

Relationship between the Guinea Current and the Coastal Upwelling in Northern of Gulf of Guinea

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Abstract

The variability of ocean circulation and sea surface temperature (SST) in the tropical Atlantic, especially in the Gulf of Guinea (GG), defines this region as exceptionally rich from an oceanographic perspective. The Guinea Current (GC), as the major surface current, plays a significant role in marine productivity and coastal upwelling in the GG. This coastal upwelling is known to influence the climate of the surrounding region, primary productivity and local fisheries. Studies on GC variability and its impact on this coastal upwelling have highlighted that the upwelling downstream of Cape Palmas is influenced by GC detachment, topographic variations and advective processes leading to significant vertical mixing. This study aims to analyze the interannual variability of the GC and its impact on coastal upwelling using the Coastal and Regional Ocean COmmunity model (CROCO). The model's evaluation is conducted using observational data, specifically Geostrophic and Ekman Current Observatory (GEKCO) and Ocean Surface Current Analysis (OSCAR) for currents, and Air-sea Fluxes for the global Tropic ocean-description (TROPFLUX) and Optimum Interpolation-Sea Surface Temperature (OI-SST) for temperature. Thus, the model evaluation indicates that it accurately replicates ocean circulation and SST patterns in the tropical Atlantic and the GG. The joint analysis of upwelling indices (surface and intensity) and the position of the GC core allowed us to conclude that the displacement of the GC core does indeed influence the upwelling indices in the northern part of GG. However, other oceanic and atmospheric mechanisms such as vertical diffusion and horizontal advection as proposed by previous studies may also affect the year-by-

year variability of coastal upwelling in the northern GG.

Keywords

Guinea Current, Sea Surface Temperature, Coastal Upwelling, Gulf of Guinea, Tropical Atlantic Ocean

1. Introduction

Ocean currents are large-scale mass flows of water identified as a key regulator of climate change by moving warm and cold water masses around the globe, sequestering carbon dioxide from the atmosphere, and transporting it to the deep ocean [1]-[3]. They also have a major impact on ocean ecosystems as they help to transport and redistribute nutrients and manage marine resources [4] [5]. In the Gulf of Guinea (GG), located in the eastern part of the tropical Atlantic Ocean (Figure 1), a strong variability of the ocean currents conditions, with time scales ranging from intra-seasonal to interannual is observed [6] [7].

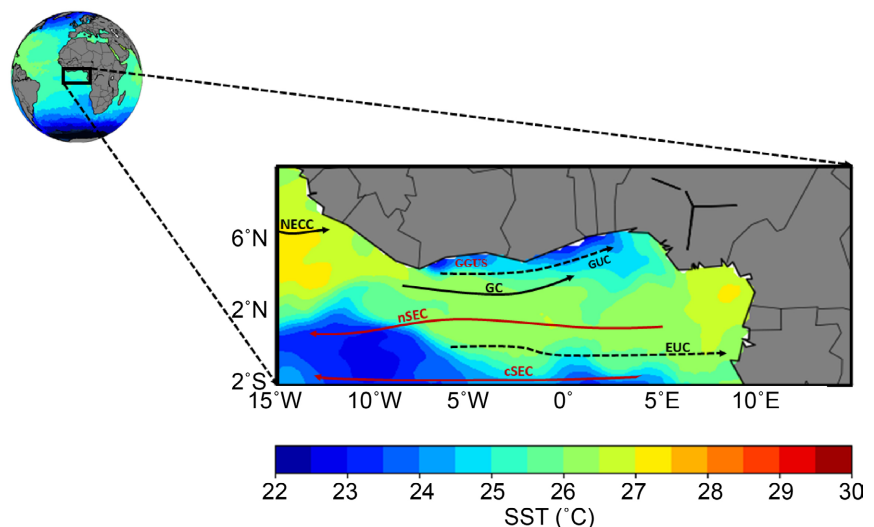


Figure 1. Global earth map with the study area in the black box. Mean Sea surface temperature ($^{\circ}\text{C}$) during the boreal summer (July–August–September) from the Microwave OI SST (1998-2020) in the eastern tropical Atlantic with circulation schematic superimposed: North Equatorial Countercurrent (NECC), Guinea Current (GC), Guinea Undercurrent (GUC), the northern, central and southern branches of the South Equatorial Current (northern branch: nSEC and central branch :cSEC) ; GGUS : Gulf of Guinea Upwelling System.

The Guinea Current, (hereafter GC) which has been found to be the eastern extension of the North Equatorial Counter Current (NECC) in boreal summer-autumn [8]-[10], is the dominant ocean surface current in the northern part of the GG. The GC plays an essential role in marine productivity and the coastal upwelling in this region [3] [11]. The GC is flowing eastward between 10°W and

6°E with an average intensity of 50 cm/s and a thickness of roughly 30 to 40 m [12] [13]. References [14] and [15] have estimated its average transport at a value of 2 to 5 Sv.

Furthermore, the recent studies of [3] on the GC variability and its relationship with the coastal upwelling, have pointed out that the geostrophic current is the dominant component of the GC. The authors have used GEKCO (Geostrophic and Ekman Current Observatory) satellite data from (2000-2018) in order to evaluate the geostrophic and Ekman components of the GC. The results also demonstrated that the summer intensification of the GC is due to the simultaneous increase in both geostrophic and wind-driven Ekman currents.

Insight into the GC dynamics is significant in understanding the GG ocean dynamics and has implications for various aspects, including marine ecosystems. Indeed several studies with observation databases have shown the link between the GC intensification and the coastal upwelling in the northern GG [12] [16]-[18]. This coastal upwelling has been found to modulate the regional climate and the primary production, the marine ecosystems and local fisheries [15] [19]-[23].

In addition to the following studies, [11] used a regional oceanic model to investigate the GC and coastal upwelling relationship. Their works highlighted first of all that the GC conforms within an inertial boundary layer. Its lateral extension is highly sensitive to inertia. Then, the results depicted that east of Cape Palmas, upwelling waters are concurrently due to inertia through the GC detachment, topographic variations, and advective terms effects resulting in important vertical pumping. Following [11], [3] have indicated that their results seem to be in line with the latter. Nevertheless, the authors suggested further investigating this relationship by a modeling approach. Apart from the study by [3], few studies have looked at the interannual variability of GC and its relationship with coastal upwelling. The interannual of the GC is poorly documented. The objective of this paper is to improve the understanding of interannual variability of GC and the coastal upwelling intensities from high-resolution model.

2. Data and Methods

This study's data originate from the outputs of the Coastal and Regional Ocean COmmunity model (CROCO, <https://www.croco-ocean.org/>). CROCO is the oceanic modelling component of an intricate coupled system which includes the atmosphere, biogeochemistry, ecosystems, surface waves and marine sediments. CROCO is developed on the basis of ROMS_AGRIF [24] and the non-hydrostatic kernel of SNH to address high-resolution coastal and regional ocean phenomena such as coastal upwelling, by using the generalized sigma coordinate on its vertical [25]-[27]. The interactions between very fine scales and larger scales are depicted.

The domain is implemented over the tropical Atlantic (60°W-15°E; 10°S-10°N), at a horizontal resolution of 1/5° and over the GG (12°W-15°E; 4°S-9°N) at a horizontal resolution of 1/15° [11] [22] [23] [28]. The model is driven by the European Centre for Medium-Range Weather Forecasts (ECMWF, [29]) ERA-

Interim interannual winds (1979-2014) and the initial and boundary conditions derived from the Simple Ocean Data Assimilation (*SODA* 3.3.1; [30]). Interannual model outputs were averaged over two days with a spin-of 11 years. We therefore used outputs from over 22 years (1993 to 2014) for this study. For a more detailed explanation of the implementation, please refer to [23].

Satellite and reanalysis data have been used in order to test the ability of the numerical model to reproduce the ocean key features of the GG. The model mean circulation is evaluated against two ocean current observation products.

The Geostrophic and Ekman Current Observatory (GEKCO) dataset from the Laboratoire d'Études en Géophysique et Océanographie Spatiale (LEGOS), offers daily data with a horizontal spatial resolution of $1/4^\circ$ between grid points. This dataset includes the zonal and meridional components of wind-driven currents (Ekman currents), geostrophic currents, and total current. Detailed documentation on this product, including different approaches to estimating geostrophic and Ekman currents and their validation, can be found in [31]. For this study, the daily data were averaged over the period from 1993 to 2014.

The Ocean Surface Current Analysis Real-time (OSCAR) product is generated by Earth Space Research (ESR) and available from the NASA (National Aeronautics and Space Administration) Physical Oceanography Data Center (<http://podaac.jpl.nasa.gov>). This product contains near-surface ocean current estimate using quasi-linear and steady flow momentum equations. Surface velocities are calculated from sea surface height, surface wind speed, and sea surface temperature using quasilinear equations of motion by combining geostrophy, Ekman and Stommel shear dynamics formulations and a complementary term from the surface buoyancy gradient [32]. This data covers the period from 1993 to 2014 with $1/3^\circ$ spatial resolution and with 5 days of temporal resolution.

In this study we used two Sea surface temperature (SST) databases. The TropFlux (Air-sea Fluxes for the global Tropic oceans-description) SST product, derived from a combination from ERA-I (Reanalysis of the global Atmosphere-Interim) reanalysis data and ISCCP (The International Satellite Cloud Climatology Project) surface radiation data. There are interpolated on a 1° resolution grid and available from 1979 to 2016 [33].

Optimum Interpolation Sea Surface Temperature (OISST) [34] product from the National Oceanic and Atmospheric Administration's (NOAA) is a global daily with 1° spatial resolution based on observations from different platforms satellites, ships, buoys and Argo floats. The dataset is interpolated to fill gaps on the grid and create a spatially complete map of sea surface temperature, and it was analyzed from 1993 to 2014.

For this study, we used composite analysis, which gives the spatial structure of a parameter over a specific period. Thus, the upwelling indices of [35] were used to assess the intensity of upwelling at the coast from one year to the next. Detailed documentation on the upwelling index can be found in by [36]. The monthly anomalies were determined by subtracting the climatological seasonal cycle,

which is especially prominent in the tropical Atlantic [11]. This calculation was performed over the period from 1993 to 2014, aligning with the common time frame for most of the available variables.

3. Results

3.1. Evaluation of the Model

In this section, the model's ability to simulate the physical characteristics of the study area is evaluated. The assessment of the ocean surface circulation in the tropical Atlantic and the SST in the northern GG is carried out on both a mean and temporal scale.

Zonal surface currents in the tropical Atlantic are shown in **Figure 2**. Zonal velocities, averaged from 1993 to 2014 are represented by observational data (GECKO, **Figure 2(a)**) and OSCAR, **Figure 2(b)**) and by the CROCO model (**Figure 2(c)**). Overall, the same spatial structure is observed for the model as for the observations. The main zonal speeds of the current system in the tropical Atlantic are highlighted. The North Brazil Current (NBC) is located to the west of the Atlantic basin between 8°N-5°S; 34°W-60°W for the model and between 8°N-4°S; 34°W-60°W for both GEKCO and OSCAR datasets. The maximum speeds of the NBC reached 0.9 m/s and 0.7 m/s respectively for the model and the observations. Following this, the northern and southern branches of the South Equatorial Current (SEC) are observed on either side of the equator. The maximum speed of the SEC is 0.7 m/s for the model and 0.5 m/s for the observations.

The North Equatorial Countercurrent (NECC) is also observed moving eastwards between latitudes 4°N-10°N for both model and observational data. However, the simulated velocities are ~0.2 m/s higher than the observed velocities. In the Gulf of Guinea, the GC flows eastward between 2°N and 5°N in both the model and observations. This current is approximately 200 km wide with a longitudinal extension from 10°W to 3°E. However, the maximum simulated GC observed around 4°N and 6°W is about 0.15 m/s higher in intensity than in the OSCAR dataset and 0.45 m/s higher than in the GEKCO dataset.

Figure 2(d) shows the seasonal variability of the GC in the box (7°W-4°W; 4°N-6°N) for the GECKO and OSCAR products and the CROCO model. The seasonal cycle of the GC is fairly well reproduced by the model. All the data show two acceleration seasons in boreal winter and summer. First, the GC intensifies from May to September, reaching a maximum of 0.42 m/s in August. It then decreases until November for OSCAR and December for GEKCO and the model. The model also shows a slight drop in current in May. This decrease is pronounced in April for the OSCAR model and absent for GECKO.

The mean spatial structure of SST during the main upwelling season (July, August, September) is depicted in observations (TROPFLUX, **Figure 3(a)**); OI-SST, **Figure 3(b)**) and the model (**Figure 3(c)**) in the GG. Overall, the spatial distribution of SST is similar between the model and observations. Three distinct

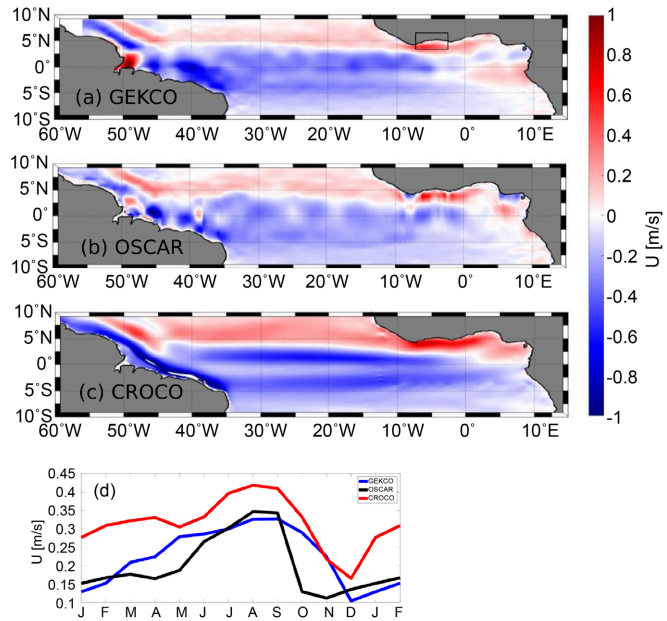


Figure 2. Spatial distributions of zonal currents in the tropical Atlantic for (a) GEKCO, (b) OSCAR (surface) and (c) CROCO averaged from 1993 to 2014. The intervals contours are 0.1 m/s. (d) Seasonal cycle of zonal velocity over the same period and calculated in the box (7°W-4°W; 4°N-6°N) for CROCO model and OSCAR and GEKCO observations.

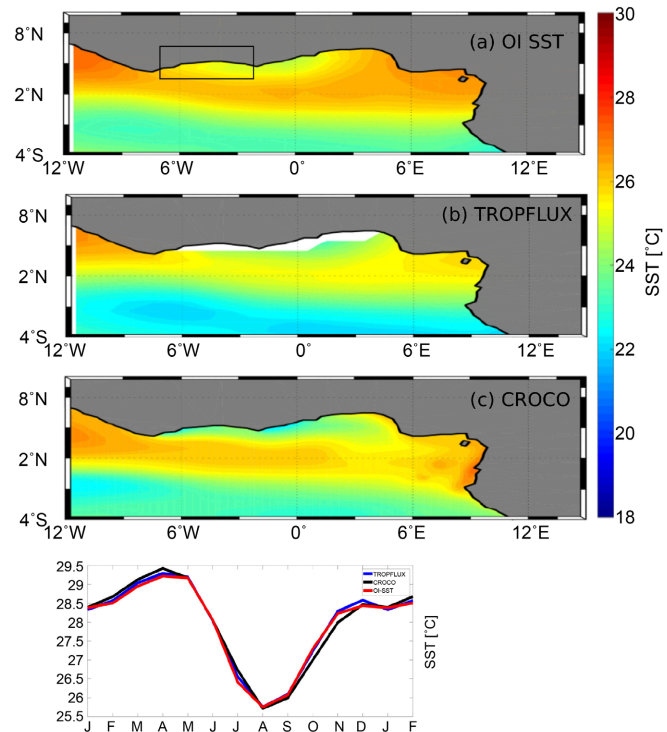


Figure 3. Spatial distribution of the mean Sea Surface Temperature (SST) (°C) averaged from 1993 to 2014 during the major upwelling season (July-August-September) in the northern Gulf of Guinea for (a) OI-SST, (b) TROPFLUX (c) CROCO. The intervals between contours are 0.2°C. (d) Seasonal cycle of SST over the same period and calculated in the box (7°W-4°W; 4°N-6°N) for CROCO model and TROPFLUX and OI-SST.

zones can be identified across all datasets: a cold water area along the north coast of the GG between 8°W and 3°E, with an average temperature of 24.4°C, representing the northern GG upwelling area; a warm band extending from east to west with temperatures reaching up to 27°C, located between 2°N and 4°N latitudes; and a colder zone between 2°N and 4°S latitudes with temperatures equal to or less than 24°C. These cold waters represent the Atlantic Cold tongue. The coastal upwelling is adequately represented by the model, as observed with TROPFLUX. The model identifies two zones of intense upwelling downstream of Cape Palmas and Cape Three Points. However, OI-SST data for the entire GG shows relatively warm temperatures compared to other datasets, particularly along the northern coasts of the GG.

Figure 3(d) displays the seasonal cycle of SST in the GG within the box (7°W-4°W; 4°N-6°N) for the CROCO model alongside the TROPFLUX and OI-SST products. The seasonal cycle shows nearly identical patterns between the model and the observations. The four oceanic seasons are well represented: the cold season from January to March, corresponding to the minor upwelling season, with temperatures around 28.5°C; the major warm season from March to June, peaking in April (29.4°C for CROCO, 29.2°C for TROPFLUX, and 29.1°C for OI-SST). There is also a warm bias of 0.2°C for CROCO compared to TROPFLUX and a bias of 0.3°C compared to OI-SST. The cold season corresponds to the major upwelling period from July to September, with a minimum temperature of 25.7°C in August; and the minor warm season from October to January.

The structure of large-scale currents (in the tropical Atlantic basin) and small-scale currents (in the Gulf of Guinea), as well as the spatial structure and seasonal temperature cycle, have been evaluated using various available observational products. The simulation of overall currents is quite accurate, with the major components of the equatorial current system well represented. At a smaller scale, the model closely reproduces the spatial distribution of isotherms in the Gulf of Guinea. Additionally, the simulated seasonal variability in temperature corresponds well to the observed cycle, especially in the coastal upwelling zone. Therefore, the simulation effectively captures the characteristics of the oceanic environment in the tropical Atlantic and GG region, making it a suitable tool for further study.

3.2. The Interannual Variability of the Guinea Current Core and Coastal Upwelling in the Guinea Gulf

In this section, using the Coastal and Regional Ocean Community (CROCO) model, we examine the interannual variability of the GC and its impact on the Ivorian-Ghanaian upwelling.

Figure 4 shows the average spatial representation of surface currents in the GG from July to September, averaged over the period 1993 to 2014. The two major surface currents in the GG are the eastward-flowing GC and the northern part of the westward-flowing SEC. We will now examine the latitudinal extension of the

GC core. The core of the GC corresponds to the zone where velocities are highest. The maximum GC zonal velocities speeds (more than 0.5 m/s) are found around 4°N, averaging between longitudes 7.5°W and 1.5°E.

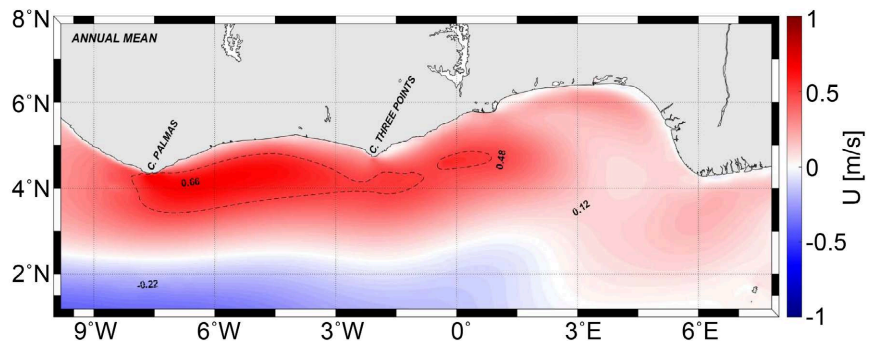


Figure 4. Annual mean zonal velocity U (m/s) for CROCO model averaged from 1993 to 2014 in the northern Gulf of Guinea. The intervals contours are 0.01 m/s. The dashed line corresponds to the isoline 0.5 m/s.

Figure 5 highlights the latitudinal extension of the Guinea Current (GC) core during the major upwelling period (July, August, and September) over the 22-year period (1993 to 2014) in the Gulf of Guinea (GG). The position of the core during these years will be compared with the average position shown in **Figure 4**. In specific years such as 1996, 1999-2001, and 2008-2009, the core is positioned just above the mean (north of 4°N). It was closer to the coast in 1999 and 2001, around 4.5°N. During years like 1995, 1998, 2005, and 2010-2014, the GC core is around 4°N, coinciding with the mean core position. Conversely, in years 1993-1994, 1997, 2002-2004, and 2006-2007, the core is located south of 4°N (south of the mean position). For instance, in 1994, it was notably distant from the coast, situated around 3.2°N. The latitudinal extension of the GC is constrained by a shear zone between the GC and the South Equatorial Current (SEC), as depicted in **Figure 4** and **Figure 5**.

SST maps in the eastern Atlantic basin during the major upwelling season over the period 1993 to 2014 are shown in **Figure 6**. The SSTs in the northern GG are characterized by warm periods (1995-1996, 2008-2011) and cold periods (1993-1994, 1997-1998, and 2012-2014). SSTs are generally colder east of Cape Three Points than at Cape Palmas. The coldest upwelling year is 1994, with temperatures reaching 23°C on the Ivorian and Ghanaian coasts. The year 2012 also recorded cold temperature values, especially east of Cape Three Points. During the warmest year, 2010 (described by several previous studies), temperatures of more than 27°C on average were observed in this part of the eastern tropical Atlantic Ocean basin.

The spatial representation of the upwelling indices during the major upwelling period in the GG is given in **Figure 7** over the 22-year period. In this figure, we have superimposed the core of the GC for each of these years. Low upwelling intensity (less than 1.10^5 km²) with a small surface area was observed during the

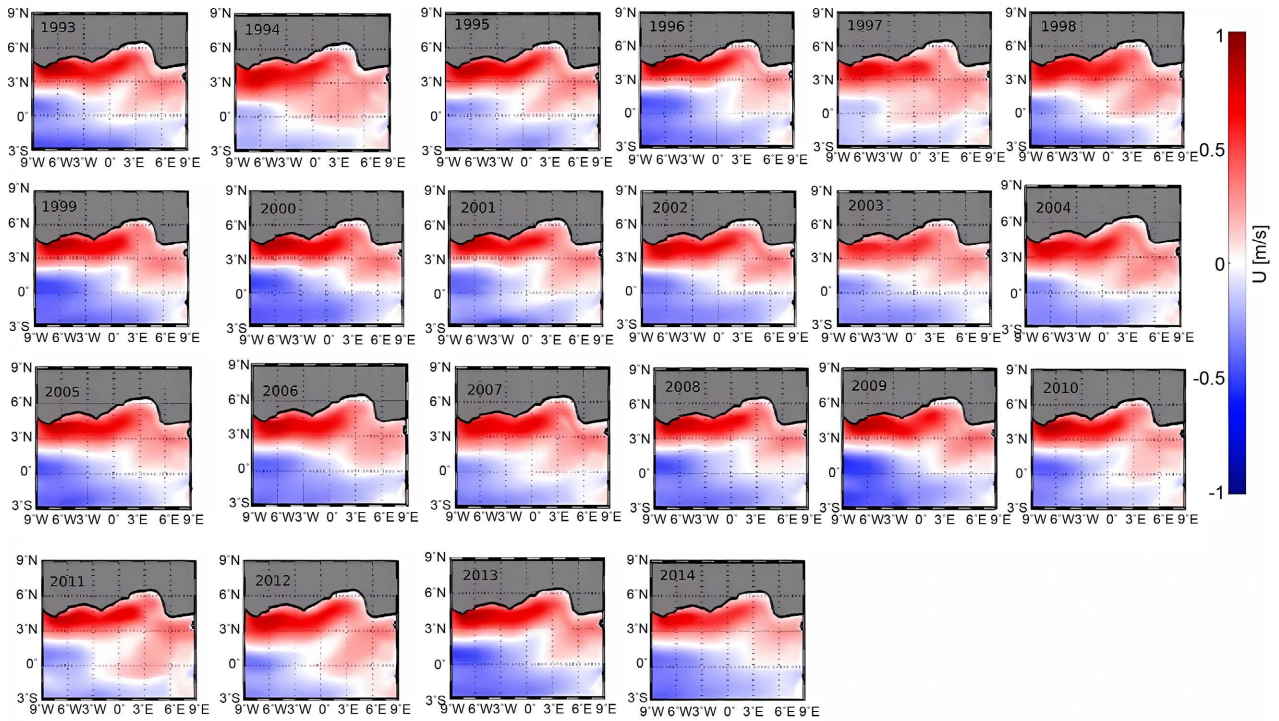


Figure 5. Interannual mean spatial distributions of zonal currents from 1993 to 2014 during the major upwelling season (July-August-September) in the northern Gulf of Guinea for CROCO model. The intervals contours are 0.01 m/s.

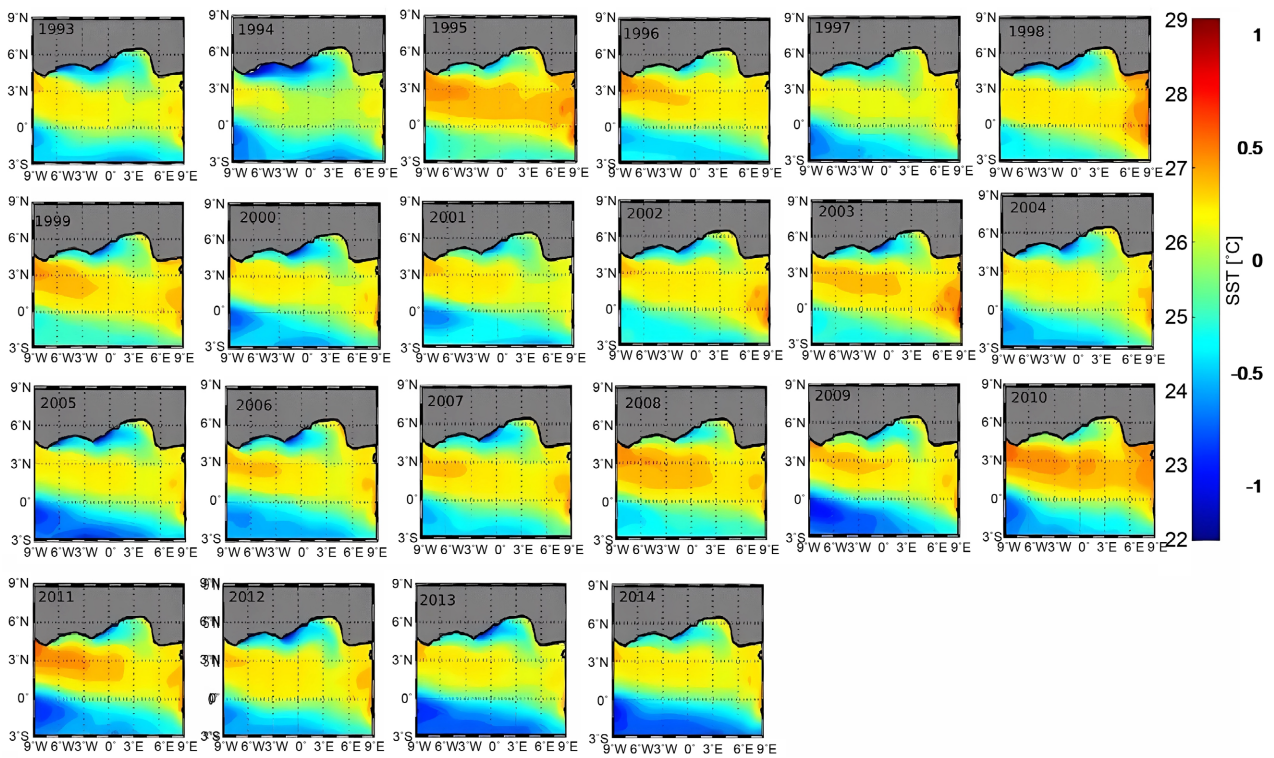


Figure 6. Interannual mean spatial distributions of Sea Surface Temperature (SST) (°C) from 1993 to 2014 during the major upwelling season (July-August-September) in the northern Gulf of Guinea for CROCO model. The intervals between contours are 0.2°C.

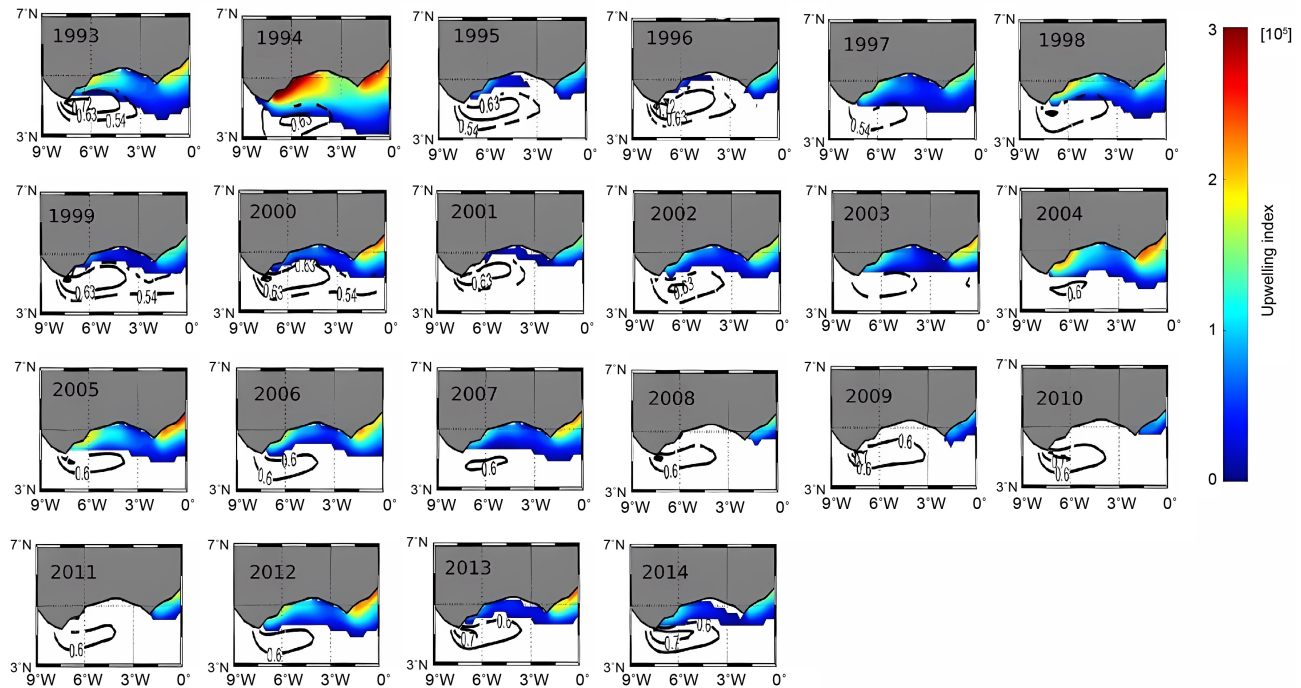


Figure 7. Interannual spatial distributions of upwelling index (color-coded) (10^5 km^2) and the Guinea Current (GC) core in (contour) during the major upwelling season (July-August-September) over the period 1993-2014. The contour interval is 0.1 m/s for the horizontal velocity.

years 1995-1996, 1999-2001, and 2013. This typically coincided with the core being closer to the coast, except in 1995 and 2013 when the core was near the average position. From 2008 to 2011, the upwelling area was nearly zero, with high SST values (Figure 6), regardless of the core's position. Indeed, this period is characterized by more pronounced warming, particularly from 2008 to 2011 (Figure 6). This warming or another phenomena may have significantly affected the cooling surface along the Ivorian coast, resulting in a complete absence of upwelling during those years using the threshold of 25°C (Caniaux upwelling index). The intensity of the GC core fluctuated between 0.54 and 0.72 m/s. The year 1994 was the coldest, featuring an upwelling area of approximately $3 \times 10^5 \text{ km}^2$.

4. Discussion and Conclusions

The GC has been found to be influenced by inertia. The lateral extension of the GC is determined by inertial terms [11]. The results of this study also suggest that the coastal upwelling downstream of Cape Palmas vanishes without the absence of the GC detachment. Indeed, unlike the upwelling east of Cape Three Points, the Ivorian upwelling appears to result from the combined effects of inertia, topographic variations, and advective terms, leading to significant vertical pumping.

In this study, the interannual variability of the GC and its impact on the Ivorian-Ghanaian upwelling were analyzed using CROCO model simulations. The model evaluation was conducted to assess its performance. The main zonal velocities of the current system in the tropical Atlantic simulated by the model are in

good agreement with observations and the studies by [3] [37] [38]. The seasonal cycle of the GC shows two periods of acceleration, consistent with the findings of [39], which indicate that this current accelerates in winter and summer.

The variability of the SST in the GG shows that the coldest areas on the north coast are located to the east of Cape Palmas and Cape Three Points, as indicated by several studies [11] [15] [19]. The seasonal evolution of the SST indicates the four oceanic seasons highlighted by [40] for both the model and observations. Thus, the model evaluation shows that the model reproduces effectively ocean circulation and SST patterns in the tropical Atlantic and the GG. It should be noted that the outputs used are the same as those used by [23]. These outputs have already been used for studies of ocean dynamics in the Gulf of Guinea. The position of the GC core has been studied from one year to the next.

The core has a latitudinal displacement [11] [17] that varies around a mean position (4°N and 7.5°W - 4.5°W) over the years. Reference [11] suggested that the GC detachment is modulated by non-linear terms (the effects of inertia) in the horizontal momentum equilibrium. However, the position of the GC core also seems to depend on the front between the SEC and the GC. Indeed, the southern limit of the GC is a shear zone between the GC and the SEC [41]. Reference [42] also showed that the GC is pushed offshore by the westward-directed Guinea Counter Current during the major upwelling season. The positioning of the GC core therefore depends on a fairly complex system. There may be feedback between inertial effects, the SEC, and the GCC. It should be noted that the studies by reference [15] suggested that the GCC is merely a consequence of energy transfer from cyclonic eddies to the mean circulation.

The strength of the cooling of the SST downstream of Cape Palmas depends on the latitudinal position of the GC, as shown in **Figure 6** and **Figure 7**. The greater the meridional extent of the GC core (between 3°N - 4°N), the greater the cooling, as observed in 1994. These results support the work of [11] [12] [17]. According to their view, the latitudinal extension and intensity of the offshore GC cause high vertical velocities, leading to significant upwelling. However, some results show a warmer SST in 1995, 2006, and 2010-2011 despite the core extending offshore, and the opposite effect was observed in 1999 and 2000. References [43] [44] explained that the warming of SST observed in 2010 was caused by the weakening of the trade winds in the tropical Atlantic. The coldest SST observed on the Ivorian-Ghanaian coast in 2012, has been found to be induced by horizontal advection and vertical diffusion [45]. Furthermore, the inter-annual evolution of the SST shows two periods (cold and warm), which is consistent with the results of [36]. These authors indicated that upwelling on the north coast of the GG has been decreasing since 2005.

Analysis of the inter-annual variability of the upwelling indices shows stronger indices when the GC core extends further offshore, as expected [11]. **Figure 6** and **Figure 7** highlight the connection between the upwelling indices and the cooling observed in the northern part of GG. Strong upwelling indices correspond to greater cooling along the coast. This correlation was noted by [46], who found a

positive relationship between upwelling intensity, minimum SSTs, and the extent of upwelling area. For instance, the warming period observed from 2008 to 2011 was characterized by nearly zero upwelling surface area and intensity. Conversely, in 1994, the coldest SSTs in our study period were observed, with a large surface area and high upwelling intensities.

The detachment of the GC indeed plays a role in cooling the SST in the northern NGG. However, the year-to-year cooling may also be influenced by other atmospheric and oceanic phenomena (e.g., horizontal advection, vertical diffusion). A climatological study of the heat balance in the mixed layer in areas of upwelling maxima could provide further insights. This study is a perspective for future research. Additionally, an investigation into the modes of variability of the GC will complement this study.

The objective of this study is to demonstrate the influence of inter-annual Guinea Current (GC) variability on the Ivorian-Ghanaian coastal upwelling using a high-resolution ocean model. Key findings include (i) enhanced upwelling downstream of Cape Palmas when the GC core extends farther offshore [11]; (ii) the intensity of this upwelling may be affected by various oceanic and atmospheric factors. This study provides greater insight into the mechanisms driving the coastal upwelling in the NGG, at an interannual scale.

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Data Availability Statement

The model output datasets generated and analyzed during the current study will be available upon request to the authors.

Author Contributions

S. D., Y. K., K. B, M. K. organized, sampled the datasets and performed analyses. V. K. performed the model simulation. K. Y. K. supervised the study. All co-authors reviewed and contributed to the writing of the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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