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Wind Induced Resuspension in a Shallow Tropical Lagoon

R. Arfi, D. Guiral and M. Bouvy

Centre de Recherches Océanologiques-ORSTOM, BP V18 Abidjan,
Côte d'Ivoire

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In shallow environments, particle resuspension can induce large ecological effects. Under some certain conditions of fetch, wind velocity, bathymetry and bed roughness, resuspension is generated by wind induced waves. During December 1991, a shallow station (1 m depth) in the north shore of a tropical lagoon (Côte d'Ivoire) was investigated in order to study the impact of wind induced resuspension on the ecosystem. In this area, Austral Trade winds are dominant almost all year long, and their velocity shows a marked diel pattern. During the survey, three sequences were distinguished: a period of Austral Trade winds (with possible resuspension), a period of Boreal Trade winds (no wind induced waves at the station) and a period of transitional Trade winds. Only Austral Trade winds with a speed $>3\ \mathrm{m\ s^{-1}}$ allowed particle resuspension. For chlorophyll, mineral seston and ammonia, significantly higher values were noted during the windy sequences. Conductivity and water colour varied in relation to tides. Granulometric and mineralogical analyses showed that only the 0–3 cm superficial level of the sediment was involved in resuspension. This process 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 pore water, (3) a modification of the sediment granulometric characteristics and (4) an increase in the food available for planktonic filter feeders since algal cells were periodically resuspended in the whole water column. Wind induced resuspension occurred in 10% of the Ebrié lagoon. In this area, the daily alternate of resuspension–sedimentation sequence is then a major factor controlling the productivity of a system which is potentially highly productive (high nutrient load, favourable climatic conditions) yet characterized by high turbidity. These observations can be generalized to comparable systems in the tropical area.

Introduction

Once sedimented, living or inert particles are considered as lost from the pelagic ecosystem. However, resuspension generated by tidal currents or by wind induced waves can, to some extent, balance the sedimentation process. The tidal currents are linked to the neap-spring cycle. Their effects on the sediment are strongly influenced by the bathymetry and the bed roughness lengthscale. Wave effects are also related to these factors, but they depend additionally on the wave height and the wave period which are directly linked to the fetch and the wind velocity.

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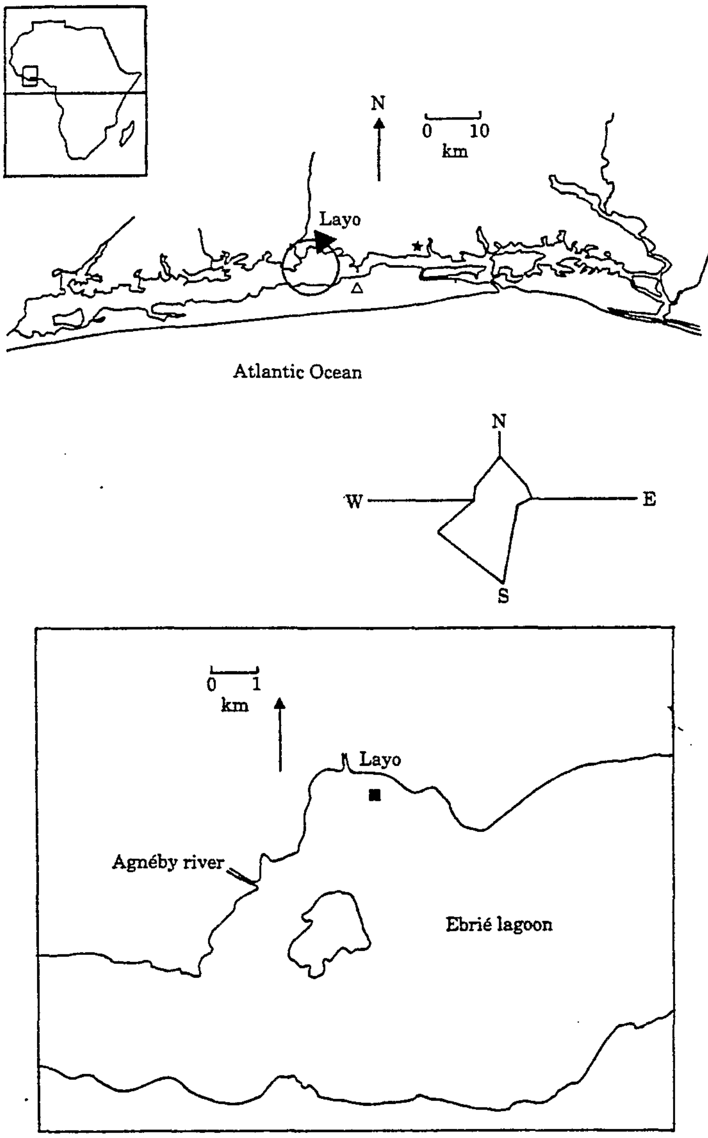

Figure 1. Map of the Ebrié lagoon showing the location of the sampling station and the Jacqueville dike (△), the yearly wind direction pattern recorded at Adiopodoumé weather station (*) and an enlargement of Layo area.

the biological impact of the turbulent mixing on phytoplankton through the nutrient availability and the chlorophyll biomass and (ii) the impact of resuspension on the water-sediment interface by a comparison of the characteristics of sedimented and suspended mineral particles.

Material and methods

The sampling site (mean depth 1 m) is located 400 m offshore from the Layo Aquaculture Station (5°20′N, 4°20′W), on the north shore of the Ebrié lagoon and near the mouth of a

TABLE 1. Symbols and abbreviations used in equations (1)–(4)

Symbol	Unit or value	
h	m	station depth
L	m	wavelength
H	m	wave height
T	s	wave period
w	s^{-1}	wave frequency
k	m^{-1}	wave number
g	$9{\cdot}81\ m\ s^{-2}$	gravitational constant
U	$m\ s^{-1}$	wind speed
F	m	effective fetch
N^2	s^{-2}	Brunt–Väisäla frequency
r_w	$1{\cdot}025\ 10^3\ kg\ m^{-3}$	water density
r_a	$1{\cdot}2\ kg\ m^{-3}$	air density
C_{10}	$1{\cdot}3\ 10^3$	drag coefficient
K_w	$4\ 10^2$	wind coefficient
$\delta^0{}_w/\delta z$		vertical density gradient in z metres
n	$0{\cdot}01\ cm^2\ s^{-1}$	kinematic viscosity of water

(CERC, 1977) using the half wavelength method. Wavelength in deep open water is related to its period following the equation:

$$L = gT^2/2\pi \tag{1}$$

Assuming that the wind has a constant velocity over one hour, T is related to wind speed (U) and a given fetch (F) following the empirical equation:

$$gT/2\pi U = 1{\cdot}20 \tanh(0{\cdot}077(gF/U^2)^{0{\cdot}25}) \tag{2}$$

From L, the depth reached by the minimal movement ($h = L/2$) is calculated. This model was used by Carper and Bachmann (1984), Shideler (1984) and Simon (1989) in shallow water of lacustrine and estuarine systems. (b) the second one was proposed by Demers *et al.* (1987), using the turbulent kinetic energy (TKE) and the Brunt–Väisäla frequency (N^2) related to overturning eddies. The minimum wind speed inducing vertical turbulence in the water column is calculated from:

$$U_{min} = hN[(r_w 10^{-2})/(r_a C_{10} K_w)]^{0{\cdot}33} \tag{3}$$

where N^2 is the Brunt–Väisäla frequency,

$$(g/r_w)(\delta r_w/\delta z) \tag{4}$$

Complementary details on that method can be found in Denman and Gargett (1983). Data necessary to calculate the water density (temperature and conductivity in the water column every 10 cm between surface and bottom) were measured on several occasions during the survey.

From the wave characteristics (wave height, periodicity and wavelength) in a well established wind situation (wind speed $> 3\ m\ s^{-1}$), the bottom stress associated with the waves (t_{wave}) was estimated from the relation proposed by Luettich *et al.* (1990) for smooth turbulent flow:

$$t_{wave} = Hr_w(nw^3)^{0{\cdot}5}/2\sinh(kh) \tag{5}$$

TABLE 2. Percentage of wind direction occurrences at Adiopodoumé weather station in December 1991

	Harmattan	East winds	Trade winds	West winds
		%		
Whole sequence	29	9	54	8
4–15 December	9	11	74	6
16–19 December	93	0	7	0
20–26 December	36	0	48	16

Results and discussion

Winds in the Ebrié lagoon

In this coastal area of West Africa, winds are usually weak and regular (Monteny, 1984). In an average year, South–West Trade winds (Austral Trade winds deviated at the Equator) are predominant between March and November. Their velocity decreases inland from the coastline, and on the north bank of the lagoon, they can be compared to solar winds, characterized by a marked diel pattern (Durand & Guiral, 1992). From December to February, North–Eastern winds (Boreal Trade winds, 'Harmattan') are predominant, with a marked interannual variability of intensity and southern extent. At the beginning of the Harmattan period, alternation of Trade winds and North wind sequences is often observed.

Winds in Layo area during December 1991

During the study, three sequences were distinguished according to the prevailing wind direction (Table 2): a period of Trade winds from 4–15 December, a period of Harmattan from 16–19 December, a transitional Trade winds period from 20–26 December, characterized by winds oriented more West and North than during the first sequence.

The periodogram of the Trade wind velocity time series (4–15 December) showed a marked periodicity [24·4 h, Figure 2(a)]. This diel pattern was also observed for the transitional Trade winds, whereas an opposite pattern characterized the Harmattan period [Figure 2(b)]:

—on an average day, the hourly mean of Trade winds' speed was minimum (1 m s^{-1}) between 8 and 9 am, and increased until 2 pm. Maximum values were recorded between 2 and 5 pm (>3 m s^{-1}). After sunset, wind velocity decreased slowly until midnight and values were close to 2 m s^{-1} between 1 and 7 am. Once established, these winds blew regularly from the south. But at the end of the night and before sunrise, a rotation of the wind direction to the west was often observed.

—the mean diel pattern during the Harmattan sequence featured minimum speeds after sunset (around 1 m s^{-1} between 6 and 11 pm), an increase during the night, and high values after sunrise (maximum of 3 m s^{-1} around 8 am). During the day, wind velocity fluctuated between 1·8 and 2·2 m s^{-1}. Wind direction was steady and orientated from the North all day long.

Wind induced waves

In this environment where tides play a limited role in turbulence generation (very slow tidal currents), the wind is the main factor setting up vertical circulation. Owing to the geographical configuration of the Layo site, a sufficient fetch is only possible for south and

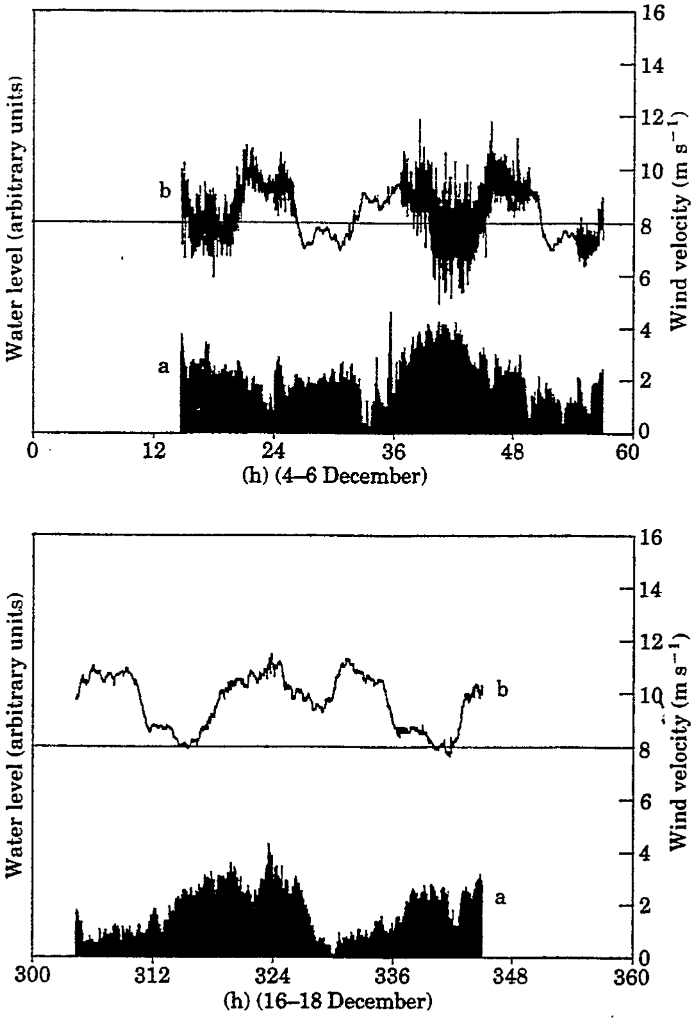

Figure 3. Time series of wind velocity (a) and water level (b, combining tide and wavelet effects, in arbitrary units from a theoretical basic line) from 4–6 December (Trade winds) and 16–18 December (Harmattan).

after the wind speed had increased and (2) after 2 am, the waves disappeared completely in spite of a significant wind speed. Lags observed on the Trade winds hourly pattern between the wind speed and wave heights might be due to wind difference. Flat water sequences were clearly related to a reorientation of the winds at the end of the night: a rotation to the west direction (winds blowing from 230 to 300°) with a comparable wind velocity was enough to break down the wavelet effect, since the fetch was then considerably reduced. In the morning, the winds rotated back to the south direction (180 to 225°), allowing an increase of the effective fetch and thus production of waves.

The relation between south to south-west wind speed and wave height based on successive thresholds. For wind velocity $<1{\cdot}5\,\mathrm{m\,s^{-1}}$, wave heights were low (estimates <2 cm); a significant increase was observed for wind speeds between $1{\cdot}5$ and $3{\cdot}5\,\mathrm{m\,s^{-1}}$

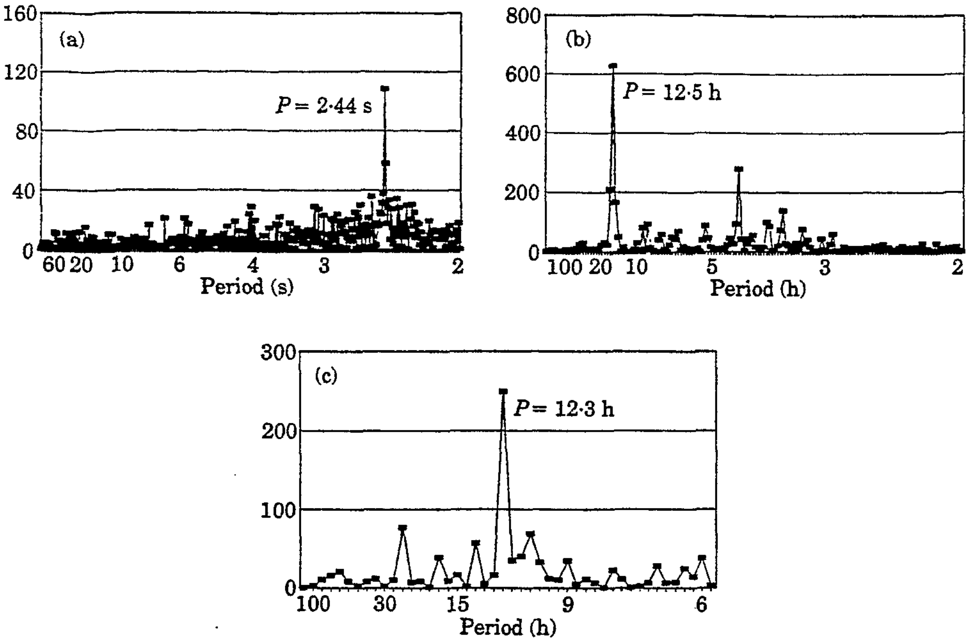

Figure 6. Periodograms of (a) part of the wave height time series ($n = 720$, time lag 1 s), (b) the water level time series ($n = 300$, time lag 1 h) and (c) the conductivity series ($n = 92$, time lag 3 h) recorded during the Trade winds period.

TABLE 3. Statistical values for the hydrological descriptors

	Cond. mS cm^{-1}	Colour abs.	Chl. mg m^{-3}	SiO_3-Si µM	PO_4-P µM	NO_3-N µM	NH_4-N µM	Seston mg l^{-1}
Whole time series								
average	3·91	0·08	20·2	115·1	0·8	3·0	4·4	12·1
SD	1·00	0·06	8·5	32·5	0·4	2·7	3·8	5·2
CV (%)	25	74	42	28	49	88	87	43
minimum	2·36	0·04	5·6	8·1	0·1	0·5	0·5	3·3
maximum	6·16	0·81	47·9	158·1	3·1	15·2	24·5	45·0

Cond.: conductivity; Chl.: chlorophyll biomass.

Hydrological characteristics at the sampling station

Table 3 summarizes the statistics of hydrological parameters. All the time series were characterized by a high frequency variability, which originated from two processes, tide effects and wind induced waves. The conservative variables (conductivity, water colour) were influenced only by tidal effects, while non-conservative parameters (nutrients, pigment biomass and mineral seston) were mainly influenced by wind effects.

Tide effects

The experiment was conducted at the end of the rainy season when the water in Layo area was least saline (mean conductivity: 3·91 mS cm^{-1}, SD: 1·00 mS cm^{-1}). At this time of

TABLE 4. Results of Student *t*-test performed on data sampled during the Trade winds and Harmattan periods, comparing calm and windy sequences

H_0: equality of means	Trade wind period	Harmattan period
Descriptors	H_0 ( ) significance	H_0 ( ) significance
wind velocity	rejected ($<0·001$)	accepted
conductivity	accepted	accepted
water colour	accepted	accepted
chlorophyll	rejected ($<0·001$)	accepted
ammonia	rejected ($<0·001$)	accepted
silicate	accepted	accepted
phosphate	accepted	accepted
nitrate	accepted	accepted
seston	rejected ($<0·01$)	accepted

H_0: mean equality.

TABLE 5. Granulometric characteristics (percentage by weight) of the mineral fraction (sediment and suspended particles)

Samples/sediment	Clay	Silt	Coarse silt	Fine sand	Coarse sand
to −3 cm	16·4	4·7	18·0	32·5	28·2
−3 to −6 cm	15·3	2·4	4·7	18·9	58·7
−6 to −9 cm	15·5	3·2	4·1	15·1	62·2
−9 to −12 cm	23·5	19·2	10·7	40·5	6·0
−12 to −15 cm	18·9	18·4	14·3	47·1	1·2

Suspensions	Clay	Fine silt	Coase silt	Sand (fine and coarse)
S1	55·4	25·4	13·2	6.3
S2	67·5	24·7	2·8	4·9
S3	58·1	24·7	12·4	4·8

nutrients showed more important fluctuations in spring tide situations. The enhancement of hydrodynamism in the area allowed a rapid succession of nutrient-rich and nutrient-poor waters (independently of their conductivity); this phenomenon was probably related to biological processes of nutrient uptake and excretion.

Suspended and sedimented particles

The sampling station was located close to the mouth of the Agnéby river and near-shore. At this site, the sediments were characterized by the superposition of two distinct sedimentological assemblages: between 0 and −9 cm, a level of coarse sand made of fluviatile quartz, muscovite and geothite iron hydroxide pseudo-oolithes (Tables 5 and 6); from −9 cm and over, a marked transition to a fine sand layer made of quartz and muscovite, while the geothite pseudo-oolithes were not observed.

In the whole core, clays were not abundant. Kaolinite and illite were present over the whole core and smectite was only observed in levels under 6 cm (Table 6).

movement to reach the bed was calculated for different water levels. It was estimated to be 2·1 m s^{-1} for the neap tide (h = 1 m), 1·8 m s^{-1} for the spring tide, low tide, and 2·5 m s^{-1} for the spring tide, high tide. In these situations, the wavelet periods would be respectively 1·1, 1·0 and 1·2 s.

On some occasions during the Trade winds sequence, the TKE method was tested. From relations (3) and (4), at the sampling station depth and for an average environmental situation at noon (conductivity around 3 mS cm^{-1}, water temperature close to 32° C, reduced vertical density gradient), the minimum wind velocity required to induce a sediment resuspension was also calculated. It was estimated to be 2·6 m s^{-1} for the neap tide, 2·3 m s^{-1} for the spring tide, low tide, and 2·8 m s^{-1} for the spring tide, high tide.

The two methods give similar values for the minimum wind velocity necessary to allow the oscillatory movement to reach the sediment. For these wind velocities, typical wave heights were between 6 and 8 cm (Figure 4). The bottom stress induced by the waves associated with these values was estimated as 0·2–0·3 dyn cm^{-2} using the relation (5). A higher shear stress was probably necessary in order to initiate a turbulence near the bed, and to resuspend the sediment. The wind speed threshold for resuspension seemed to be >3 m s^{-1} (period: 1·4 s, wavelength: 3 m, wave height comprised between 10 and 12 cm, bottom stress $>0{\cdot}5$ dyn cm^{-2}). During the survey, such velocities were observed every day of the Trade winds sequence between 2 and 5 pm.

In spite of a poor knowledge of lagoon bathymetry, the area likely to be affected by sediment resuspension was estimated by using a planimeter to be 10% of the Ebrié lagoon surface, and 15% of the surface of the lagoon situated west of Abidjan.

Conclusions

During the sequence characterized by Trade winds, the day was divided in two roughly equal periods, with (between noon and midnight) and without (between midnight and noon) waves. During the calm period, sedimentation was enhanced, and particles entering the water column (lateral inputs, new algal production, fecal pellets) sedimented more or less rapidly according to their weight and shape. In that shallow environment, typical sinking rates for living and inert particles proposed in the literature (0·1–1 m h^{-1}, Lännergren, 1979; Bienfang, 1980; Burns & Rosa, 1980) allowed the seston to reach the bottom in few hours. During the windy period of the day, wave induced resuspension was certainly possible between 2 and 5 pm. But this process which occurs over at least a 10 month period each year can be the main physical factor structuring the pelagic ecosystem in this part of the Ebrié lagoon. This phenomenon induces resuspension of sedimented particles with several consequences:

(a) A periodic redistribution of phytoplankton into the euphotic layer. The diel pattern induced by the physical forcing (minimum chlorophyll concentrations between 6 and 9 am, maximum between 3 and 6 pm) is different than that observed in area of the Ebrié lagoon not concerned by resuspension (fetch not effective, deepest water column). In this case, the minimum chlorophyll concentrations were observed between 12 pm and 4 am, and the maximum between 10 am and 2 pm (Torréton, 1991). This discrepancy can be explained by cell number variations when physical control occurs. In case of biological control, this difference may be related to the grazing processes in relation to the zooplankton vertical migration. Alternatively, it may be based on variations of the cellular chlorophyll content, in relation to the light diurnal cycle.

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