumulated in the earth’s atmosphere (Bakun, 1990).

On one hand, the results from analyzing trends in the NOAA-AVHRR SST were not consistent with the hypothesis by Bakun (1990), that is at first sight, the existence of significant decreasing trends in both the minor and major upwelling intensity revealed by the dataset for the Gulf of Guinea coastal upwelling region indeed seemed to contradict the global nature of increasing coastal upwelling intensity as proposed by Bakun (1990). On the other hand, a trend obtained for the Gulf of Guinea areas off West Africa argued that the upwelling intensity had decreased over the last decade. Considering the hypotheses made by Bakun (1990), later taken up by McGregor et al. (2007) for NW Africa which proposes a general increase in coastal upwelling in the later part of the 20th century due to global warming, it can be suggested that, coastal upwelling intensity is increasing in some upwelling regions and decreasing in others.

It was noted that the trend obtained from the upwelling intensity in both the minor and major upwelling demonstrated a significant decrease of upwelling intensity even when upwelling favorable winds (West Atlantic easterlies) showed a significant increase as observed (figures 4.12, 4.13 and 4.14). The minor upwelling intensity showed a cool period from 1985-1986 and an alternative cool and warm periods from 1987-2007 with the warm periods dominating. The major upwelling showed the same pattern, with strongest upwelling experienced in 1986 and 1990-1992, and the weakest upwelling in 1999, 2006 and 2007. Also an extreme weak upwelling was observed in 1985 and 1987 which could be attributed to the presence of the Atlantic El-Niño. However, the an unusual cooling observed during the major upwelling between 1992-1993 in the Gulf of Guinea could be linked to the El-Nino effect on the Atlantic Walker circulation over South America which strengthens the easterly trade winds in the Western equatorial Atlantic. Moreover, an extended period of slightly weak upwelling was observed from 2000-2007.
The Gulf of Guinea coastal upwelling is sometimes subject to basin-scale climate oscillations like the Atlantic Multidecadal Oscillation (AMO), the North Atlantic Oscillation (NAO) and the Pacific Decadal Oscillation (PDO). So the trends observed in the upwelling intensity could be affected by these basin-scale oscillations. It is also believed that the Thermohaline circulation of the ocean leads to warming of the Atlantic Ocean compared to other ocean basins. Alterations in the quantity of atmospheric greenhouse gases determine the amount of solar energy retained by the planet leading to Global warming thereby warming the oceans over the past century. This and other effects have led to the gradual reduction in strength of the upwelling over the past period.

However observed local change of both the major and minor upwelling is that, the relative intensity of the (major vs. minor) upwelling of this region had changed. The intensity of the minor/winter upwelling decreased at a faster rate of 0.027 for every 15yrs as compared to that of the major upwelling, decreasing at the rate of 0.017 for every 15yrs. This made it clear that the winter months are warming faster than the summer months under the influence of Global warming and all the other factors mentioned earlier.

It could be argued, since the upwelling in the Gulf of Guinea had been investigated to be dominated by remote forcing, then the gradual increase in the zonal wind stress of the West equatorial Atlantic should gradually increase the upwelling intensity of the Gulf of Guinea. But rather a decreasing trend in both the minor and major upwelling intensity was noticed. This therefore explains that, due to the effect of global warming, the ocean surface temperature is increasing at a rapid rate as compared to the gradual rate of 0.0001N/m² increase of the zonal wind stress for every 15yrs, thereby causing a gradual warming of the equatorial subsurface Kelvin waves responsible for dominating the onset of the upwelling in the Gulf of Guinea. Also, due to Global warming, there is a gradual warming of the subsurface sea temperature, making upwelled water warmer than usual. This scenario further convinces that, the variations in sea surface temperature in the Gulf of Guinea is not 100% dependent on the West Atlantic zonal wind stress, although they are strongly correlated with a coefficient of 0.5401 but not fully correlated and there exist other long term factors such as Global warming and thermohaline circulation affecting the SST in the Gulf of Guinea.

Therefore the observations and analysis made from this paper contradicts the hypotheses that ‘There is an intensification of the minor upwelling’ since a decreasing trend in the intensity of both the minor and major upwelling was noticed.

Global warming has become a topic of concern (IPCC, 2007), and the commensurate rise in sea surface temperature, therefore, might be expected to play an important role in the ocean dynamics of upwelling regions such as the Gulf of Guinea.
5.4. Is there a link between the Gulf of Guinea coastal upwelling and the equatorial upwelling of the Central Eastern Atlantic Ocean?

What then is the connection between the coastal and equatorial upwelling? The meridional side lengths of each are sufficiently short that the two regimes are separate and distinct. Of particular interest is the time lag in the onset of the upwelling at the two locations.

The two curves depicted in figure 4.15 were in phase. A positive (negative) peak in the SST anomaly of the Central Eastern Atlantic Equatorial upwelling region corresponded to a positive (negative) peak in the SST anomaly in the coastal upwelling region of the North Gulf of Guinea. A strong positive correlation with a correlation coefficient of 0.8329 was computed between the Equatorial upwelling in the Central Eastern Atlantic and the Coastal upwelling in the Gulf of Guinea. A long lasting equatorial upwelling was observed in the Central Eastern Atlantic, commencing in June, increased gradually from July to August (where it’s maximum was experienced) and decreased slowly to February and almost became unnoticeable in March and April. Also, two seasons of coastal upwelling was observed; a minor (January-March) and a major (July- September) with the major upwelling commencing in July. However, it was observed that the equatorial upwelling was highly intense with a wide spatial distribution as compared to that of the coastal upwelling.

A relaxation of the easterly wind in the western equatorial Atlantic in June as already observed excited an internal upwelling Kelvin wave travelled at a speed of 2m/s (http:en.wikipedia.org/wiki/Kelvin_wave) and induced an equatorial upwelling in the central eastern Atlantic 20 days after. So, assuming there is an increase of the easterly wind in the West Equatorial Atlantic on the 1st of June, an internal upwelling Kelvin wave is excited and travels at a speed of 2m/s. This wave travels eastward to induce an equatorial upwelling in the Central Eastern Atlantic 20 days after, which will be on the 20th of June. The Kelvin wave further travels east and upon reaching the African continent, it reflects as coastal Kelvin waves and Rossby waves, the coastal Kelvin waves are trapped along the Coast and propagate poleward, the Rossby waves propagate westward on both sides of the equator. The coastal Kelvin waves travel along the Gulf of Guinea coast where it induces a coastal upwelling after 18 days of travel from the Central Eastern Equatorial Atlantic on the 7th of July marking the onset of the major upwelling. This then explained clearly the lag existing between the onset of the Equatorial upwelling and that of the Coastal upwelling.

5.5. Is there another upwelling phenomenon in the Gulf of Guinea?

Coastal upwelling usually manifests itself as a depression in the sea surface temperature often times bringing them close to thermocline or sub thermocline levels. The spatial distribution of sea surface temperature along the Southern coast of Nigeria showed alternate distribution of warm and cold periods. The fall in sea surface temperature to near thermocline levels in July-September and a minor fall in January suggests that upwelling, which is feeble and with low spatial distribution, occurred about this period and in this
region. There were two seasons of upwelling in this region: The minor upwelling observed in January and the major upwelling commencing in July and running through to September.

It is evident that Ekman layers exist off the south facing coast of Nigeria and that provided persistent winds of adequate strength blow from the appropriate direction of the West Atlantic inducing kelvin waves, zonal upwelling would be induced. The west-east trend of the coastline of Nigeria necessitates that such upwelling induced waves (Kelvin waves) should move along the coast of Nigeria.

A correlation analysis performed showed a very weak correlation between the local zonal/meridional and their resultant wind stress and the sea surface temperature of the Nigerian coast. Also a strong correlation of 0.5210 existed between the zonal wind stress of the West Atlantic and the SST of the Nigerian coast. This then explained that, the feeble upwelling observed in the inshore waters of the Nigerian coast is also dominated by remote forcing. Moreover, the monthly wind data observed in the region exhibited very weak zonal and meridional magnitudes hence not favorable enough to induce upwelling. But the above analysis indicated that the zonal wind stress data of the West Equatorial Atlantic accounted for about 52% of the periodic drops in the sea surface temperature over the region.

So is it possible that the cool surface water resulted from the seasonal cooling of the South and Central Atlantic during the Southern hemisphere winter? Could it be that waters upwelled off Ivory Coast and Ghana at about the period were transported eastwards? Or perhaps it was merely a reflection of the cooler atmospheric conditions normal over these periods of each year? However, the magnitude of the temperature drops cannot all be explained by this correlation of 0.5210. In fact other environmental parameter changes such as increased salinity and lower dissolved oxygen content which are also traceable to upwelling might also influence the south Nigerian coastal upwelling.

The weak upwelling intensity observed in the Nigerian coast can also be attributed to the shallow lying thermocline of about 40m making the upwelled subsurface water not as cold as that observed in the Cape Three point.

Furthermore, The hovmuller plot (figure4.18) exhibited the monthly variations in SST of the Nigerian Coast over the 23yr period with the very colder periods observed between July-September marking the major coastal upwelling off the coast of Nigeria, the slightly cold periods in January marking the minor coastal upwelling, and the very warm periods in December-November and in March – May representing the non-upwelling periods. The plot showed temperature variations in the region for tree different months (January, May and September) over a period of 22yrs. Alternating warm and cold temperatures existed in each of the months with May recording the very warm temperatures above 29°C, January
recording the slightly cold temperatures of about 27°C and September exhibiting the very cold temperatures of about 25°C below the mean temperature over the period. The observed varying temperatures of the Nigerian Coast further proved the occurrence of a period of very cold Sea Surface Temperatures known as the period of upwelling in the region.

Hence the postulation in this paper was that, truly some upwelling, largely dynamic in nature, does occur off Nigeria coast at least spells. It is possibly supplemented by some transitory upwelling coastal Kelvin waves.
Chapter 6

Conclusion and Recommendation

6.1 Conclusion

This study was designed to investigate the upwelling mechanism in the Gulf of Guinea from satellite remote sensing data between January 1985 to December 2007. Results from the study showed the usefulness of remote sensing for investigating the upwelling mechanisms in the Gulf of Guinea by matching sea wind stress and SST, despite the large levels of cloud cover and atmospheric water vapor contamination in the region. Additionally, many of the features observed were interpretable in terms of physical processes known to exist in the region and analysis of these data can aid understanding of the underlying physical ocean dynamics. Of particular interest were observations associated with the coastal and equatorial upwelling. Some of these observations buttress earlier theories postulated to be regulating oceanographic processes in the region including the westward movement of the upwelling (Picaut 1983) and the ‘cape effect’ (Marchal and Picaut 1977).

The main conclusions of this thesis were:

- The Gulf of Guinea upwelling (coastal and equatorial) was been investigated to be governed by both remote and local forcing with the remote forcing dominating. A strong positive correlation of 0.5401 existed between the zonal wind stress in the Western equatorial Atlantic and the SST in the Gulf of Guinea. The local zonal/meridional and their resultant (T) wind in the Gulf of Guinea blows along to the coast throughout the year making it favorable to solely induce upwelling, but could not, due to the low magnitudes of the wind stress recorded. A relaxation of the zonal wind stress in west equatorial Atlantic lags the onset of the coastal upwelling in the Gulf of Guinea by a month (38days) and that of the equatorial upwelling by 20days considering a 2m/s travel speed of the Kevin wave.

- Studies of Bakun (1990) and Pezzenec and Bard (1992) noted an intensification of the minor upwelling season and a reduction in strength of the major upwelling intensity. However, from this study it appeared that both the minor and major upwelling have been decreasing in intensity over the last 20yrs with a decreasing rate of 0.027 and 0.017 respectively for every 15yrs. On the other hand, it was observed that the minor upwelling is decreasing at a faster rate as compared to the major upwelling thereby contradicting the hypotheses made by Pezzenec and Bard, and modifying Bakun’s hypotheses that the
upwelling intensity is not only increasing, but rather it is increasing in some areas and decreasing in other areas. The observed decrease in the upwelling intensity over the last 20yrs was attributed to the factors such as Global warming affecting the Thermohaline circulation which is believed to contribute to about 5°C warming of the Atlantic Ocean.

- An observed link between the onset of the Central Eastern Atlantic Equatorial upwelling and the Coastal upwelling in the Gulf of Guinea was shown with the equatorial upwelling lagging the coastal upwelling by 18 days. A strong positive correlation of 0.8329 existed between these two upwelling in the Gulf of Guinea with the Equatorial upwelling commencing in June and the Coastal upwelling commencing in July. The only observed difference between these two upwelling is the broad spatial distribution and high upwelling intensity of the equatorial upwelling than the coastal upwelling. Moreover, it was also observed that both the coastal and equatorial upwelling in the Gulf of Guinea have their maximum intensity in August. Also a similar trend in upwelling was noticed in both regions except in November and December which were upwelling seasons in Central Eastern Equatorial Atlantic but were non-upwelling periods in the coast of the Gulf of Guinea.

- Observation from this study proved the existence of another upwelling phenomenon in the Gulf of Guinea as reported by the on-going Guinea Current Large Marine Ecosystem Project. Two periods of upwelling was observed in the Southern Nigerian Coast, a minor upwelling in January and a major upwelling between July and September. From analysis, it was also proved that the feeble upwelling occurring in the south Nigerian coast was dominated by remote forcing with a strong correlation coefficient of 0.5210.

- Finally, in this study, a westward propagation of the upwelling signal along the coast of the Gulf of Guinea was also noticed. This then further proved the hypotheses made by Picaut in 1983 about the propagation of the seasonal upwelling in the Eastern Equatorial Atlantic.

### 6.2. Recommendation

The mechanisms responsible for the upwelling in the Gulf of Guinea continues to be very interesting as there are outstanding questions still to be answered.

It was investigated that the upwelling in the Gulf of Guinea is dominated by remote forcing, whose influence to the onset of the Gulf of Guinea upwelling forms about 54% and a 22% influence from the local forcing. From the analysis, an increasing trend in the West equatorial Atlantic zonal wind stress and a decreasing trend in both the minor and major upwelling in the Gulf of Guinea were observed over the last 20yrs. Moreover, it was known that a relaxation of the zonal wind stress in the West Atlantic causes SST drops (intensifying upwelling) in the Gulf of Guinea but what do we see, a gradual reduction in upwelling strength over the last 20yrs. This then proved that, the upwelling in the Gulf of Guinea is not only influenced by the remote and local forcing mechanisms. Future attempts to investigate the upwelling mechanisms in this region should further concentrate on the
other mechanisms influencing the onset of the Gulf of Guinea upwelling other than the remote and local forcing mechanism. Additionally, to investigate if the upwelling in the Gulf of Guinea is governed by local process or remote forcing, alternatively, the upwelling velocity can also be computed from the acquired wind data in the gulf of guinea area and plotted for comparism with the SST anomaly in the area to test the hypothesis that wind-driven upwelling was responsible for the SST variations in the gulf of guinea. Yoshida's equation (Yoshida, 1955; Smith, Pattullo & Lane, 1966) can be used for the computation of upwelling velocity:

\[ W = \left( \frac{K}{\rho f} \right) T^* e^{-K_Y} \]

where \( W \) is the upwelling velocity, \( f \) is the coriolis parameter, \( \rho \) is the density of the layer of water involved in the upwelling, \( \Delta \rho \) is the density difference between the layer of water involved in the upwelling and the layer beneath it, \( h \) is the thickness of the layer involved, \( T^* \) is the wind stress component parallel to the local coastline and \( Y \) is the distance offshore perpendicular to the local coastline.

Again, nobody as yet, has observed a change in the atmospheric forcing in this region that is strong enough to generate the required coastal wave to induce the upwelling. So at the present time, the only plausible explanation to the upwelling in the Gulf of Guinea is remote forcing due to wind change west of the Gulf of Guinea.

Lastly, a clear understanding of the forcing mechanism responsible for the coastal upwelling in this region is made difficult because of the potential influence of a number of local factors. First, the local wind has a direction that is favorable to upwelling but is weak. The amplitude of the SST change during the upwelling is greatest east of Cape Palmas at 8°W and Cape Three point at 20°W. This could arise from the more favorable orientation of the coastline with respect to the local wind in addition to the influence of the cape on the coastal current. Finally, there is the geostrophic adjustment of the density field to the eastward Guinea current. Its seasonal variation reported by Ingham (1970), Bakun (1978) and Philander (1979) has shown how this could arise from the seasonal intensification of the cross-equatorial winds. However, the relationship between the structures of the current to the coastal upwelling needs to be properly investigated.

Finally, information gabs remain as to the details of causes, timing, persistence and effects of the possible upwelling phenomenon of the Nigerian coast and needs to be considered.
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INVESTIGATION OF THE UPWELLING MECHANISM IN THE GULF OF GUINEA

Mémoire de Master of Science
En
Océanographie Physique et Applications

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Cotonou, Rép. du Bénin, 27 octobre 2010
DECLARATION

I, Napoleon Addison,

declare that the thesis entitled

Investigation of the upwelling mechanism in the Gulf of Guinea

and the works presented in it are my own. I confirm that:

- this work was done wholly or mainly while in candidature for a Master of Science degree at the University;
- where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
- where I have consulted the published work of others, this is always clearly attributed;
- where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
- I have acknowledged all main sources of help;

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Napoleon Addison

(Student)

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Dr. George Wiafe

(Supervisor)
DEDICATION

This work is dedicated to my dearest family

Margaret

Austin

Helena

Gifty

&

Lawrence
Praise be the ONE whom praise is due. This work would not have seen the light of day without the inspiration, vision, knowledge, wisdom, strength and guidance from the ALMIGHTY GOD.

Secondly, I wish to express my indebtedness to Dr George Wiafe, my supervisor for his splendid assistance and suggestions, without him the project wouldn’t have been a success.

Thirdly my fervent gratitude goes to my mother Mrs Margaret Darkwaa for her motherly advice and her inspiring words.

I owe lots of gratitude to Dr. Bernard BOURLES for the selfless effort he put in the organization of the program and the regular advice he gave me on my work.

Many thanks to Prof. Norbert HOUNKONNOU, Dr.Ezinvi BALOITCHA and the entire staff and students of CIPMA, you were a perfect team.

Special thanks goes to IRD (Institute of Research Development), TOTAL, University of Paul Sabatier and the French Embassy in Ghana for financial support.

A very special thanks to Mr Armah for all his support before, during and even after my work. Also, many thanks to Kwame Agyekum for his friendship and help with Matlab, data management etc…

I will also extend my profound appreciation to my siblings, Austin, Helena, and Lawrence for their prayers and encouragements, my cousins and friends especially Dennis, Michael, Robert, and most of all Gifty (my sweetheart) for their support.

I cannot forget the contributions of the Senior Members of the Department of Oceanography and Fisheries, University of Ghana for all the support.

Finally I am grateful to every individual whose contribution, direct or indirect, helped made this project a SUCCESS.
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