10 Seasonal and Interannual Particle Fluxes in the Eastern Equatorial Atlantic from 1989 to 1991: ITCZ Migrations and Upwelling

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10.1 INTRODUCTION

The NE and SE trade winds are a dominant feature in the eastern Atlantic Ocean and largely determine biological production and sedimentation in the coastal and equatorial upwelling regimes off Africa. The trade winds are separated by a calm zone, the Intertropical Convergence Zone (ITCZ) which is characterized by high atmospheric and oceanic temperatures. In the eastern equatorial Atlantic (Guinea Basin), this zone migrates seasonally from about 2–4°N in March to 8–12°N in August (Figure 10.1) in response to larger-scale climatic variations and the intensity of the trade winds (Servain and Legler, 1986). The wind regime is strongly coupled with oceanic and biological processes operating in this area. The equatorial "upwelling" zone is believed to be a production regime with elevated biomasses and biological production especially during the boreal summer when the southeasterlies are commonly strong and sea surface temperatures (SST) are relatively low (Voituriez and Herbland, 1982). Consequently, during the boreal summer, high export fluxes of organic carbon and other biogenic components were expected. Due to a distinct interannual variability in wind forcing and ocean response (Houghton and Colin, 1986; Peterson and Stramma, 1991), year-to-year flux variations may also be anticipated. The intensity of upwelling may decrease in certain years (Voituriez and Herbland, 1977) and is occasionally accompanied by large anomalies in sea surface temperatures linked to anomalous southerly positions of the ITCZ (Merle, 1980).

With this long-term flux study conducted at 10°W in the Guinea Basin, we monitored the seasonal and year-to-year variations in sedimentation comparing a northern (GBN) and a southern site (GBS) (Figure 10.1). Both sites were located close to the equatorial upwelling area. The northern site (GBN) was located in the vicinity of the mean southernmost boundary of the ITCZ in boreal winter and is

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expected to be substantially affected by precipitation and influx of land-derived materials. The southern site was located close to a thermal ridge at 2–3°S which is a permanent feature of the equatorial circulation in the Gulf of Guinea during the warm spring season (Voituriez and Herbland, 1977). We attributed the seasonal peaks of total matter, organic carbon, carbonate and biogenic opal to corresponding summer upwelling influenced by the zonal winds or to thermal ridging in spring representing the "typical tropical situation" (TTS; Voituriez and Herbland, 1977, 1981, 1982) and tried to monitor these variations on a longer time scale.

10.2 MATERIAL AND METHODS

Time-series sediment traps were used to measure export fluxes well below the mixed layer and at least 500 m above the seafloor to minimize a strong dominance of "swimmers" in the trap samples and, on the other hand, reduce the influx of resuspended material from the seafloor (Gardner and Richardson, 1992). For our studies, we deployed cone-shaped multisample sediment traps (Aquatec, Kiel, Germany) with 20 cups and 0.5 m^2 collection area. All traps were fitted with a grid at the top. The sampling cups were filled with filtered seawater to which Suprapur NaCl was added to increase the density (increase of the salinity to around 40‰). The solution was poisoned with $HgCl_2$ prior to and after deployments. Samples were carefully wet-sieved through a 1 mm screen and "swimmers" were removed by hand. The < 1 mm fraction was split into aliquots and the freeze-dried material was analyzed as described by Fischer and Wefer (1991). Lithogenic matter (Lith.) was estimated according to: Lith. flux = total flux - (opal flux + carbonate flux + 2 x C_{org} flux). Biogenic opal was determined by automated wet leaching (Müller and Schneider, 1993). Fluxes were not corrected for dissolution in the sampling cups. From measurements of the cup solutions, we conclude that dissolution in the cups was rapid and not related to the deployment time, and thus affects all samples to a similar extent. We therefore regard all fluxes as minimal values.

10.3 OCEANOGRAPHIC AND BIOLOGICAL SETTING

The large variability of the surface currents in the Gulf of Guinea is due to a combination both of local and remote wind forcing (Richardson and Walsh, 1986; Servain et al., 1985; Servain and Legler, 1986; Houghton and Colin, 1986, Houghton, 1989). The oceanographic situation is characterized by the westward flowing South Equatorial Current (SEC) (Figure 10.1), which is underlain by the eastward flowing Equatorial Current or Lomonossov Current at more than 50 m depth (EUC) (Peterson and Stramma, 1991; Voituriez and Herbland, 1982;

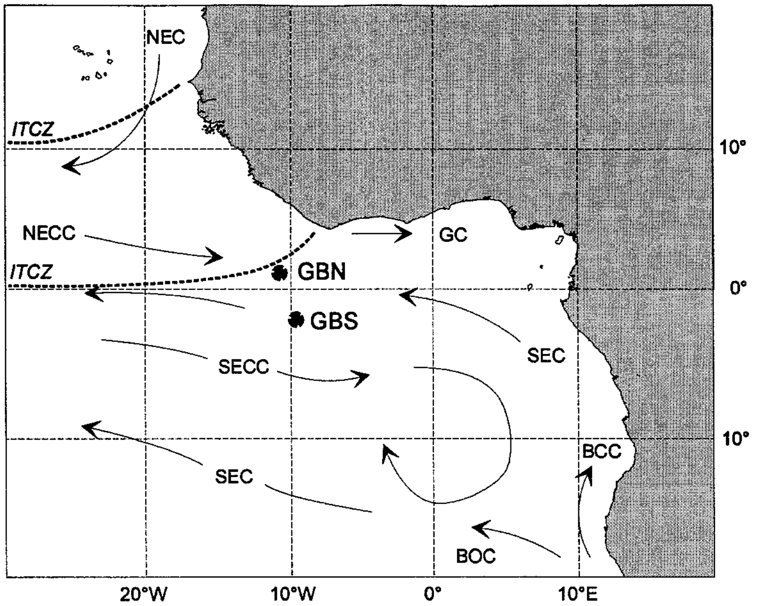

Figure 10.1 Simplified map of surface currents in the eastern Atlantic (NEC = North Equatorial Current; NECC = North Equatorial Counter Current; GC = Guinea Current; SEC = South Equatorial Current; SECC = South Equatorial Counter Current; BCC = Benguela Coastal Current; BOC = Benguela Oceanic Current). The seasonal boundaries of the ITCZ are shown by stippled lines. The trap sites were named GBN and GBS.

Hastenrath and Merle, 1987). The high production upwelling area in the tropical Atlantic where both sites (GBN and GBS) (Figure 10.1) were located is at least partly controlled by the superficial equatorial countercurrent systems which supply nutrients through the South Atlantic Central Water (SACW) (Voituriez and Herbland, 1982). The northern Guinea Basin is also partly influenced by the eastward flowing coastal-near Guinea Current (GC) which is the prolongation of the North Equatorial Counter Current (NECC). The SEC, the NECC and the GC are strongest in the boreal summer when the ITCZ is farthest north (Figure 10.1).

The interannual variability in SST in the eastern Atlantic is stronger than previously thought (Servain and Legler, 1986). A zonal band of maximal SST follows the ITCZ shifting from 8–12°N during the boreal summer to its southernmost position in winter at 2–4°N, close to the position of the northern study site (GBN) (Figure 10.1). The NE and the SE trades differ seasonally (Servain and Legler 1986): the magnitude of the SE trades is strongest in June-July whereas the NE trades are strongest in February. Although the monthly SE trade wind values are smaller than the northeasterlies, they have, due to their longer duration, a mean magnitude of the same order.

Nitrate is the limiting nutrient in the entire tropical Atlantic throughout the year except along the equatorial divergence zone during the cold summer season (Voituriez and Herbland, 1981). The SE trades result in a strong westward advection of the SEC, a shallowing of the thermocline (Voituriez and Herbland, 1981; 1982; Düing et al., 1980) and the presence of maximal nutrients notably around 10°W (Voituriez and Herbland 1981, 1982). Primary production reaches 500 mgC m^{-2} d^{-1} at this point (Voituriez and Herbland, 1981). This zone of higher biomass and production ("active upwelling") occurs between 0°30’N and 1°30’S in the eastern Atlantic and is characterized by SST between 22° and 25°C (Voituriez and Herbland, 1977).

In the boreal winter, the ITCZ is at its southernmost position and is then located nearby the northern trapping site GBN (Figure 10.1). Westward advection of the SEC is weakened, turbulent mixing ("upwelling") is strongly reduced and SST are between 26° and 28°C (Düing et al., 1980; Voituriez and Herbland, 1981). During this season, the southern site (GBS) (Figure 10.1) was located close to a thermal ridge centered at between 2° and 3°S characterized by a deep chlorophyll maximum and elevated biological production (Voituriez and Herbland, 1977). According to Voituriez and Herbland (1981, 1982), this production system is characterized by nutrient depletion in the surface layer ("typical tropical situation", TTS). Primary production is then largely determined by the nitracline depth in relation to optimal light conditions.

10.4 OCEAN CURRENTS

In combination with the traps, Aanderaa current meters were deployed. At the northern Guinea Basin sites, current velocities in the AAIW (Antarctic Intermediate Water) layer during 1989 (GBN6 upper trap) were generally lower than 20 cm s^{-1}. However, some spikes of up to 45 cm s^{-1} were recorded which were, however, not related to the measured fluxes. Directions revealed two maxima with roughly east-west and west-east directions. Fluxes increased during changes to the west-east direction, e.g., in August. In the deeper waters (NADW, North Artlantic Deep Water, GBN6 lower trap) current speeds were still relatively high, mostly between 10–20 cm s^{-1}. Again, some peak velocities of short duration were measured with values of up to 50 cm s^{-1}. Current directions were generally south to southeastwards. At the southern sites, currents in 726 m water depth were measured during the GBZ5 deployment. They oscillate around 10 cm s^{-1} with some peaks of 30 cm s^{-1} in June and July. No correlation to fluxes was observed. Current directions in this water mass (AAIW) were commonly to the east, mostly ESE, and rarely NE.

10.5 RESULTS AND DISCUSSION

10.5.1 SEASONALITY AND INTERANNUAL VARIABILITY OF FLUXES AND COMPOSITION

10.5.1.1 Northern Guinea Basin sites (GBN)

In the upper trap level total flux peaks were observed in spring (115.3 to 197.5 mg m^{-2} d^{-1}) and summer (212 to 240.5 mg m^{-2} d^{-1}) which generally recurred with similar timing (Figure 10.2a). The deeper trap fluxes revealed a similar but somewhat smoothed pattern (Figure 10.2b) with higher average values due to a larger contribution of terrigenous material (see Richardson and Gardner 1991). However, peak fluxes in spring and summer were still present. By comparing the timing of the upper and lower trap flux peaks, we estimated average sinking velocities for the total particulate matter in the order of 150 m d^{-1}. This appears to be a typical range for settling velocities of larger particles; i.e., fecal material (Honjo and Roman, 1978). A study performed by Bishop et al. (1977) close to our site indicated that 99% of the vertical mass flux through 388 m water depth was probably transported via fecal matter. Terrigenous fluxes constituted between 15 and 20% of the total particulate mass at this site and peaked generally in spring. An exception was 1991, when consistently higher background fluxes were observed throughout the year (Figure 10.2). Biogenic fluxes were clearly dominated by carbonate (e.g., foraminifers and nannofossils) reaching from 19.7 to 80.7% of the total mass. The most prominent carbonate signals were measured during the boreal summer, particularly during 1989 (131.7 mg m^{-2} d^{-1}) (Figure 10.3).

Biogenic opal, mostly composed of diatoms and radiolariansm, showed maximal fluxes in spring and summer on the seasonal cycle (Figure 10.3) and constituted only between 1.9 and 19.7% of the total mass. Spring fluxes were highest in 1989; the summer sedimentation peaks were almost identical in 1989 and 1991 (Figure 10.3). Detailed studies on the seasonal diatom distribution conducted by Lange et al. (1994) revealed highest valve fluxes in spring (March-April) and another maximum in summer 1989 (August-September). The summer signal in 1989 was almost exclusively manifested by small bicapitate *Nitzschia* species representing 68–83% of the total diatom fluxes. This group is known to be typical for tropical oceanic waters (Sancetta, 1992). Radiolarian fluxes showed a rather similar pattern with prominent peaks in spring and summer to fall (Boltovskoy et al., 1993).

Organic carbon which contributed 4.1 to 28.2% to the total material showed a bimodal flux pattern with maxima in spring and particularly in summer, displaying only small interannual variation (Figure 10.3). The spring organic carbon flux signal in 1989 is characterized by relatively high C/N ratios (10–11.6) and low $\delta^{13}C_{org}$ ratios (-22.4 to -22.8‰) which indicates a significant contribution of terrestrial organic matter supplied by the NE trades. In addition, the spring opal

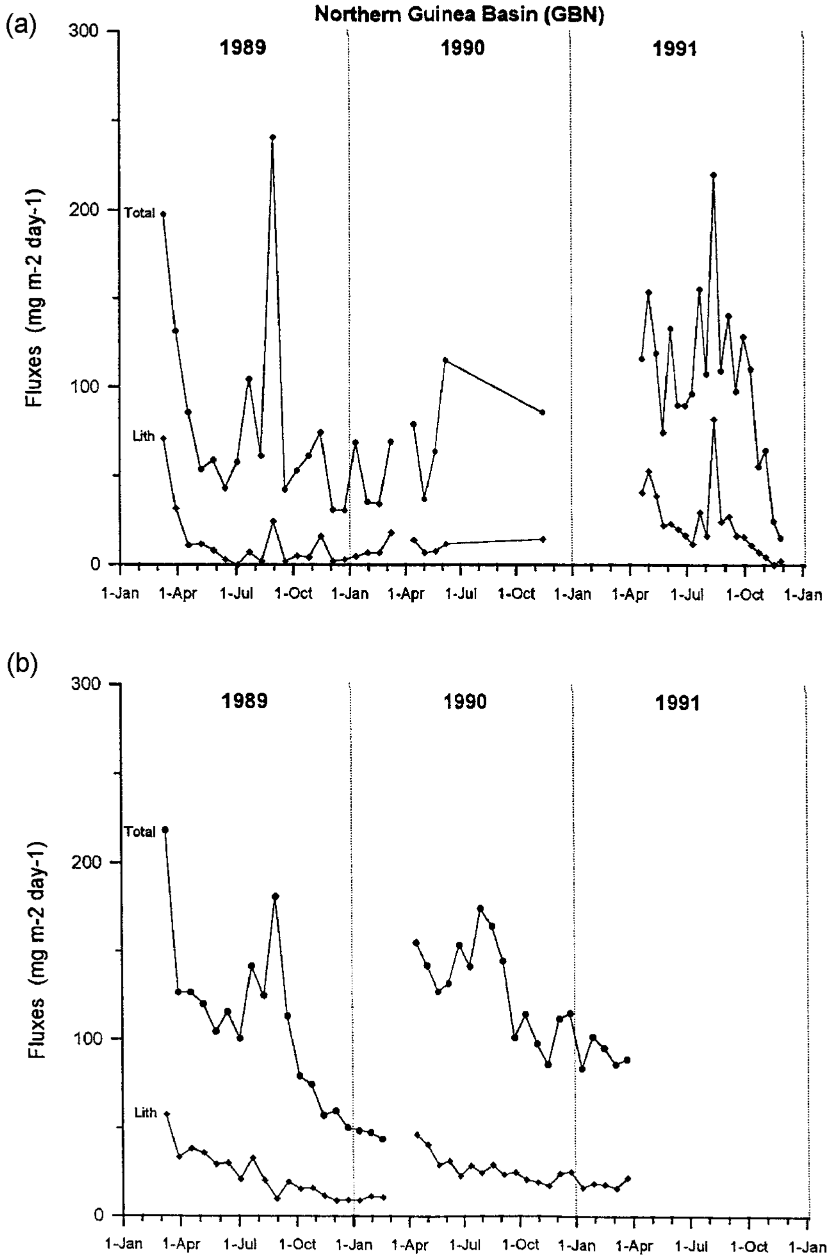

Figure 10.2 Seasonal total and lithogenic fluxes in the northern Guinea Basin (GBN). (a) upper traps (853–953 m). (b) lower traps (3921 and 3965 m; see Table 10.1).

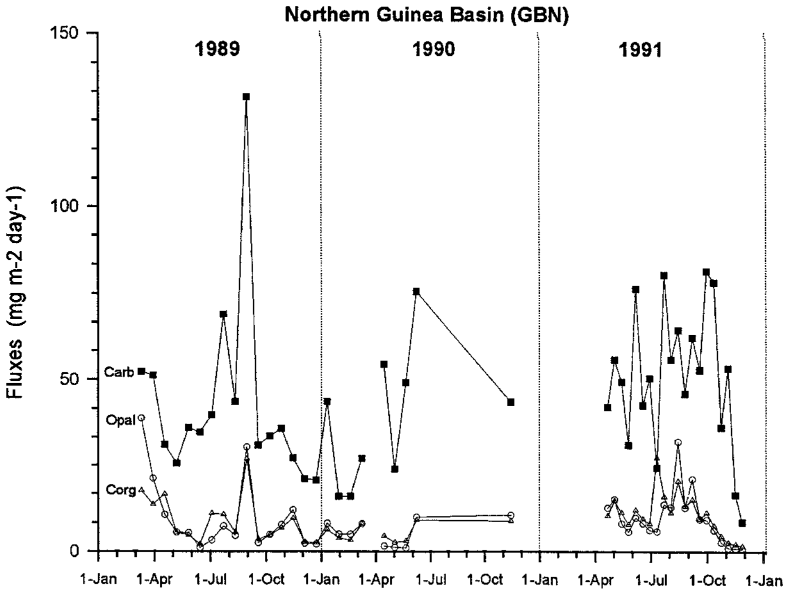

Figure 10.3 Seasonal carbonate, opal and organic carbon fluxes at GBN (upper traps: 853–953 m).

Table 10.1 Description of the sampling sites.

Site name	Long	Lat	Water depth (m)	Trap depth (m)	Sampling duration	Samples x days
a) Northern Equatorial Upwelling Area (GBN)						
GBN3	01°48.N	11°08.W	4481	853 3921	03/01/89– 03/16/90	20 x 19 19 x 19
GBN6	01°47.N	11°08.W	4522	859 3965	04/04/90– 04/07/91	4 x 18, 1 x 297 20 x 18
EA2	01°47.N	11°15.W	4399	953	04/13/91– 11/29/91	20 x 11.5
b) Southern Equatorial Upwelling Area (GBS)						
GBZ4	02°11.S	09°54.W	3912	696	03/01/89– 03/16/90	20 x 19
GBZ5	02°12.S	09°56.W	3920	597 3382	04/01/90– 03/30/91	2 x 4.75, 12 x 29.6 20 x 18
EA4	02°11.S	10°06.W	3906	1068	04/13/91– 11/29/91	20 x 11.5

peak in 1989 (38.9 mg m^{-2} d^{-1}) was characterized by a significant contribution of freshwater diatoms and phytoliths (Lange et al., 1994) obviously transported by the NE trades and precipitated within the ITCZ which is normally located at its southernmost position during this period (Servain and Legler, 1986). In contrast, the spring signal in 1991 appeared to be much less influenced by terrestrial input as deduced from a low C/N ratio of 8.9 and a relatively high $\delta^{13}C_{org}$ value of -21.7‰. The summer upwelling events were generally characterized by lower C/N and higher $\delta^{13}C_{org}$ ratios; 8.9 and -21.1‰ in August 1989 and even 6.1 and -19.6‰ in August 1991. These isotope values are typical for a marine endmember at low latitudes (Hedges and Mann, 1979) and document a high contribution of phytoplankton, particularly in 1991.

10.5.1.2 Southern Guinea Basin sites (GBS)

This flux pattern, in contrast to the site further north is characterized by (1) a less clear bimodal distribution, (2) lower total, biogenic and lithogenic fluxes and (3) higher spring relative to the summer fluxes (Figure 10.4). Peak fluxes at both depth levels occurred in spring (89.5 to 165.5 mg m^{-2} d^{-1}) and summer to fall (32.6–167.3 mg m^{-2} d^{-1}). However, no distinct summer peak representing the cold upwelling season was observed in 1989. Lithogenic fluxes were significantly smaller compared to the GBN site and revealed slightly higher values in spring. Biogenic carbonate constituted the main proportion of the total fluxes (14.3–85%). Spring sedimentation increased from 1989 to 1991 and a summer upwelling peak was only present in 1991 (Figure 10.5). However, in 1990, a second prominent maximum occurred in fall, probably documenting equatorial upwelling.

Opal flux peaks were recorded in spring and obviously increased from 1989 to 1991; fluxes in summer-fall were highest in 1990 and lowest in 1989 (Figure 10.5). Similar to the GBN site, we found relatively low contributions of biogenic opal (0.5–14.1%). Mean diatom fluxes were about three times lower in 1989 compared to the site further north (Lange et al., 1994) and the spring flux peak was characterized by lower abundances of freshwater diatoms. The opal peak during the equatorial upwelling season was rather weakly expressed in the summer of 1989 (July). However, the summer diatom assemblages were similar to GBN, also dominated by oceanic *Nitzschia bicapitata* (Lange et al., 1994).

Organic carbon, which constituted 3.6 to 23.8% of the total flux, also peaked in spring, except in 1990 when a distinct fall maximum was present (Figure 10.5). Similar to the GBN site, the spring organic carbon flux in 1989 was marked by a high C/N ratio (13.5) and a low $\delta^{13}C_{org}$ value of -23‰ suggesting a contribution of terrestrial organic carbon delivered by the NE trades and precipitated at the southernmost boundary of the ITCZ. In contrast, spring peaks in 1990 were characterized by C/N and $\delta^{13}C_{org}$ ratios of 9.9 and -22.8‰; in 1991 these values were 10.9 and -22‰ during the sampling period. These data appear to document