Journal of Biodiversity and Environmental Sciences (JBES)
ISSN: 2220-6663 (Print) 2222-3045 (Online)
Vol. 4, No. 1, p. 72-80, 2014
http://www.innspub.net

RESEARCH PAPER OPEN ACCESS

Inter-annual variability on the influence of equatorial upwelling on biological productivity along 10°W in the Eastern Equatorial Atlantic (EEA)

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Article published on January 02, 2014

Key words: Equatorial upwelling, biological productivity, eastern equatorial Atlantic, equatorial undercurrent, nutrients.

Abstract

Of the 3 boreal summers covered by the EGEE oceanographic cruises between 2005 and 2007, equatorial upwelling was strongest along 10°W in June 2005 and weakest in June 2006. In response to the shoaling pycnocline, cold nutrient-rich waters upwelled to the euphotic layer and significantly influenced the biological productivity of the region in June 2005. Using profiles for temperature, salinity and dissolved oxygen (at the latitude of Equatorial Under-Current (EUC) velocity core) and chlorophyll fluorescence profile (at the latitude of maximum occurrences within the EUC latitude bands), the hypothesis of the EUC contributing to the equatorial fertility process along 10°W was captured. While nitrate was limiting to phytoplankton growth in June 2006 and June 2007, phosphate stress was observed in June 2005.

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Introduction

The equatorial Atlantic Ocean is an important region with respect to large-scale oceanic circulation which influences the climate of the region (Kerr 1999; Hardman-Mountford 2000; Bourlès *et al.*, 2002). Upwelling in this region has significant impact on the climate and fisheries of the area (Hardman-Mountford *et al.,* 2000). The month of June is the transition month that heralds the onset of equatorial upwelling in the Gulf of Guinea (Gallardo, 1993). The geostrophic component of the south equatorial current (SEC) is strongest during the boreal summer (Molinari, 1982). The shoaling of the EUC and the acceleration of the westward SEC has been linked to thermocline shoaling, and consequently to equatorial upwelling and enhanced vertical mixing in the EEA (Voituriez & Herbland 1977; Bourlès *et al.,* 2002; Jouanno *et. al.,* 2011). Uplift of the thermocline has been shown to supply the EUC with nutrients (Oudot and Morin 1987); and vertical mixing, resulting from the vertical share between the EUC and SEC enriches the surface layer (Jouanno *et. al.,* 2011). Vertical mixing has been shown to be more important than vertical advection in the process of nutrient enrichment of the euphotic layer in the equatorial Atlantic (Voituriez and Herbland 1979). Reduction of the salinity maximum of the EUC and the parallel increase of the surface salinity, decrease of the surface temperature and increase of the surface nitrate concentration have been considered as arguments in support of the hypothesis of vertical mixing (Hisard, 1973; Voituriez & Herbland, 1979; Kolodziejczyk *et. al.,* 2013). The annual mean upwelling in the eastern equatorial Atlantic has been found to be supplied by the EUC during boreal summer (when south-easterly winds are intensified) and contributions made also by the South Equatorial Under-Current (SEUC) (Hormann and Brandt 2007). The growth of phytoplankton occurs in the layer where both light and nutrient concentrations are sufficient, and with increase of the upwelling nutrient flux, the conditions of phytoplankton growth become better and the maximum of its vertical distribution moves to shallower layer (figure 1). The seasonal cycle of Chl-a in the equatorial belt has been shown to reflect seasonal variations of upwelling and equatorial zonal winds that follow the seasonal march of the Intertropical Convergence Zone (Grodsky *et. al.*, 2007). The seasonal peak of Chl-a on the equator occurs in boreal summer when the ITCZ is in its northernmost position and zonal winds over the equator are enhanced.

Table 1. Summary of the EGEE cruises during the EOP (2005 – 2007) (Baurand, 2008; Kolodziejczyk *et.al.* 2009)

Cruise	Date	Vessel	Hydro - Stations	No of Sample	CTD	SADCP (KHz)
EGEE 1	June 2005	Le Suroit	55	522	yes	150
EGEE 2	Sept 2005	Le Suroit	61	666	yes	150
EGEE 3	June 2006	L'atalante	72	1116	yes	75
EGEE 4	Nov 2006	L'antea	42	460	yes	75
EGEE 5	June 2007	L'antea	50	534	yes	75
EGEE 6	Sept 2007	L'antea	41	443	yes	75

Understanding the biophysical processes operational in the tropical Atlantic oceans in order to describe the hydrology and productivity of the region has been the goal of several measurement programs (Eqaulant, Cither, Focal, etc). Recent oceanographic cruises have yielded new information with respect to equatorial upwelling and its influences on the productivity in this region. This work was therefore aimed at studying the potential influence of equatorial upwelling on nutrients distribution with relation to the biological productivity in the EEA.

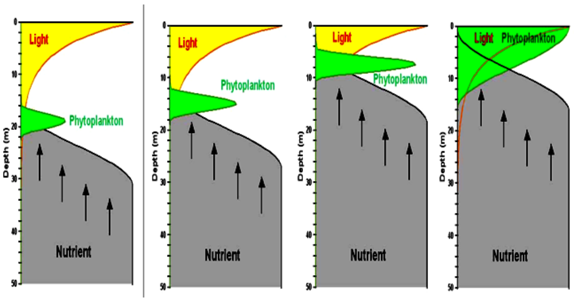

Fig. 1. Vertical distribution of Phytoplankton relative to light and nutrient intensity (source: http://www.eeb.ucla.edu/test/faculty/nezlin/PrimaryProduction.htm)

Materials and methods

The EGEE experiment (Etude de la circulation océanique et des échanges océan-atmosphère dans le Golfe de Guinée) was the oceanographic component of the African Monsoon Multidisciplinary Analyses (AMMA) program. It was carried out during the Enhanced Observing Period (EOP; 2005 – 2007) to assess inter-annual and seasonal variability in the Gulf of Guinea (Bourlès *et al.,* 2007). Six EGEE cruises in the Gulf of Guinea (GG) (figure 2) were conducted with two cruises per year during the three EOP years (2005-2007).

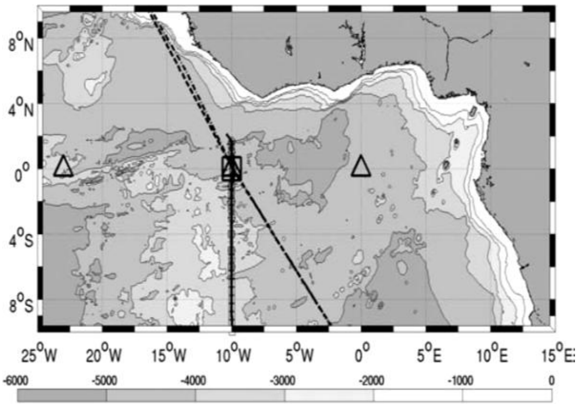

Fig. 2. Track lines of some cruises along 10oW in the Gulf of Guinea carried out between 1997 and 2007. CORIOLIS 2003 and 2004 (dash-dotted line and dashed line, respectively) cross the equator at 10°W. EQUALANT, PIRATA, and EGEE cruises are shown by the solid line along the 10°W section, and CTD stations are shown by stars, squares, and circles (Source: Kolodziejczyk *et.al.* 2009).

Cruises were made to coincide with the monsoon onset and development of equatorial upwelling in the Gulf of Guinea (GG) in boreal spring and summer (end of May to July) and again during the mature phase of the monsoon (September-October), when the cold tongue was still well developed in the GG and the ITCZ begins its southward migration (Bourlès *et al.*, 2007). For the purpose of this study, data collected during the onset in May – June was considered. Seasonal and inter-annual variability was measured along several meridional sections, with primary focus given to the 10°W section, which was occupied several times prior to EGEE by PIRATA and EQUALANT cruises (Bourlès *et al.,* 2007). The EGEE cruise track is presented in figure 2 and the summary of the cruises provided in table 1.

Samples were collected from 11 or 22 (depending on the cruise / research vessel used) hydrological bottles attached on a rosette on which is also installed a CTD-O2 (bathysonde) and lowered ADCPs. Conductivity-temperature-depth (CTD) measurements were taken with SeaBird probes. The CTD sensors were systematically calibrated before and after the cruises and the accuracy is around ±0.003°C for the temperature and ±0.003 for the salinity. The horizontal resolution of the CTD profiles along 10°W is generally of 1/2° of latitude, but is 1/3° between 1°S and 1°N (Kolodziejczyk *et.al.* 2009). Determination of nitrate was done according to Benschneider & Robinson (1952) and phosphate was determined according to Murphy & Riley (1962).

Results

Zonal Currents in the upper layer

Figure 3 presents the vertical sections for the zonal currents (ms^{-1}) along 10°W in June of 2005 (upper tray), 2006 (middle tray) and 2007 (bottom tray) during EGEE1, 3 and 5 respectively. It shows for all the years the eastward EUC with velocity cores of >0.9m/sec, <0.8m/sec, and 0.8 m/sec in 2005, 2006 and 2007 respectively at mean depths of about 50m within 1^{o}N and 1^{o}S latitudes. The SEUC was located between 4.5^{o}S and 5.5^{o}S latitudes for the studied years with their cores below 100m depth. Also located between 1^{o}N and 1.5^{o}N is the northern branch of SEC (nSEC) which was most enhanced in June 2007 (figure 3).

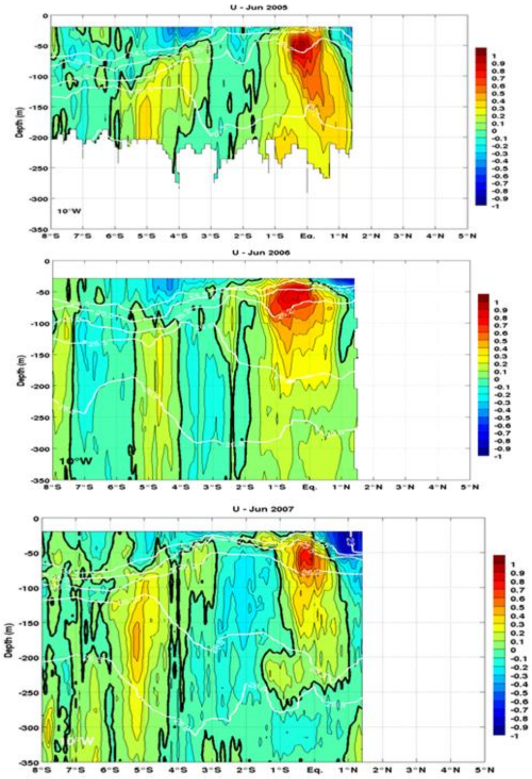

Fig. 3. Vertical section for the zonal current velocity (ms^{-1}) along 10^{o}W in June of 2005 (upper), 2006 (middle) and 2007 (bottom). (white lines are pycnoclines).

Temperature in the upper layer

The vertical sections for temperature (^{o}C) along 10^{o}W in June of 2005 (left), 2006 (middle) and 2007 (right) during EGEE1, 3 and 5 respectively are presented in figure 4. Water (with temperatures lower than 22^{o}C) was observed at the surface between latitudes 1.5^{o}N and 2^{o}S in June 2005 (figure 4/left). In June 2006, warm waters with temperatures greater than 24^{o}C dominated the entire surface area (figure 4/middle). In June 2007, water with temperatures lower than 24^{o}C was observed between latitudes 1^{o}N and 4^{o}S and at the equator there was an outcropping of colder waters with temperature of about 22^{o}C at the surface (figure 4/right).

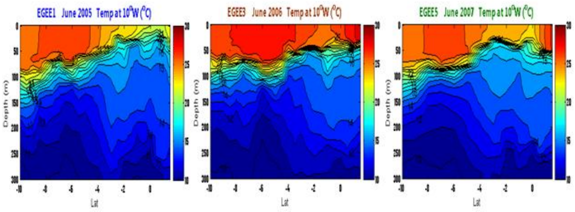

Fig. 4. Vertical sections (0 – 300m) for temperature along 100W in June of 2005 (left), 2006 (middle) and 2007 (right).

Salinity in the upper layer

Figure 5 presents the vertical sections for salinity (PSU) along 10^{o}W in June of 2005 (left), 2006 (middle) and 2007 (right) during EGEE1, 3 and 5 respectively. Salinity maximum which is the signature of subtropical waters was observed south of 6^{o}S from the surface to about 150m depth in June of the three years (figure 5). In June of 2006 (figure 5/middle) and 2007 (figure 5/right), salinity maxima (>36 PSU) were observed at the locations of the EUC and SEUC which serve as their respective signatures. The imprint of the EUC salinity maxima was most intense in June 2006 (figure 5/middle) and least observed in June 2005 (figure 5/left).

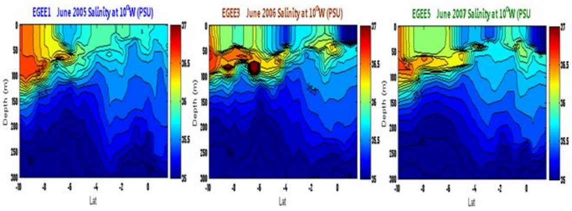

Fig. 5. Vertical sections (0 – 300m) for salinity along 100W in June of 2005 (left), 2006 (middle) and 2007 (right).

Dissolved oxygen and nitrate in the upper layer

Figure 6 presents the vertical sections for dissolved oxygen (upper tray) and nitrate (lower tray) along 10^{o}W in June of 2005 (left), 2006 (middle) and 2007 (right) during EGEE1, 3 and 5 respectively. In June of the studied years, there was deepening of the isopleth within the equatorial belt in the subsurface, and this gives evidence of the EUC characterized by a higher oxygen concentration than the northern and southern adjacent waters. The oxygen maximum extends deeper to about 200m between 1°S and 1°N along 10°W (figure 6/upper). The oxygen maximum between 4°S and 5°S (from 150m downwards), although less intense in June 2007 (figure 6/upper/right), was associated with the SEUC located at this point during the periods of study (figure 3; figure 6/upper).

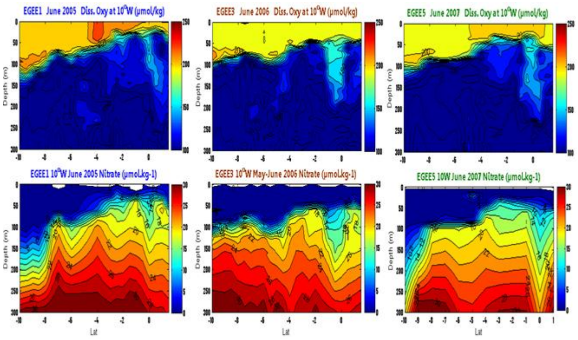

Fig. 6. Vertical sections (0 – 300m) for dissolved oxygen (upper tray) and nitrate (lower tray) along 10°W in June of 2005 (left), 2006 (middle) and 2007 (right).

The entire surface area in June of the study years was nitrate depleted (figure 6/lower) with deepening of the isopleths (steepest in June 2007) around the equator (figure 6/lower); however June of 2005 experienced strongest surface enrichment in terms of nitrate concentrations as waters with nitrate concentrations of about 2µmol/kg were observed closest to the surface between 1°S and 1°N (figure 6/lower/left). The maxima for nitrate levels at the mean depths of the EUC within the EUC latitude band were 18µmol/kg, 10µmol/kg and 12µmol/kg in 2005, 2006 and 2007 respectively.

Chlorophyll fluorescence in the upper layer

The vertical sections for chlorophyll fluorescence (Åµ/l) along 10°W in June of 2005 (left), 2006 (middle) and 2007 (right) during EGEE1, 3 and 5 respectively are presented in figure 7. Chlorophyll fluorescence levels were highest at the surface in June 2005 (figure 7/left), with values greater than 0.8Åµ/l observed at the surface within 1°N and 1°S. Slightly above 50m depth within the same latitudes, chlorophyll levels of about 0.3Åµ/l and 0.8Åµ/l were observed in June of 2006 (figure 7/middle) and 2007 (figure 7 /right) respectively. Appreciable levels of chlorophyll fluorescence also made appearance between 2 and 4°S at depths above 50m in June of all the years studied (figure 7); and this secondary bloom was highest in June 2005 (figure 7/left).

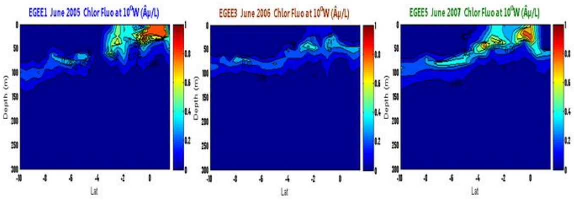

Fig. 7. Vertical sections (0 – 300m) for chlorophyll fluorescence along 10°W in June of 2005 (left), 2006 (middle) and 2007 (right).

Discussion

For the purpose of this work, emphases were laid on the equatorial upwelling region between 1°N and 1°S, and particularly at 0.5°S which was where the EUC velocity core was located during the periods of study. Emphasis was also given to depths between 0 to 100m where biological activity was prevalent. The involvements of the equatorial current systems (both surface and undercurrents) in the equatorial fertility process were captured in the vertical distribution of the studied parameters. Thermocline was shallowest (deepest) in June 2005 (June 2006), with coldest waters at the surface in June 2005. In agreement with the work of Marin *et al.*, (2009), this change in the slope of the equatorial thermocline, being response to changes in the trade winds over the western equatorial Atlantic led to an outcropping of cold thermocline waters in June 2005 in the EEA, but not in the June 2006. The trend for the depth of the thermocline at 0.5°S along 10°W was June '06 > June '07 > June '05 (Fig. 8).

Also the imprint of the EUC salinity maximum at the 50m mean depths was observed to be strongest in June 2006 (figure 5/middle and figure 9) and in line with the hypothesis of Hisard (1973) and Voituriez and Herbland (1979), this suggests a reduced vertical mixing in June 2006 as there was erosion of the salinity maximum in June 2005 induced by the outcropping of the thermocline in the mixed layer and/or by enhanced vertical diffusion in the surface layer as pointed out by Kolodziejczyk *et.al.,* (2013).

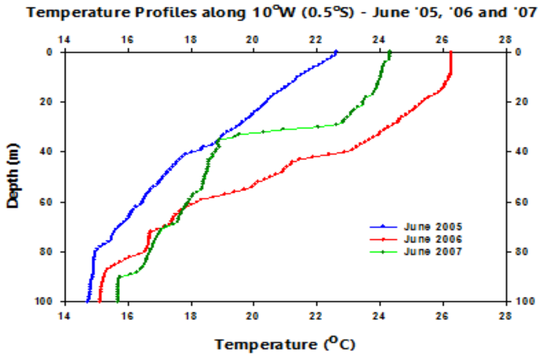

Fig. 8. Profiles for Temperature at 0.5°S along 10°W in June '05, June '06, and June '07.

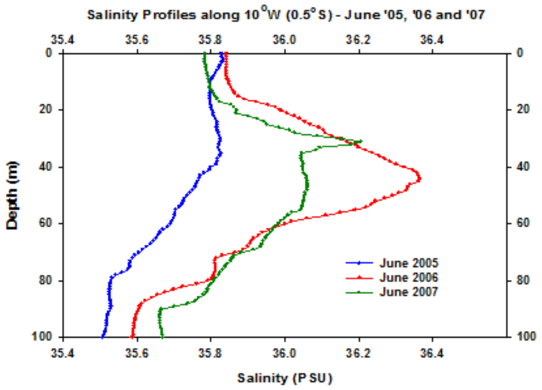

Fig. 9. Profiles for salinity at 0.5°S along 10°W in June '05, June '06, and June '07.

Apart from the fact that the oxycline shoaled mostly in June 2005 (figure 6/left and figure 10), highest levels of dissolved oxygen were observed at the surface - an indication that coldest (nutrient-rich) water from beneath upwelled to the surface layer, and enhanced the solubility of oxygen.

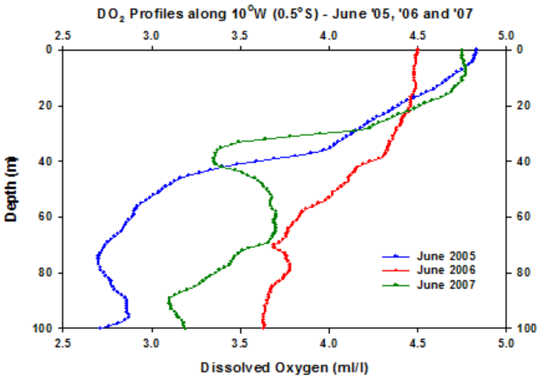

Fig. 10. Dissolved oxygen profiles at 0.5°S along 10°W in June '05, June '06, and June '07.

Away from the surface layer, the levels of dissolved oxygen gradually drop in June 2005 (figure 10), and with lowest values from about 50m to 100m depth. This is an indication that biological activities involving oxidation of organic particles were highest during the onset of equatorial upwelling in June 2005.

Productivity (chlorophyll fluorescence) profiles at the location of maximum occurrence within the EUC latitude band in June of 2005, 2006 and 2007 are provided in figure 11. The maximum for biological productivity in terms of chlorophyll fluorescence levels was highest in June 2005 and with its position shallowest within the EUC latitude band. The maxima near the surface for chlorophyll fluorescence levels in June 2005 (>1.2Åμ/l), June 2006 (0.4Åμ/l), and June 2007 (0.85Åμ/l) were observed around 20m, 50m, and 30m depths respectively (figure 11). This suggests that the highest nutrients influx to the surface which resulted into increased phytoplankton biomass was witnessed in June 2005.

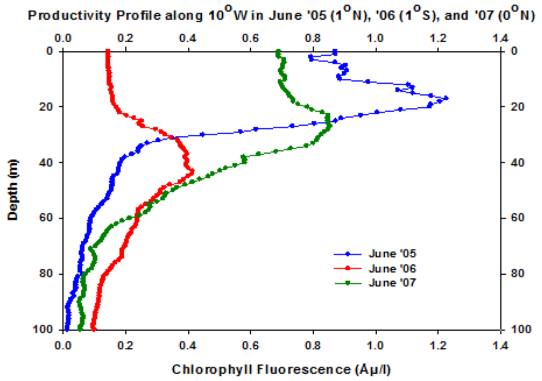

Fig. 11. Chlorophyll fluorescence profiles along 10°W in June '05 (1°N), June '06 (1°S), and June '07 (0°N).

The profiles for these parameters gave a clear indication that equatorial upwelling and its influence on biological productivity was strongest in June 2005, and the inter-annual trend was June 2005 > June 2007 > June 2006. Analysis of the relationship between nitrate and phosphate (Redfield ratio – RR) also provided useful information on the availability of these nutrients for biological production (Gillooly *et* *al.,* 1992). The nitrate-phosphate ratio in June of 2005, 2006 and 2007 were estimated by least square fit to be 18.10, 15.64 and 15.56 respectively (figure 12). The nitrate-phosphate ratio was higher than the theoretical RR of 16 in June 2005, and making phosphate to be limiting to phytoplankton growth during this period. Furthermore, due to strong equatorial upwelling witnessed in June 2005 which reflected in the levels of chlorophyll fluorescence at the surface (figure 7/left), available phosphate was rapidly consumed leaving nitrate to build up significantly, thereby making phosphate to be limiting. It was a period of nitrate stress in the boreal summers of 2006 and 2007 as the estimated values for nitrate-phosphate ratio during these periods were lower than the theoretical RR of 16.

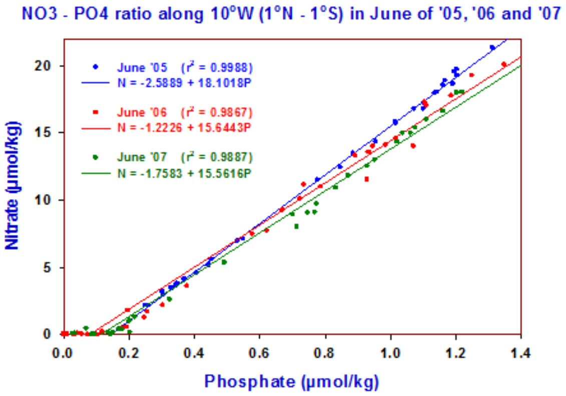

Fig. 12. Nitrate-phosphate relationship within 1°N and 1°S along 10°W in June of 2005, 2006 and 2007 for all values of nitrate between 0 and 100m.

Build up of phosphate, being firstly regenerated at the surface (Voituriez and Dandonneau 1974; Herbland and Voituriez 1977) and the presence of zooplankton which excretes ammonium and phosphate (Le Borgne 1977) may account for the low nitrate-phosphate ratios obtained in June of 2006 and 2007. From these relationships, there were clear indications that nutrient influx to the surface layer with increased productivity potential was greatest along 10°W in June 2005.

In conclusion, equatorial upwelling significantly influenced nutrient distribution and biological productivity mostly in June 2005 along region 10°W in the EEA. The involvements of the equatorial current systems (both surface and undercurrents) in the equatorial fertility process were observed in the vertical distribution of the studied parameters. High levels of nutrients and dissolved oxygen were observed at the respective EUC mean depths for each of the studied years, and this aligns with the work of Oudot and Morin (1987) who pointed out that uplift of the thermocline supplies the EUC with nutrients, and vertical mixing resulting from the vertical share above the EUC core enriches the surface layer (Jouanno *et. al.,* 2011). Recirculation and water mass exchanges between EUC and SEC as pointed out by Bonhoure *et al.,* (2004) were observed along 10°W in the hydrological structures of studied parameter in June 2005. Upwelling was observed to be weak during June 2006 and from earlier work of Marin *et al.* (2009), the weak easterlies south of 5°N during boreal spring of this year has been shown to be responsible. The aftermath of this delay in the onset of upwelling in June 2006 was seen in the poor surface enrichments and low biological productivity witnessed in the equatorial region. Of the studied years, the influence of equatorial upwelling (in terms of enhancement) on nutrient distribution and biological productivity was strongest in June 2005 and weakest in June 2006.

Acknowledgements

The authors are grateful to the Regional Program for Physical Oceanography in West Africa (PROPAO), funded by the French Ministry of Foreign Affairs for a period of 3 years (2007-2010), Institute de Recherches pour le Développement (IRD), France, CIPMA – University of Abomey-Calavi, Republic of Benin, and Nigerian Institute for Oceanography & Marine Research, Nigeria.

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