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Spatial variability in autumnal equatorial upwelling intensity within the Gulf of Guinea as inferred from *in situ* measurements

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In attempt to study the spatial differences in autumnal equatorial upwelling intensity relative to bio-productivity in the eastern equatorial Atlantic, oceanographic *in situ* data along regions 10°W, 0°E, 2.5°E and 6°E, collected in the Gulf of Guinea during autumn cruise carried out in September 2007 were analyzed. The surface mean values for temperature along 10°W, 0°E, 2.5°E and 6°E are 25.02, 26.15, 26.88 and 25.60°C, respectively. There was eastward weakening of the equatorial undercurrent from 10°W until its complete disappearance at 6°E. The highest concentration of nitrate recorded at the surface at 10°W was attributed to the shoaling pycnocline observed at this region. The surface mean values for nitrate along 10°W, 0°E, 2.5°E and 6°E are 0.37, 0.09, 0.04 and 0.04 μmol.kg^{-1}, respectively. In response to the shoaling pycnocline at 10°W, corresponding to the highest concentration of chlorophyll fluorescence was recorded at this region. The surface mean values for chlorophyll fluorescence along 10°W, 0°E, 2.5°E and 6°E are 0.34, 0.05, 0.07 and 0.08 mg/m^3, respectively. Contributions to equatorial upwelling by the equatorial undercurrent were the strongest and mostly expressed along 10°W. Profiles for apparent oxygen utilization and chlorophyll fluorescence gave indications that biological response to surface enrichments within the equatorial bands was highest at region 10°W. Vertical sections for studied parameters were unsuggestive of westward advection from 6°E to 10°W within the equatorial band, and this signifies the important role of vertical processes in equatorial enrichment at 10°W during boreal autumn.

Key words: Vertical mixing, zonal advection, equatorial undercurrent, equatorial upwelling, Gulf of Guinea, nutrients, phytoplankton biomass, surface enrichment.

INTRODUCTION

The equatorial regions of the earth's oceans are climatically sensitive regions due to the contrasts in the zonal sea-surface temperature observed there (Weisberg and Colin, 1986); understanding therefore the annual and

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inter-annual variability of this under-sampled and poorly understood region in the tropical Atlantic ocean has been the goal of several measurement programs.

Atlantic equatorial upwelling has been considered of great significance for the important role it plays in biological productivity of this region (Voituriez and Herbland, 1977; Grodsky et al., 2008; Nubi et al., 2016). In the boreal summer, equatorial upwelling is associated with the Atlantic cold tongue (ACT) that appears near 10°W (Caniaux et al., 2011). Its appearance has been correlated with the seasonal increase of the southern hemisphere trade-winds (Hastenrath and Lamb, 1978) and the northward migration of the inter-tropical convergence zone (ITCZ) (Picaut, 1983; Colin 1989; Waliser and Gautier, 1993).

Thermocline shoals dramatically in the equatorial tropical Atlantic in response to seasonal intensification of the trade winds in the western tropical Atlantic, and the dynamic uplift of the thermocline combined with mixing by local winds has been suggested to be the principal mechanism controlling vertical nutrient fluxes (Longhurst, 1993; Bourlès et al., 2002; Nubi et al., 2016).

Nutrient distribution has long been used in hydrological studies to show the vertical motions in the surface layers of the ocean (Oudot and Morin, 1987; Nubi et al., 2016). The oceanic distributions of nutrients and patterns of biological production are controlled by the interplay of biogeochemical and physical processes. Chlorophyll concentration has been used as upwelling indicator and also to study the biological productivity in the marine ecosystems (Oudot and Morin, 1987; Nubi et al., 2016); and chlorophyll fluorescence data has been proven to give a better estimate of the phytoplankton standing crop and primary productivity (Schreiber et al., 1995a; Schreiber et al., 1995b). In tropical areas, fertility depends on the rates of nutrients influx to the euphotic zone which in turn depends on physical enrichment processes such as vertical mixing through the thermocline (Eppley, 1980).

Observations during boreal summer in the eastern part of the Gulf of Guinea basin do not show a continuous westward decrease in equatorial upwelling intensity (Oudot and Morin, 1987; Nubi et al., 2016). According to Kolodziejczyk et al. (2014), saline water masses are transported eastward in the upper thermocline to the African coast within the equatorial undercurrent (EUC) latitude band during early boreal summer. While recent studies Nubi et al. (2016) show equatorial upwelling in the Gulf of Guinea to be stronger along 10°W than 3°E during boreal summer onset in June, detailed analyses of the spatial differences being extended to the final phase in September was not captured.

This study therefore was conducted during boreal autumn, the paradigm of westward zonal advection from rich coastal upwelling zone, often put forward in explaining equatorial fertility farther west within the Gulf of Guinea basin. Potential zonal trend in autumnal equatorial upwelling intensity using hydrological data along regions 10°W, 0°E, 2.5°E and 6°E was also captured.

MATERIALS AND METHODS

Source of the datasets

Oceanographic *in situ* data collected in the Gulf of Guinea during EGEE6 (Etude de la Circulation Océanique et des Échanges Océan-atmosphère dans le Golfe de Guinée) autumn cruise in September 2007 (Bourlès et al., 2007) was used for the study. The cruise was the French oceanographic component of the African Monsoon Multidisciplinary Analyses (AMMA) international program (Redelsperger et al., 2006).

Sampling and quality control

For the purpose of this study, data collected during the final phase of equatorial upwelling in September 2007 was considered. Variabilities were measured along 10°W, 0°E, 2.5°E, and 6°E meridional sections. As documented in an earlier work (Nubi et al., 2015), seawater samples were collected from hydrological bottles attached on a rosette on which is also installed a CTD-O_2 (bathysonde) and lowered ADCPs. Chlorophyll-a fluorescence (CF) which is an indicator of active phytoplankton biomass and chlorophyll concentrations in the water column, was measured with a Wetlab ECO FL sensor. The CTD sensors, which were calibrated before and after the cruises, were accurate within 0.003°C (temperature) and 0.003PSU (salinity). Nitrate was determined according to Benschneider and Robinson (1952). Duplicate analyses of individual samples were performed regularly to estimate analytical error. This study mostly focuses on analyses within the equatorial band (1°N - 1°S), and emphasis is given to depths between 0 to 100 m where biological activity is prevalent (Kolodziejczyk et al., 2009, 2014; Nubi et al., 2014, 2016) for additional details on sampling, quality control and rational for methodology (Figure 1).

RESULTS

Spatial differences along 10°W, 0°E, 2.5°E, and 6°E

Zonal currents

Figure 2 presents the vertical sections for the zonal currents (ms^{-1}) along 10°W (upper left), 0°E (upper right), 2.5°E (lower left) and 6°E (lower right) in September 2007. There was an eastward weakening of the EUC in September 2007. Except for region along 6°E where there was complete disappearance of the EUC (but strong signature of the westward flowing south equatorial current) within the equatorial band, the EUC velocity cores lied south of the equator, and with core velocities (depths) values of 1 $m.s^{-1}$ (85 m), 0.75 $m.s^{-1}$ (60 m), 0.6 $m.s^{-1}$ (60 m) at 10°W, 0°E, and 2.5°E, respectively (Table 1). Unlike the situations at 0°E, 2.5°E, and 6°E, there was shoaling of the pycnocline along 10°W with complete erosion of the 24 $kg^{-3}m^{-3}$ isopycnal south of 0.5°S (Figure 2).

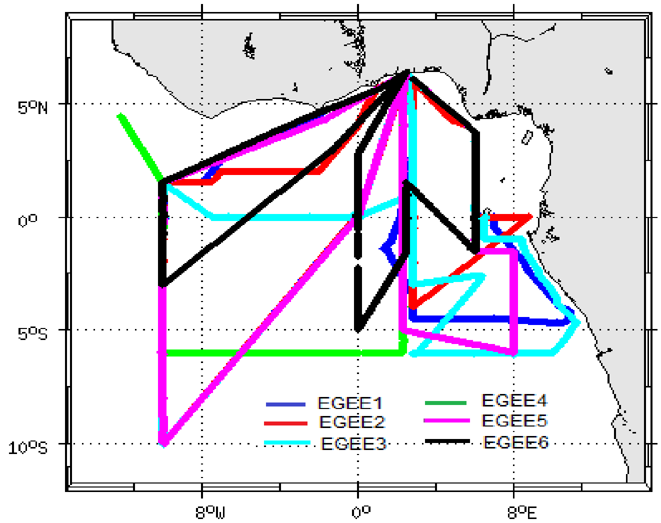

Figure 1. EGEE cruises overall track line in the Gulf of Guinea. Stations for hydrological measurements and sea water sampling during EGEE6 (black lines) were mostly done along 10°W, 0°E, 2.5°E, and 6°E.
Source: Nubi et al. (2016).

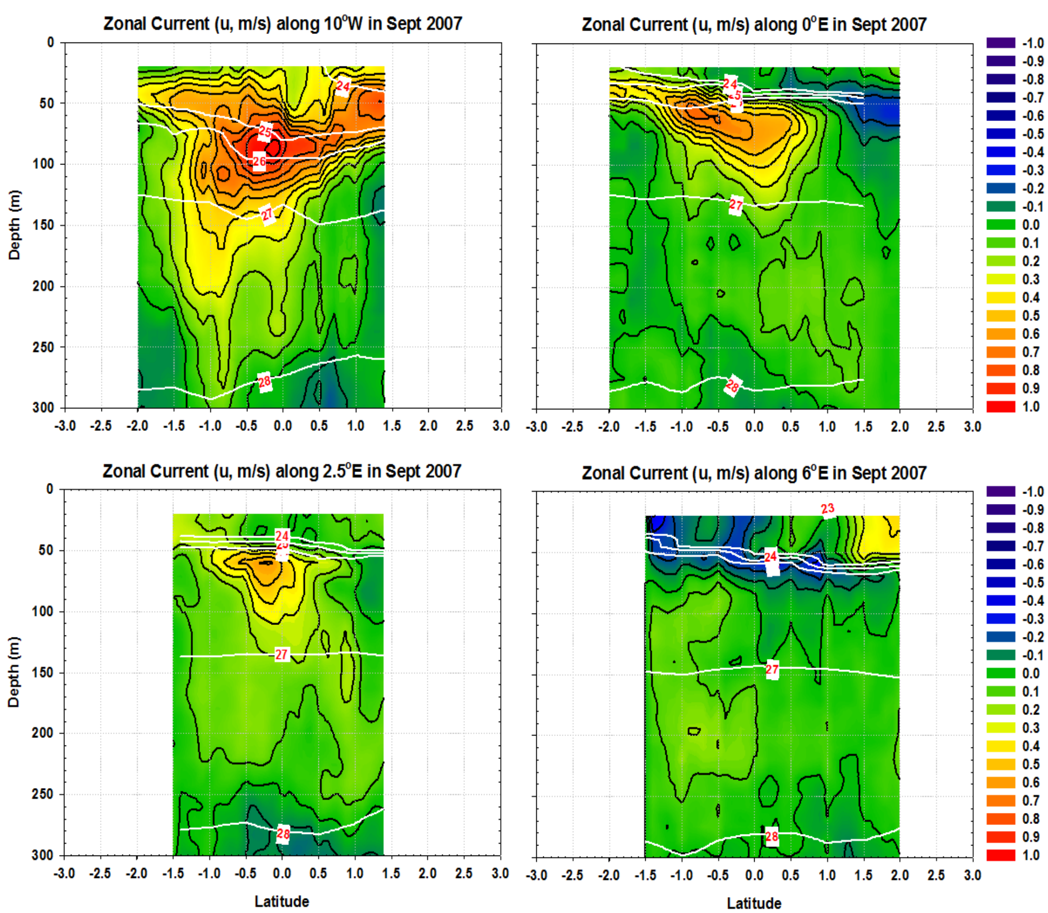

Figure 2. Vertical sections for zonal current velocity (ms^{-1}) along 10°W (upper left), 0°E (upper right), 2.5°E (lower left), and 6°E (lower right) in September 2007. Note the different latitude bands for these sections.

Table 1. Positions and values for EUC and CF maxima within 1°N - 1°S.

Longitude	EUC core (CFmax) Lat	EUC core (CFmax) depth (m)	EUC (CF) max
10°W	0.5°S (0.5°S)	85 (20)	1.0 ms^{-1} (0.68 mg/m^3)
0°E	0.5°S (1°S)	60 (34)	0.75 ms^{-1} (0.53 mg/m^3)
2.5°E	0.5°S (1°S)	60 (45)	0.6 ms^{-1} (0.58 mg/m^3)
6°E	*(1°S)	*(54)	*(0.49 mg/m^3)

*Data missing due to absence of EUC at 6°E

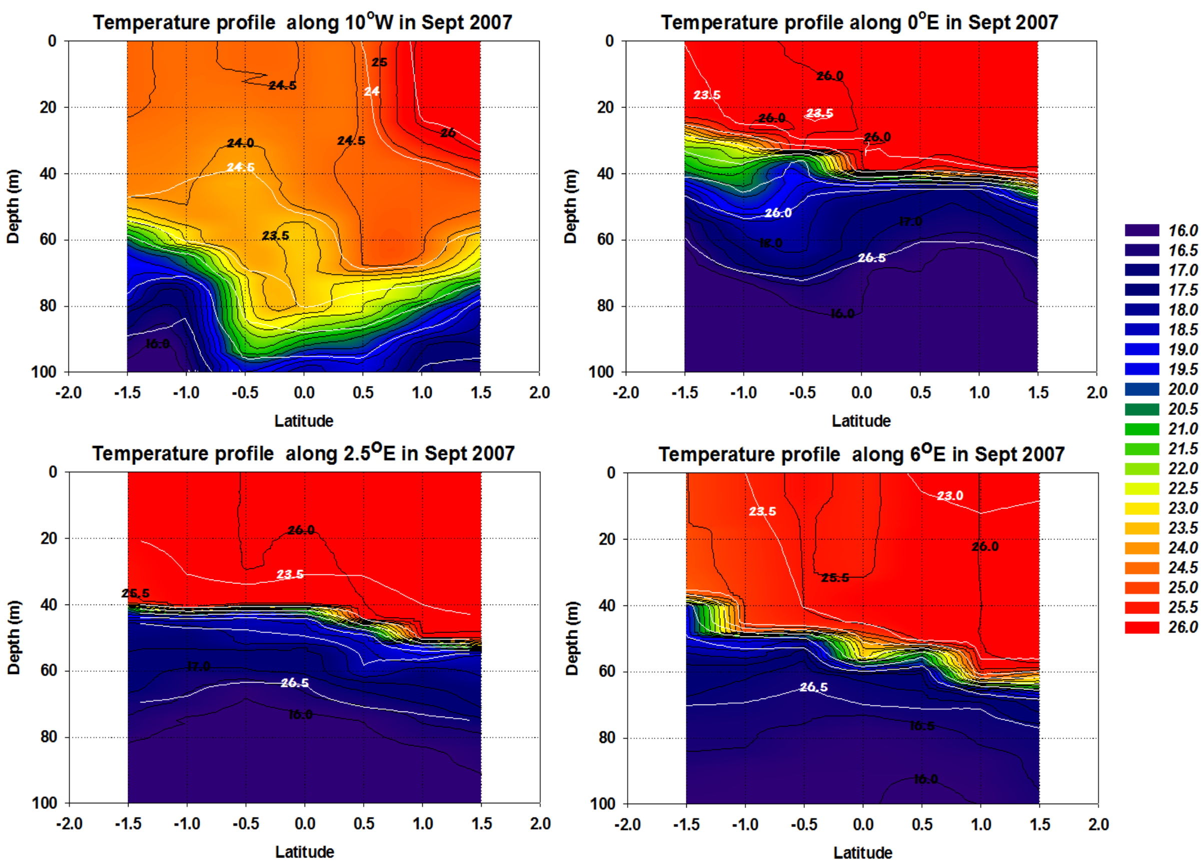

Figure 3. Vertical sections (0 - 100 m) for temperature (°C) along 10°W (upper left), 0°E (upper right), 2.5°E (lower left), and 6°E (lower right) in September 2007.

Upper layer temperature

Figure 3 presents the vertical sections for temperature along 10°W (upper left), 0°E (upper right), 2.5°E (lower left) and 6°E (lower right) in September 2007. Waters with temperatures (mean values) of about 24.5°C (25.02°C), 26°C (26.15°C), 26°C (26.88°C), and 25.5°C (25.60°C) were observed at the surface within the equatorial band along 10°W, 0°E, 2.5°E, and 6°E, respectively. There was an outcrop of cold waters south of 0°N along 0°E with temperatures ranging from 19.5 to 23°C between 30 and 40 m depths. While there was deepening of the thermocline from about 50 m depth downwards along region 10°W, uplift of the thermocline with corresponding uplift of the pycnocline was observed from about 50 m depth upwards. There was southward elevation of the thermocline from 60 m depth along 0°E, 2.5°E, and 6°E which terminates at 30, 40, and 40 m, respectively (Figure 3).

Upper layer salinity

Figure 4 presents the vertical sections for salinity along 10°W (upper left), 0°E (upper right), 2.5°E (lower left) and 6°E (lower right) in September 2007. Salinity maxima

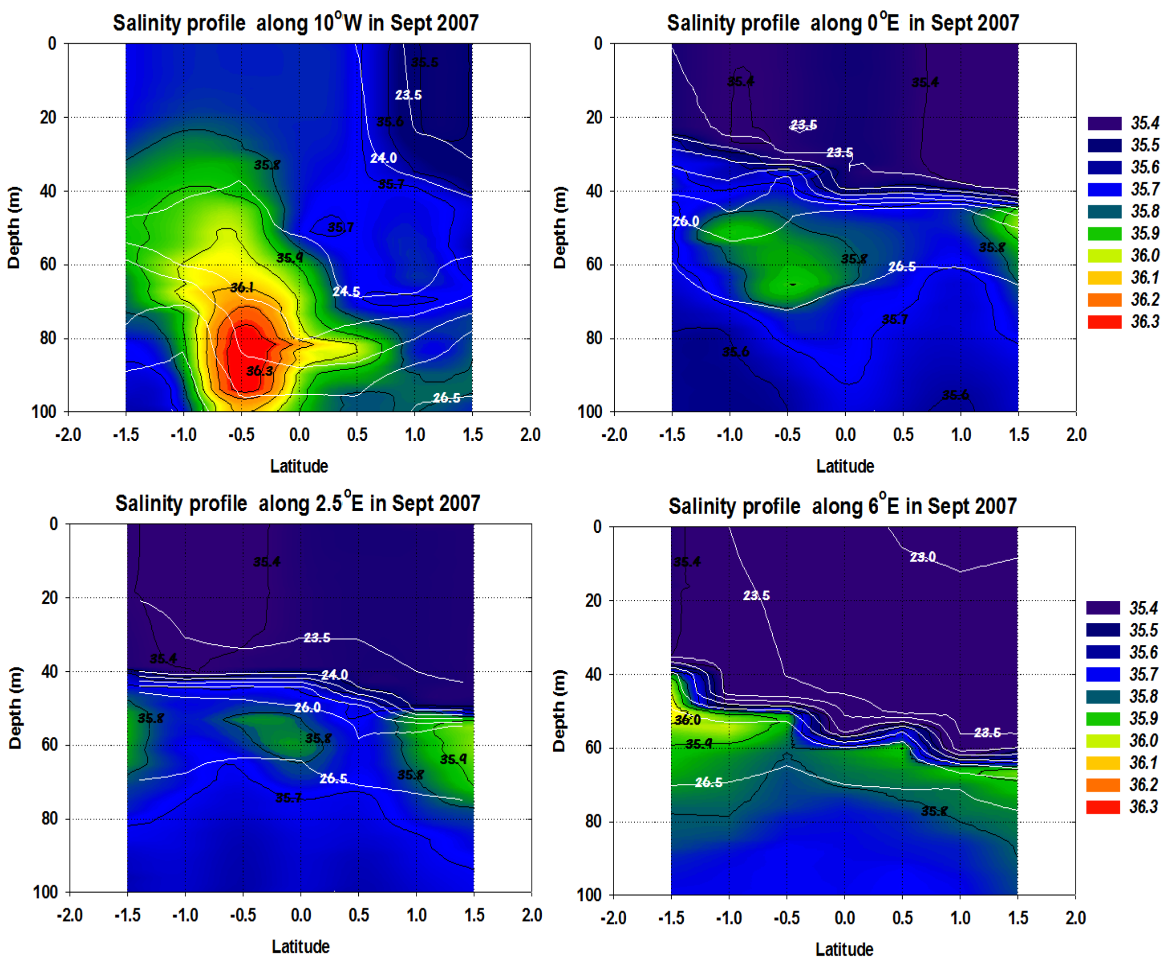

Figure 4. Vertical sections (0 - 100 m) for salinity (PSU) along 10°W (upper left), 0°E (upper right), 2.5°E (lower left), and 6°E (lower right) in September 2007.

were observed at the latitudes and mean depths of the EUC. The surface mean values for salinity along 10°W, 0°E, 2.5°E and 6°E are 35.67, 35.41, 35.45 and 35.06 PSU, respectively. There was eastward weakening of the EUC salinity maximum from 10°W to 2.5°E until its complete disappearance at 6°E. The imprint of the EUC salinity maximum (36.3 PSU) was most intense along region 10°W between 78 and 96 m depths. Similar to the signatures on the thermocline, there was also southward elevation of the halocline within the equatorial band from slightly below 60 m depth along 0°E, 2.5°E, and 6°E which terminates at 30, 40 m, and 40 m, respectively. The steepness of the halocline was the most pronounced along 6°E (Figure 4).

Nitrate and chlorophyll fluorescence in the upper layer

Figures 5 and 6 present the nitrate and chlorophyll fluorescence vertical sections along 10°W (upper left), 0°E (upper right), 2.5°E (lower left) and 6°E (lower right) in September 2007. The surface mean values for nitrate along 10°W, 0°E, 2.5°E and 6°E are 0.37, 0.09, 0.04 and 0.04 µmol.kg^{-1}, respectively. There was deepening of the nitracline along 10°W within the equatorial band. Except for region along 10°W where nitrate levels of about 0.5 and 4 µmol.kg^{-1} were observed at the surface and 20 m depth, respectively, the entire surfaces along 0, 2.5, and 6°E were nitrate depleted. Nitrate levels of about 0.5 µmol.kg^{-1} were recorded within 1°N and 1°S at depths of about 22, 35 and 35 m along 0, 2.5, and 6°E, respectively. However, water with nitrate levels of about 0.5 µmol.kg^{-1} was observed south of 1°S at about 22 m depth along 6°E (Figure 5).

The surface mean values for chlorophyll fluorescence along 10°W, 0°E, 2.5°E and 6°E are 0.34, 0.05, 0.07 and 0.08 mg/m^3, respectively. The highest levels of chlorophyll fluorescence (>0.6 mg/m^3) were recorded between 0 and 30 m depths along region 10°W within 1°S and 0°N (Figure 6 and Table 1). Chlorophyll fluorescence values increase southwards with maximum

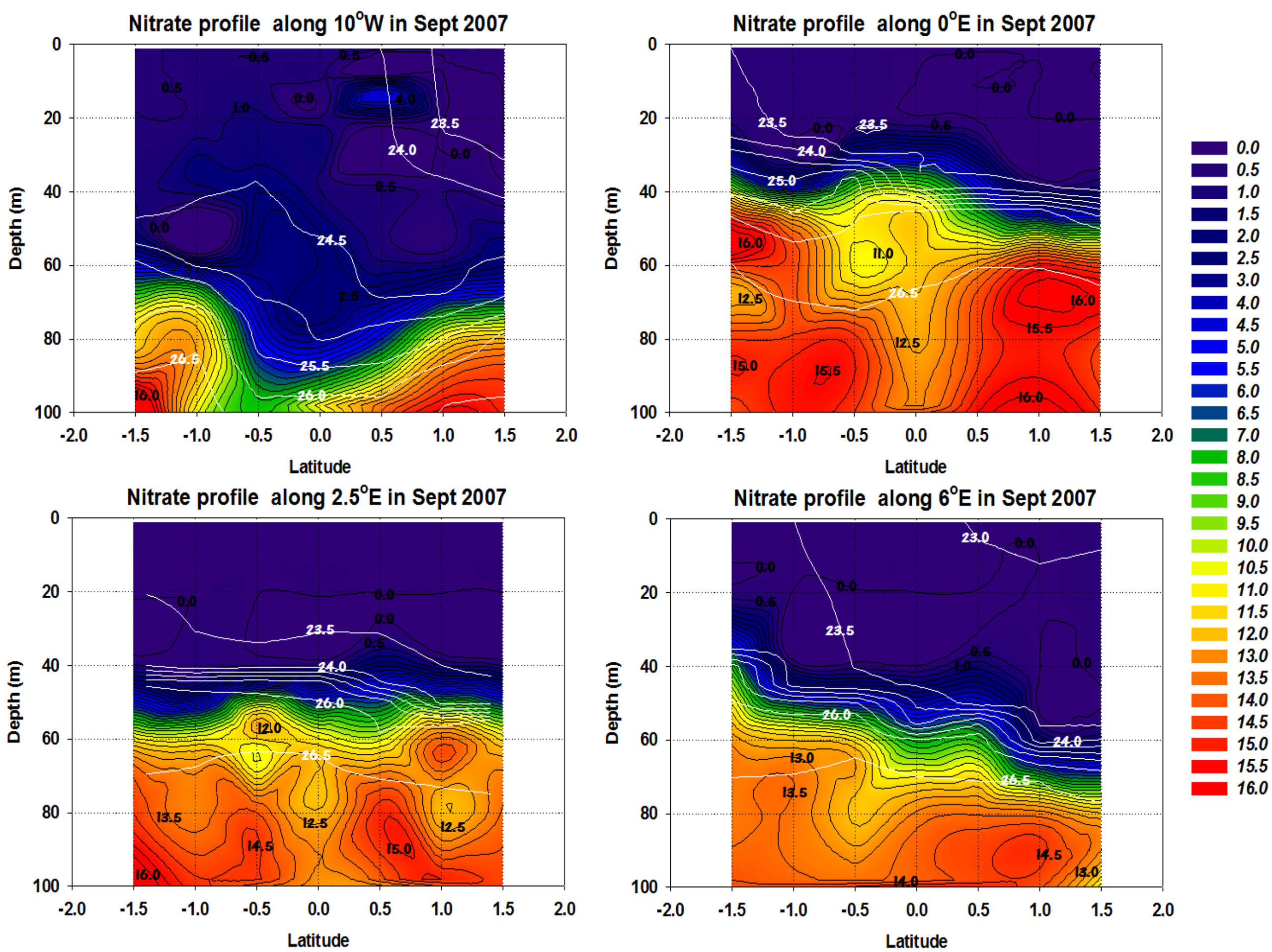

Figure 5. Vertical sections (0 - 100 m) for nitrate (μmol.kg^{-1}) along 10°W (upper left), 0°E (upper right), 2.5°E (lower left), and 6°E (lower right) in September 2007.

concentrations located south of the equator. The chlorophyll fluorescence maxima (locations, depths) observed within 1°N and 1°S along 10°W, 0°E, 2.5°E, and 6°E are 0.68 mg/m^3 (0.5°S, 20 m), 0.53 mg/m^3 (1°S, 34 m), 0.58 mg/m^3 (1°S, 45 m), and 0.49 mg/m^3 (1°S, 54), respectively (Figure 6 and Table 1).

Profiles along EUC velocity core latitudes

The influence of EUC on equatorial upwelling along the different longitudes under study was achieved by profiling temperature and salinity along the EUC velocity core latitudes (Table 1). Due to the absence of EUC along 6°E, latitude 1°S with coldest water at the surface within 1°N and 1°S was chosen and profiled for temperature and salinity. Chlorophyll fluorescence (CF) and apparent oxygen utilization (AOU) were profiled along latitude of maximum chlorophyll fluorescence (Table 1) to estimate biological response to equatorial upwelling. Based on the aforementioned, profiles for temperature (upper left), salinity (upper right), apparent oxygen utilization (lower left) and chlorophyll fluorescence (lower right) in September 2007 are presented in Figure 7. In addition to the coldest waters observed at the surface along 10°W, the thermocline was the shallowest with slight changes in temperature with depth from 0 to 40 m. Regions along 0, 2.5, and 6°E recorded deeper thermoclines with 6°E as the deepest (Figure 7). While the trend for the thermocline depth was 10°W <0°E < 2.5°E < 6°E, that of the water temperature at the surface was 10°W < 6°E < 2.5°E ≃ 0°E (Figure 7). In the same trend with the thermocline, the halocline was shallowest (deepest) at 10°W (6°E), and the water salinity at the surface was 10°W > 0°E > 2.5°E > 6°E (Figure 7). The mean depths of the EUC velocity cores along 10°W, 0°E and 2.5°E had imprints of the EUC salinity maximum. There was slight erosion of the EUC salinity maximum along these longitudes (Figure 7), but with net increment at the surface which was mostly expressed at 10°W. The value of AOU was lowest at the surface at 10°W, and varied with depth all through to about 1.5 ml/l at 100 m depth.

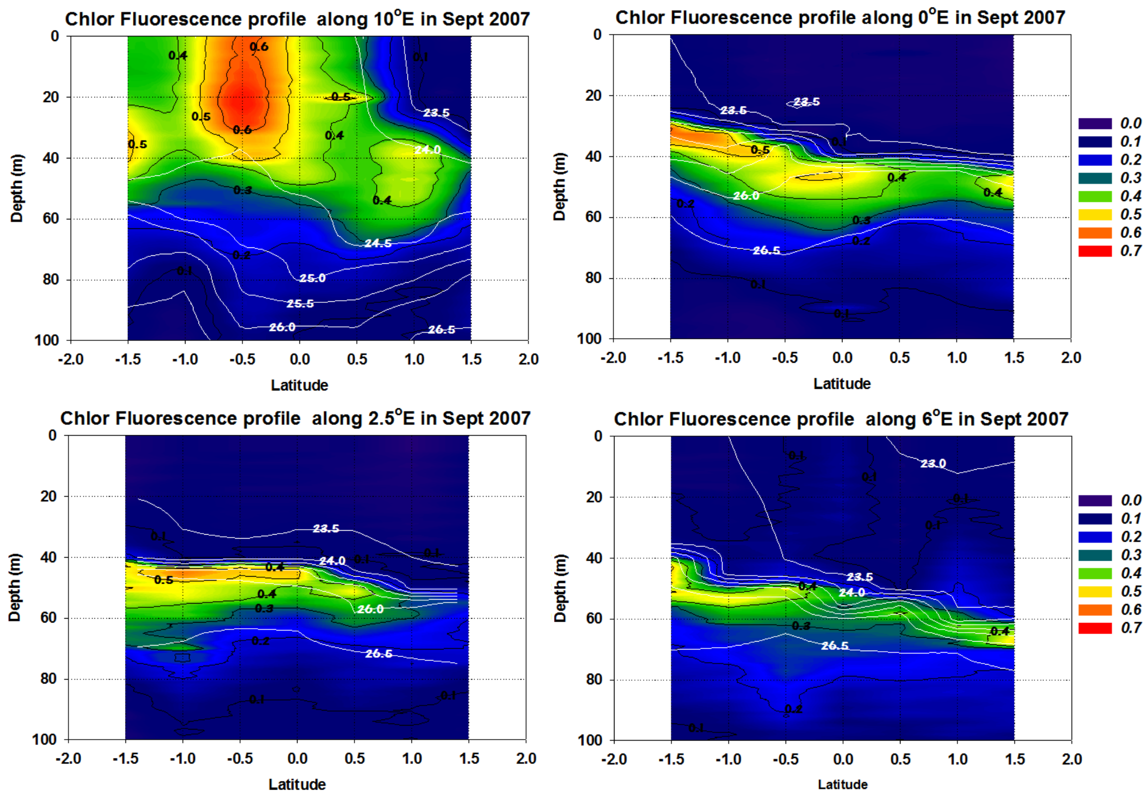

Figure 6. Vertical sections (0 - 100 m) for chlorophyll fluorescence (mg/m^3) along10°W (upper left), 0°E (upper right), 2.5°E (lower left), and 6°E (lower right) in September 2007.

There were minimal variations with depth (almost constant values) recorded for AOU along 0°E, 2.5°E, and 6°E from the surface to about 30, 40, and 50 m, respectively. The chlorophyll fluorescence maxima along 10°W (0.68 mg.m^{-3}), 0°E (0.53 mg.m^{-3}), 2.5°E (0.58 mg.m^{-3}), and 6°E (0.49 mg.m^{-3}) occurred at 20, 34, 45, and 54 m depths, respectively (Figure 7 and Table 1).

DISCUSSION

Physical considerations for zonal advection

As earlier reported by Nubi et al. (2016), the situation in September is a type of the final phase of equatorial upwelling in the gulf of guinea, the intensity of which is less pronounced when compared with the situation in June. Similarities in the hydrological features in September of 2005 (Nubi et al., 2016) and their comparisons with situations in June of 2005 (Nubi et al., 2014, 2016, 2007), Nubi et al. (2014) are indicative of an extension in the equatorial upwelling processes from onset to final phase. Similar to situation in summer, Nubi et al. (2016) the eastward weakening during autumn of the EUC within the equatorial band (until its disappearance at 6°E) and the pycnocline structures which has 24 kg^{-3}m^{-3} isopycnal eroded at the surface along 10°W but present at other regions (deepest along 6°E) did not suggest a westward advection from 6°E to 10°W. Despite the deepening of the isotherm between 1°N and 1°S from 60 m depth downwards at 10°W, coldest water was found at the surface layer along this longitude. According to Caniaux et al. (2011), coastal upwelling due to Ekman transport was contributory to the relatively cold waters observed at the surface along 6°E. The structures of the halocline in September 2007 were in association with the EUC eastward weakening. The signature of the EUC salinity maximum and the corresponding increase in salinity at the surface due to mixing of the EUC water with the surface waters (Oudot and Morin, 1987; Kolodziejczyk et al., 2014; Nubi et al., 2016) were observed to be the strongest at 10°W. In agreement with the work of Jouanno et al. (2011), a strong stratification within 1°N and 1°S, caused by the presence of warm and less-saline surface waters along 0, 2.5 and 6°E limits the vertical mixing to the upper 30, 40, and 50 m depths, respectively and disconnects the surface from subsurface dynamics.

Biochemical considerations for zonal advection

The highest levels of nitrate (5 µmol.kg^{-1}) recorded at the surface along 10°W was in response to the shoaling

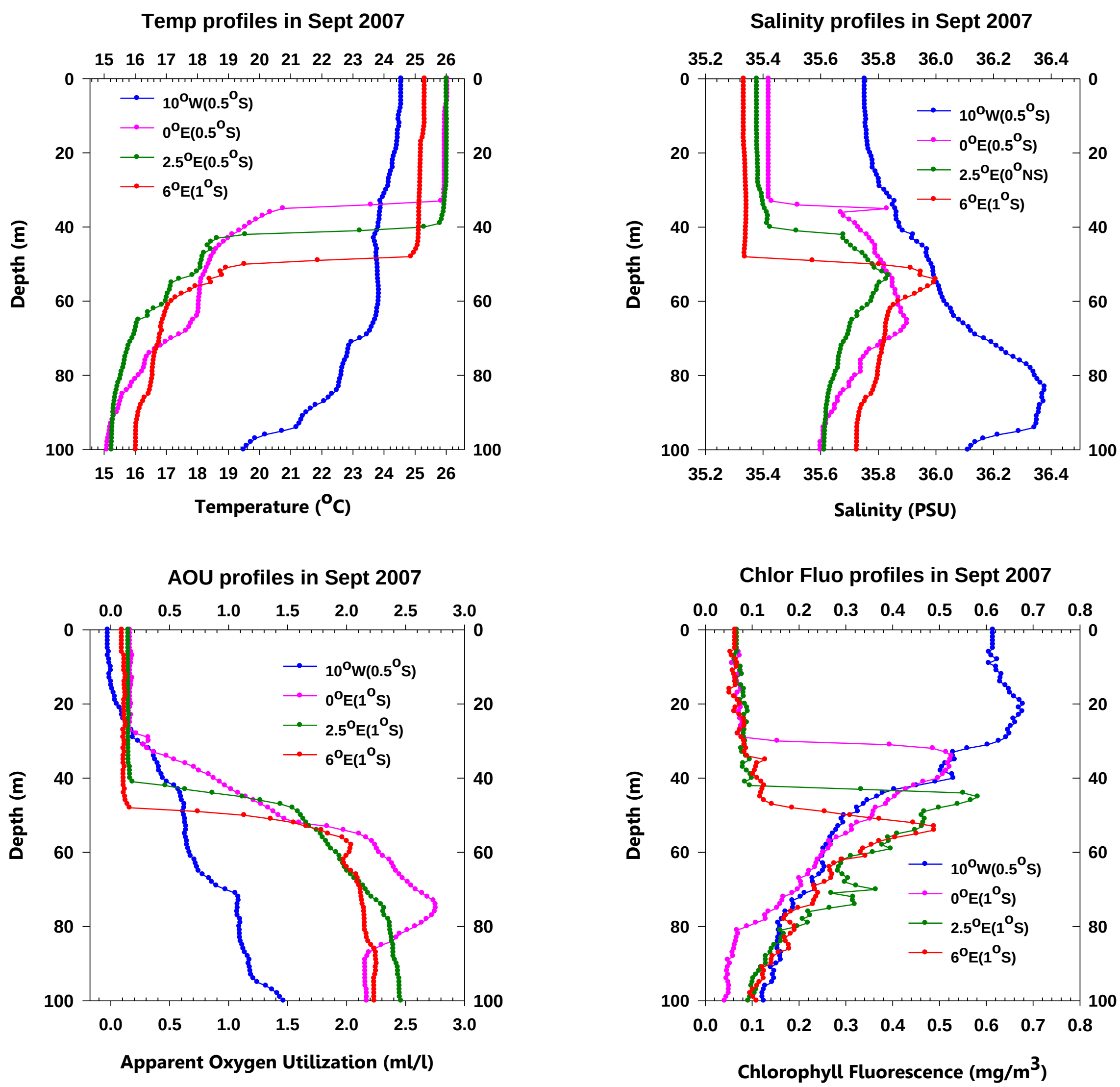

Figure 7. Vertical profiles for temperature, salinity, apparent oxygen utilization, and chlorophyll fluorescence along 10°W, 0°E, 2.5°E, and 6°E in September, 2007. Note the Different latitudes indicated as explained in the text.

pycnocline which was expressed by the erosion of the 24 $kg^{-3}m^{-3}$ isopycnal and did not support westward zonal advection from the African coastal upwelling zone, often put forward to explain the equatorial fertility far west (Oudot and Morin, 1987; Nubi et al., 2016). According to the authors, the shoaled pycnocline which supplied the EUC with nutrients played an important role in the enrichment process within the equatorial band along 10°W. Albeit, oxygen saturation was observed to be higher at other regions than 10°W, degradation of organic materials through oxygen consumption was the highest at 10°W throughout the studied depths. Using the profiles for AOU, there was little or no oxygen-dependent activities from the surface to about 30, 40, and 50 m along 0, 2.5 and 6°E, respectively due to the constant AOU values recorded at these depth ranges. The highest concentration of chlorophyll fluorescence (also at shallowest depth) along 10°W was in association with the vertical section for nitrate and profile for AOU, as increased nitrate influx to the surface along this region enhanced the conditions of phytoplankton growth and the maximum of its vertical distribution moves to shallowest layer. The profiles for these parameters gave a clear indication that equatorial upwelling and its influence on biological productivity was the strongest at 10°W, and the regional trend was 10°W > 0°E > 2.5°E > 6°E.

Conclusion

The present study provides evidences of the extension of spatial pattern in equatorial upwelling intensity and its influence on bio-productivity from boreal summer to autumn. Similar to situations in June (Nubi et al., 2016), uplift of the pycnocline and mixing resulting from vertical shear (Oudot and Morin, 1987; Bourlès et al., 2002; Jouanno et al., 2011; Nubi et al., 2016) played a major role in equatorial surface enrichment along 10°W. Despite the contribution of coastal upwelling to the outcropping of relatively cold waters (25.5°C) at the surface along 6°E, the non-involvement of EUC due to its absence at this region made surface enrichment to be least pronounced at 6°E. The presence of eastward flowing nutrient-rich EUC at 10°W, 0°E, and 2.5°E whose transport decreases eastward (Hormann and Brandt, 2007; Kolodziejczyk et al., 2009; Nubi et al., 2016) is an indication that there was no westward (that is, east-to-west) advection from 6°E to 10°W within the equatorial band in September 2007. This suggests the important role of vertical processes in the equatorial enrichment along 10°W during autumn in September 2007. Similar to the observed spatial differences in equatorial upwelling intensity within the Gulf of Guinea basin during boreal summer (Nubi et al., 2016), all the hydrological features during boreal autumn were testaments to the fact that enrichment along region 10°W was not influenced by situations close to the rich coastal upwelling zone.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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