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SEDIMENTATION MODIFIED BY WIND INDUCED RESUSPENSION IN A SHALLOW TROPICAL LAGOON (COTE D'IVOIRE).

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KEY WORDS: sedimentation; resuspension; trade winds; waves; lagoon.

ABSTRACT

In shallow environments, under certain conditions of fetch, wind velocity, bathymetry and bottom characteristics, resuspension can be generated by wind induced waves. In the tropical Ebrié lagoon, austral trade winds are dominant almost all year long, and their velocity shows a marked diel pattern with maximum speed between noon and midnight. Only austral trade winds with a speed > 3 m s^{-1} allow particle resuspension which is effective for depths < 1.5 m. In these areas, significantly higher values of chlorophyll biomass and mineral seston are noted during the windy sequences. Granulometric and mineralogical analyses showed that only the surficial sediment (0-3 cm) was involved in resuspension. This process induces several effects: 1) an increase of the suspended matter concentration in the water and thus a light attenuation due to a higher turbidity, 2) a redistribution in the whole water column of nutrients from the pore water and 3) a removal of the finer fractions from the superficial sediment. On the contrary, for depths >1.5 m, particle sinking is permanent in depressions which are spontaneously transformed into anoxic systems. At the lagoon scale, sedimentation is significantly modified by wind induced resuspension. According to the bathymetry and the distance from a river, three sedimentary facies are recognized. Their grain size distributions are parabolic in areas where resuspension occurs, logarithmic in areas where no resuspension is possible and hyperbolic in the hollows and the main channels. Finally, a large part of the allochthonous inputs (from drainage and rivers) and autochthonous pelagic production is trapped into the Ebrié lagoon and less than *10% of the particles entering the lagoon are exported toward the Atlantic Ocean.*

INTRODUCTION

In shallow environments, resuspension can be generated by wind induced waves under certain conditions of fetch, wind velocity, bathymetry, and bottom characteristics (KENNISH, 1986; PRESS and SIEVER, 1986). This process is a major factor controlling the spatial and temporal distribution of particles (CARPER and BACHMANN, 1984; FLODERUS and PIHL, 1990; LUETTICH *et al.*, 1990). Resuspension can influence algal productivity (HELLSTRÖM, 1991) as well as the sedimentation process (BENGTSSON *et al.*, 1990). In the tropical Ebrié lagoon (average depth: 4.8 m), austral trade winds are dominant, and, in favorable conditions, they can induce sediment resuspension (ARFI *et al.*, 1993). A survey was conducted at a shallow water station in order to understand the impact of this process in the pelagic ecosystem. The aims of the present work were to analyze (1) the change of seston and chlorophyll biomass in the water column and (2) the modification of the sedimentary interface using granulometric and mineralogical analyses. The fate of the suspended materials and the sedimentary zonation related to the wind induced resuspension are also discussed at a lagoon scale.

MATERIAL AND METHODS

The study was conducted in a sampling site (5°20 N, 4°20 W; mean depth 1 m) located on the

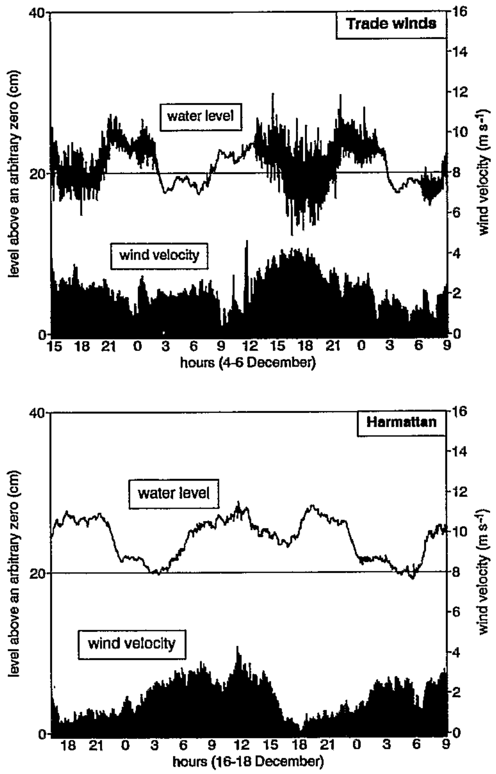

Fig. 1. Time series of wind velocity and water level during 3 days of an austral trade winds sequence and 3 days of a boreal trade winds (harmattan) sequence.

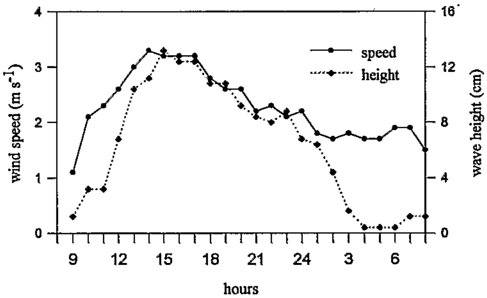

Fig. 2. Average diurnal pattern of hourly wind speed and wave height observed during the trade wind periods 4-15 and 19-26 December 1991.

north shore of the Ebrié lagoon (Côte d'Ivoire) in December 1991 (details in ARFI *et al.*, 1993). Location and geographical characteristics of study area and sampling site are reported in BOUVY *et al.* (1994). During 23 days, the wind velocity was integrated each minute and averaged over 5 min. Water level and wave height were obtained using a surface height gauge. The effective fetch was calculated according to CARPER and BACHMANN (1984) and estimated as 6800 m for the predominant southern winds. The minimum wind velocity needed to generate a wave action reaching the sediment at the sampling station was calculated according to DENMAN and GARGETT (1983) and DEMERS *et al.* (1987). Water samples were collected every 3 h using a peristaltic pump integrating from 10 cm below the surface to 10 cm above the bottom. Seston content was estimated by gravimetric determination and the mineral fraction was determined as loss on ignition. Chlorophyll biomass (corrected for phaeopigments) was measured by fluorometry after methanol extraction of pigments.

The suspended materials were sampled using traps deployed for 24 h and the mineral fractions were concentrated by acidification (pH 2.0). The organic fractions were destroyed using hydrogen peroxide with the dried samples.

At the sampling site, sediment was sampled manually with a PVC corer and frozen. Prior to their analysis, the frozen cores were cut into 3 cm thick slices. After lyophilization and decarbonatation, the organic fraction was destroyed with hydrogen peroxide. Granulometric analyses were performed on suspended and sedimented particles using a Sedigraph after these preliminary treatments. A qualitative study (nature of particles) was performed using X-ray analysis on total and <50 μm samples (Siemens 500 diffractometer, Cu anticathode). The mineralogical clay fractions were studied by X-ray analysis according to three processes (oriented slide, glycerol and heating tests).

RESULTS AND DISCUSSION

Wind and resuspension

During the study, three sequences were distinguished according to the wind direction: a period of trade winds (SW direction) from 4 to 15 December, a period of harmattan (NE direction) from 16 to 18 December and another period of trade winds (19-26 December). The trade wind periods were characterized by maximum wind speeds (>3 m s^{-1}) recorded between 14 and 17 h; after sunset, their velocity decreased slowly. At the station studied, there was sufficient fetch for these winds to generate waves, and the wave height varied according to the wind velocity (Fig. 1). A close link between the trade wind speed and the wave height

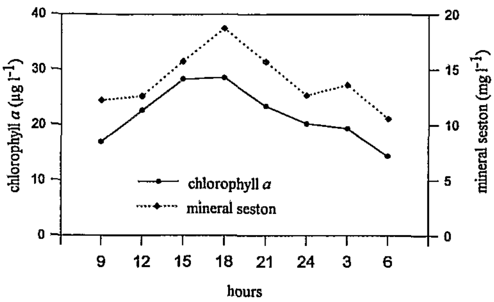

Fig. 3. Average diel cycle of chlorophyll *a* and seston concentrations observed during the trade wind periods 4-15 and 19-26 December 1991.

was observed, with marked diurnal patterns (Fig. 2). A marked increase of wave height (4 to 6 cm) was noted for wind speeds ranging from 1.5 to 3.5 m s^{-1}, and higher values (7-10 cm) were observed for wind velocity above 3.5 m s^{-1}. Due to the geographical configuration of the site, wind induced resuspension was possible only when the wind speed was above 3 m s^{-1}. During the harmattan period, no waves occurred in spite of a significant wind speed (Fig. 1), due to an insufficient fetch in the wind direction.

Effects of resuspension on seston and bed characteristics

A marked diel cycle closely associated with the wind speed variations was observed both for the mineral seston and chlorophyll biomass during the trade wind periods (Fig. 3). No such pattern was noted during the harmattan period. For both parameters, significant average differences (Student t-test after normality assessment) were observed according to wind velocity and direction. When the wave height was sufficient during the trade wind periods, the turbulence induced by winds enhanced the distribution of living and inert particles in the whole water column.

This periodic redistribution of phytoplankton into the euphotic layer induced by the physical forcing (minimum chlorophyll concentrations between 6 and 9 h, maximum between 15 and 18 h) is different from that observed in areas of the Ebrié lagoon not influenced by resuspension (fetch not effective and/or water column >3 m). In the latter case, the minimum chlorophyll concentrations were observed between midnight and 4 h, and the maximum between 10 and 14 h (TORRÉTON *et al.*, 1994). This discrepancy can be explained by variations of the phytoplankton abundance when physical control occurs, but can also be attributed to grazing processes in relation with the zooplankton photophobia. Other processes, such as variations of the cellular chlorophyll content, in relation with the diurnal light cycle might explain this phenomenon.

Suspended mineral particles were essentially clays (mainly kaolinite and illite) corresponding to the finest fractions from the surficial bed sediments (ARFI *et al.*, 1993). Owing to the wave action, these finest fractions were removed from the surficial bed sediment and distributed in the water column. However, some of the suspended particles had also an allochthonous origin (probably from the near-by Agnéby river) since vermiculite was present in the suspended assemblages but not in the bed sediment.

Only the surficial sediment (0-3 cm) was affected by the removal of the finest fractions. Below this level, the vertical heterogeneity of the sediment (granulometry, mineralogy) was conserved, indicating that erosion related to wind induced resuspension was rapidly attenuated. In the area studied, the alternation of diurnal resuspension and nocturnal sedimentation induced several effects: (1) an increase of suspended matter concentration in the water and thus a light attenuation due to a higher turbidity, (2) a distribution in the whole water column of nutrients from the interstitial water, and (3) a removal of the finest fractions from the sediment interface.

Modification of sedimentation by wind induced resuspension

At the scale of the Ebrié lagoon, the sedimentation is significantly modified by wind induced resuspension. The local bathymetry, the distance from a river (main source of suspended particles) and the eolian control (through the fetch related to the austral trade winds) are at the basis of the zonation of the Ebrié lagoon sediment. The characteristics of a given sedimentary facies are thus dependent on these 3 components of the sedimentary dynamic.

The riverine inputs and the shoreline run-off are essentially carrying clay and sand eroded from the high plateau on the north, sedimentary beach ridge on the south. Once entering the lagoon, these particles settle rapidly, either after discharge into low energy environments (in case of sands) or after flocculation (in case of clays). As a consequence of these processes, the river outfalls feature progradation areas, permanently reworked by the local hydrodynamics. These deposits contribute to the building of shoals or sand-banks, blocking the

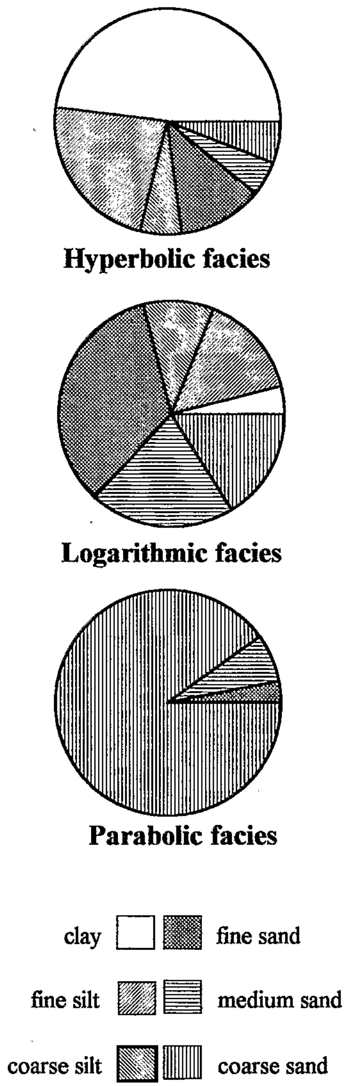

Fig. 4. Granulometric facies observed in different parts of the Ebrié lagoon: channels and hollows (hyperbolic), low energy areas (logarithmic) and areas under resuspension influence (parabolic).

channels or filling the shallow bays, the latter becoming progressively transformed in marsh lands and peat bogs (TASTET and GUIRAL, 1994). The shallow bay deposits are characterized by successions of thin layered beds, each featuring a different granulometry corresponding to alternations of coarse sand and clay-silt deposits.

In the hollows, generally located in the main channels, very fine clay muds (hyperbolic facies, average grain diameter <2 µm, Fig. 4), with a high proportion of organic matter are accumulated, thus creating anoxic environments. The deepest parts of the lagoon (>5 m) are then the ultimate catchment basins of the particles entering the lagoon, directly from the riverine inputs or indirectly, after several phases of settling and resuspension. Areas where particle settling is predominant (hollows) represent 57% of the lagoon surface. In these depressions, particles are no more reworked by hydrodynamics, explaining that less than 10% of particles entering the lagoon are exported toward the Atlantic Ocean (TASTET and GUIRAL, 1994).

In shallow areas not affected by wind induced waves (south shoreline of the Ebrié lagoon), the deposits are featuring the same sedimentary dynamics as in the deeper hollows, but the granulometry is different, with poor graded bedding (heterogeneous sediments, characterized by a logarithmic facies, Fig. 4). At the opposite, in shallow areas influenced by wind induced waves and resuspension (north shoreline of the lagoon), the sediments are permanently reworked, especially the finer fractions which are carried away by the local hydrodynamics. The beds are then characterized by an upward-coarsening graded bedding, with average particle diameters ranging from 40 µm to 2 mm (parabolic facies, Fig. 4). These sediments have generally a high porosity, and the water-bed interface is oxygenated.

Like most aquatic systems organized and structured by hydrodynamics, the Ebrié lagoon is physically controlled (GUIRAL, 1992). When the geographical configuration (depth and fetch conditions) and the bottom characteristics (sediment composition, bed roughness, particle size distribution) allow wind induced resuspension, this process is an important factor of the overall functioning of the ecosystem. More generally, resuspension must be considered as a major process controlling particle sedimentation, but also the ecological functioning of benthic and pelagic systems (HOPKINSON, 1985). In shallow areas, resuspension can be compared to an upwelling, by its generating mechanism (wind) as well as by its effects (enrichment of the surficial trophogenic layer by compounds from lower levels). But its consequences are different because the convection is accompanied by a significant increase of turbidity (HELLSTRÖM, 1991). Despite low wind velocity, further studies of ecosystems under solar wind influence have to be conducted in order to analyze the ecological changes induced by a wave driven resuspension and the community adaptation to this phenomenon.

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