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Sedimentation of Particulate Matter in the South-west Lagoon of New Caledonia: Spatial and Temporal Patterns

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Suspended and sedimented particulate materials were assessed monthly at five sites on the south-west lagoon of New Caledonia, from May 1986 to April 1987. Sedimentation of particulate matter was measured using sediment traps for 24 h. Resuspension, which accounted for more than 80% of the total sedimentation, was distinguished to calculate net sedimentation values. The mean net sedimentation rate for the lagoon varied according to the site from 0·481 to 1·157 $g\,C\,m^{-2}\,day^{-1}$ with a general mean value of 0·756 $g\,C\,m^{-2}\,day^{-1}$. An increasing gradient from the reef to the shore stations was observed for both suspended and sedimented particles. The standing stocks and the fluxes of suspended particles were maximal in February, during the warm season associated with maximal rainfall, and minimal in August. The high C/N ratio in sedimented material (26) compared to suspended particles (11) indicated that organic matter degradation had occurred preferentially in the water column. The mean particulate organic carbon flux was about twice the lagoon pelagic primary production; sedimented plant material only accounted for a small part of the organic carbon flux. The major source of sedimented organic carbon was therefore allochthonous and derived both from the reef and the shore. The latter seemed to predominate. Relative uncoupling between benthos and pelagos is suggested.

Introduction

The south-west lagoon of New Caledonia covers an area of 2066 km^2, 5% of which is occupied by reef structures. The great extent of sediments in this region has led us to focus our interest on soft bottoms (Chardy & Clavier, 1988a; Chardy *et al.*, 1988; Boucher & Clavier, 1990; Boucher *et al.*, 1994). The main purposes of our studies are to obtain a comprehensive view of the functional ecology of the benthos and to evaluate its contribution to the energy budget of the entire lagoon. An initial attempt to estimate the carbon flows in the south-west lagoon of New Caledonia was made by Chardy and Clavier (1988b).

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TABLE 1. Main characteristics of the study sites

Station	Name	Depth (m)	% Mud	Bottom type
1	Maa bay	12	50	Mud deposits
2	Station côtière	28	45	Mud deposits
3	Rocher à la Voile	11	7	Grey sand bottoms
4	Larégnère	16	10	Grey sand bottoms
5	Mbere reef	12	5	White sand bottoms

% Mud is the percentage of particles <63 μm. Bottom types are defined by Chardy *et al.* (1988).

Particulate organic matter which originates from seston is, with photo- or chemo-lithotrophic production within the sediment, the major source of organic carbon input to benthic organisms in shallow coastal waters (Smetacek, 1984; Hansen *et al.*, 1992). The quantitative evaluation of the organic matter flux is therefore a prerequisite for the establishment of a carbon flow scheme in an ecosystem (Hartwig, 1976; Taguchi, 1982). Moreover, in low-nutrient environments, re-mineralization of organic input to the sediment is an important pathway of recycling (Kinsey, 1985) and sedimentation of organic matter at the water–sediment interface is one of the factors that governs rates of nutrient regeneration from sediments (Koop & Larkum, 1987). Sedimentation of organic matter to the sea-bed is, therefore, likely to be a fundamental factor influencing benthic community structure, biomass and metabolism (Mills, 1975; Jørgensen, 1983; Smith, 1987; Grebmeier & McRoy, 1989). In the present paper we examine the distribution and fluxes of total and organic particulate matter in the south-west New Caledonia lagoon to define spatial and temporal patterns of the process and to give a first insight into the origin of particles.

Materials and methods

Suspended and sedimented materials were studied monthly from May 1986 to April 1987. Five permanent sampling stations were located in the three bottom types previously recognized in the lagoon: mud deposits, grey sand bottoms and white sand bottoms which occupy 35, 50 and 15% of the lagoon area, respectively (Chardy *et al.*, 1988) and exhibit distinct functional characteristics (Boucher & Clavier, 1990; Figure 1, Table 1). Mean tidal current velocity in the south-west lagoon of New Caledonia is about 5–10 cm s^{-1} (Jarrige *et al.*, 1975; Douillet *et al.*, 1989). Theoretical considerations and field assessments (Gardner, 1980*a*,*b*; Blomquist & Kofoed, 1981) have shown that cylindrical traps with a width height ratio >3 may collect sinking material accurately, for velocity flows up to 15 cm s^{-1}. Furthermore, cylinder diameter must be large enough to avoid the differential sedimentation of particles by flow separation around the trap (Hargrave & Burns, 1979). A minimal trap diameter of 4·5 cm was recommended by Blomquist and Kofoed (1981). Sedimented particles were collected in PVC cylinders (16 × 50 cm; *c.* 10 l)fastened 2 m above the substratum on an anchored rope held vertically by a subsurface float. Sediment traps were left for 24-h periods only to minimize decomposition effects (Taguchi, 1982; Koop & Larkum, 1987). The traps were implanted and retrieved by SCUBA diving.

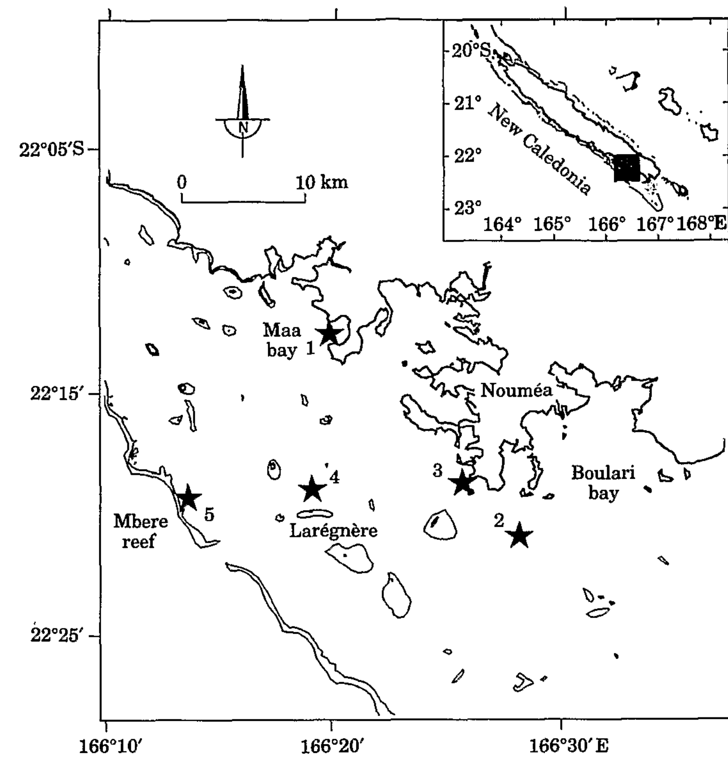

Figure 1. Location of sampling stations in the south-west lagoon of New Caledonia.

The collected material was resuspended in the water content of the trap. This suspension was kept homogeneous by agitation and subsamples were taken for various analyses. Total particulate material (TPM) was filtered onto pre-ashed glass-fibre filters (Whatman GF/C) of known weight. The material was washed with demineralized water to remove salts and dried at 60 °C for 48 h before weighing. The particulate inorganic matter (PIM) was then determined by weight loss on ignition at 550 °C for 2 h. The ash-free dry weight was calculated by difference between TPM and PIM. We assumed that ignition loss was equal to the particulate organic matter (POM). The carbonate content of the samples was estimated by weight difference after HCl fume treatment to remove inorganic carbon. Particulate organic carbon (POC) and nitrogen (PON) were determined with a CHN analyser (Hewlett-Packard 185B) on pre-combusted Whatman GF/C filters and carbon values were amended according to the carbonate content of samples. Plant pigments were extracted in 90% acetone after ultrasonic extraction (Parsons, 1966). Chlorophyll *a* and pheopigments were measured on a fluorometer. A similar set of analyses were applied to the suspended particulate matter collected by a diver 1 m below the sea surface. Samples were taken at the onset of sediment trap experiments.

In shallow waters, setting sediment traps 2 m above the bottom does not avoid resuspended material collection (Taguchi & Hargrave, 1978). A ratio method, taking chemical compositions of particulate materials in the water column, in the trap and in the sediment into account was used (Gasith, 1975). The concentration of any chemical compound in the trapped material can be expressed as a function of its value in the sediment and its value in the suspended material: $Ct = XCs + (1 - X)Cr$, where X is the proportion of sedimented material in the trap and Ct, Cs and Cr are, the chemical composition of the material from the trap, the water column and the bottom sediment (upper 1 cm), respectively. POM was used as the basis for computation in the present study as in Gasith's (1975) original method and Taguchi's (1982) Kaneohe Bay, Hawaii, study.

Temporal and spatial fluctuations were assessed by two-way analysis of variance (ANOVA) with month and site as fixed factors, after verification of data homogeneity of variances (Hartley, 1962). When the homogeneity hypothesis was rejected by ANOVA, Newman & Keuls *a posteriori* multiple-comparison tests were used to separate possible sets of homogeneous means.

Results

Suspended particulate matter

The amount of suspended particles is relevant to sedimented material characteristics and composition. In coastal waters, suspended materials are subjected to short-term variations, such as diurnal and tide-related ones (Boto & Bunt, 1981; Youakim & Reiswig, 1984). Superposition of these variations on long-term, large-scale relationships, causes variability in our data because of the relatively loose timing of our sampling design. Thus, only general trends will be considered here.

Mean values for eight parameters are presented in Table 2. Overall station values differed significantly for any variable (ANOVA, $P<0{\cdot}001$). Station 4 and 5 values were the lowest for almost any parameter. They are very close overall and only differed for PON and chlorophyll *a* (Newman & Keuls tests, Table 3). These stations are located in the middle part of the lagoon and near the reef, respectively (Figure 1). Pheopigments were lower in station 2 but did not differ significantly (Newman & Keuls tests). On the contrary, stations 1 and 3, located close to the coast, were the richest. Station 1, situated in a bay, always exhibited the highest values except for pheopigments and total pigments. Station 2 values were generally intermediate. These results revealed a suspended material gradient from the shore to the barrier reef, coastal stations being the richest.

Temporal changes of six parameters are shown in Figure 2. Chlorophyll *a* and pheopigment patterns were similar to total pigment evolution and they are not represented. Overall monthly mean values for any parameter differed significantly (ANOVA, $P<0{\cdot}001$). As with spatial distribution, Newman & Keuls tests allowed a more accurate analysis of the data to be made (Table 4). Three main periods were defined: suspended material concentrations were minimal from July to October, intermediate in November, December and January, and maximal from February to June. This general pattern, which is more or less apparent depending on the parameter taken into account, suggests the existence of an annual cycle in suspended material concentration illustrated by the monthly evolution of plant pigments (Figure 2).

The mean organic matter percentage in total suspended material was 59·6% for all samples. This value was relatively high compared to the organic material content of the first centimetre of sediment (4·1%). The C/N ratio (weight) mean value was 11 and remained fairly constant for the five sampling sites. The mean percentage of pheopigments, corresponding to chlorophyll degradation, in the total pigments was 18%. This value increased slightly from the coastal bay (13%) to the reef (21%) stations.

TABLE 2. Mean (SD) values of parameters for suspended (mg m^{-3}) and net sedimented (mg m^{-2} day^{-1}) materials

	Station 1	Station 2	Station 3	Station 4	Station 5	Lagoon
Suspended material						
TPM	1368 (124)	1096 (62)	1346 (91)	880 (56)	882 (82)	1114 (63)
POM	717 (46)	684 (28)	657 (34)	602 (35)	581 (33)	648 (26)
PIM	651 (96)	412 (44)	689 (81)	278 (32)	301 (59)	466 (48)
POC	268 (14)	225 (30)	238 (20)	191 (11)	190 (17)	222 (19)
PON	25 (1)	22 (1)	22 (1)	21 (1)	17 (2)	21 (1)
PP	0·693 (0·057)	0·446 (0·028)	0·713 (0·077)	0·430 (0·026)	0·395 (0·036)	0·535 (0·035)
Chl*a*	0·602 (0·052)	0·371 (0·031)	0·575 (0·063)	0·352 (0·026)	0·310 (0·036)	0·442 (0·032)
Pheo	0·091 (0·011)	0·075 (0·001)	0·138 (0·027)	0·078 (0·012)	0·085 (0·012)	0·093 (0·011)
Net sedimentation						
TPM	3317 (332)	4022 (446)	3114 (267)	2003 (188)	2602 (423)	3011 (155)
POM	1905 (191)	2597 (288)	1850 (158)	1413 (133)	1799 (292)	1912 (108)
PIM	1412 (142)	1425 (158)	1264 (108)	590 (56)	803 (131)	1099 (56)
POC	936 (82)	1157 (114)	611 (33)	481 (27)	595 (87)	756 (35)
PON	35 (2)	38 (3)	32 (7)	20 (1)	23 (2)	30 (1)
PP	0·894 (0·074)	1·417 (0·185)	0·775 (0·086)	0·635 (0·107)	0·424 (0·052)	0·829 (0·050)
Chl*a*	0·457 (0·042)	0·622 (0·079)	0·348 (0·037)	0·260 (0·30)	0·205 (0·020)	0·378 (0·021)
Pheo	0·437 (0·040)	0·795 (0·111)	0·427 (0·055)	0·375 (0·082)	0·219 (0·037)	0·451 (0·032)

TPM, Total particulate matter; POM, particulate organic matter; PIM, particulate inorganic matter; POC, particulate organic carbon; PON, particulate organic nitrogen; PP, plant pigments; Chl*a*, chlorophyll *a*; Pheo, pheopigments.

TABLE 3. Classification of sampling station means for suspended and sedimented particles

	Suspended material					Sedimented material				
TPM	4	5	2	3	1	4	5	3	1	2
POM	5	4	3	2	1	4	5	3	1	2
PIM	4	5	2	3	1	4	5	3	1	2
POC	5	4	2	3	1	4	5	3	1	2
PON	5	4	3	2	1	4	5	3	1	2
PP	5	4	2	1	3	5	4	3	1	2
Chl*a*	5	4	2	3	1	5	4	3	1	2
Pheo	2	4	5	1	3	5	4	3	1	2

Newman & Keuls test, $P<0{\cdot}05$.
Mean values increase from left to right. Figures jointly underlined indicate no significant difference. For abbreviations see Table 2.

Sedimented particulate matter

Results of 24-h sediment trap experiments were less influenced by short-term variations than suspended particle data. Mean values for the five sampling stations are summarized in Table 2. These results correspond to the net sedimentation calculated after deduction of resuspended trapped material. The null hypothesis of mean global homogeneity must be rejected in any case (ANOVA, $P<0{\cdot}001$). As for suspended material, Newman & Keuls tests allow a more refined analysis to be made (Table 3). Station hierarchy (2, 1, 3, 5 and 4 in decreasing rank) is apparent, with lowest sedimentation rates near the barrier reef. Only photosynthetic pigments were more abundant in station 4 than in station 5. Station gradings according to suspended and sedimented particles were roughly similar except for the deepest station (no. 2) at which sedimentation rates were always the highest.

Temporal changes in the main parameters (Figure 3) support the existence of an annual cycle of sedimentation. The null hypothesis of mean monthly value homogeneity must be rejected (ANOVA, $P<0{\cdot}001$). Newman & Keuls tests (Table 4) allow three main periods to be distinguished: high sedimentation from February to June, medium sedimentation in November, December and January, and low sedimentation from July to October. General maxima were observed in February and minima in August. This sequence coincides with the temporal changes in suspended materials.

Resuspension mostly concerns mineral matter because of the low organic matter content in sediments. At each station, more than 80% of the total sedimentation was linked to deposition of resuspended benthic material. This feature was particularly conspicuous for the two muddy substrate stations (1 and 2) with a 90% rate. Organic material resuspension was lower and also mostly involved muddy bottoms (20–30% of sedimented organic matter). Other bottom types were less affected by the process (10% of sedimented organic matter). In the New Caledonian lagoon, mean current velocity was 5–10 cm s^{-1} during calm weather conditions. This value increased two-fold when trade winds occur (Douillet *et al.*, 1989). In New Caledonia, trade winds coming from the South-east are a major feature: the mean number of days when the wind is blowing over 20 knots is 275 each year. We tried to correlate mean resuspension rates with wind speed. The best relationship was found with the average wind speed during the couple of days preceding our sampling ($r=0{\cdot}75$, d.f.$=10$, $P<0{\cdot}01$). This result supports the wind-driven resuspension process of bottom sediments in the lagoon.

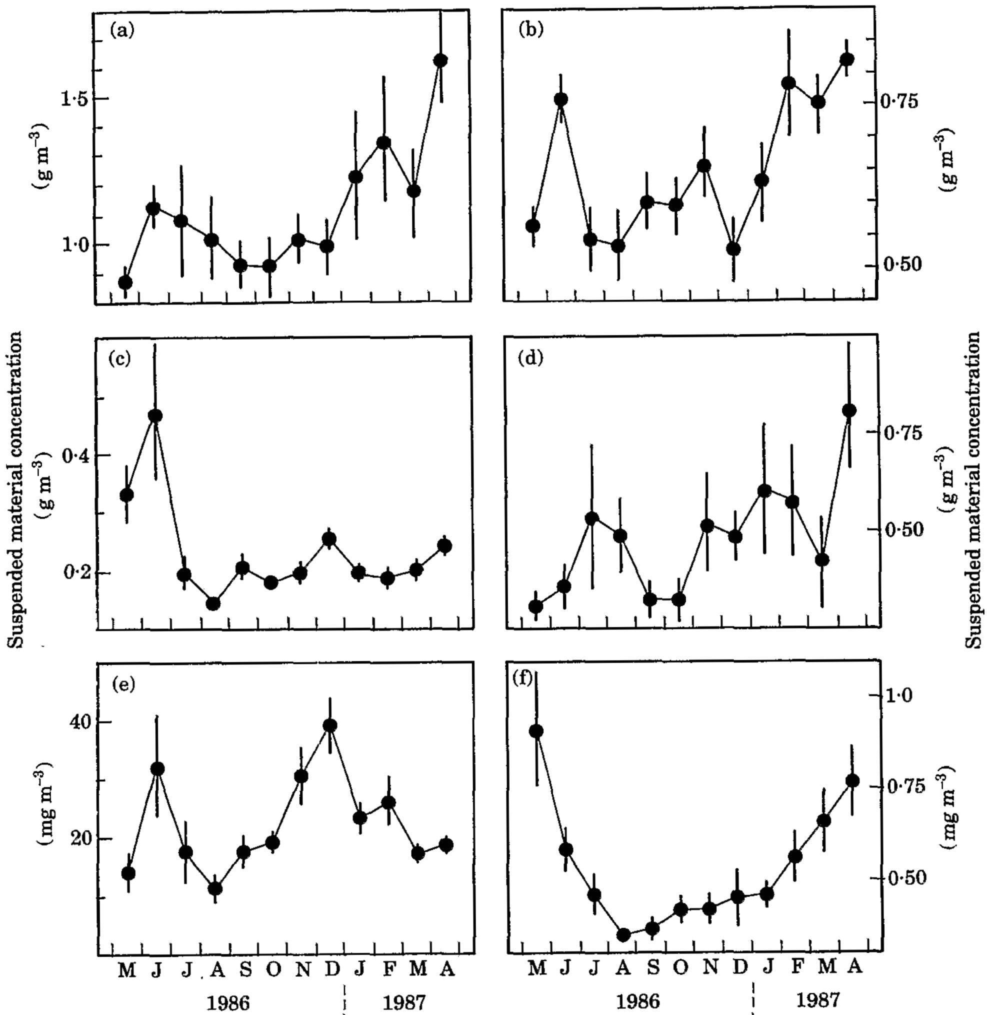

Figure 2. Monthly evolution of mean (a) total particulate matter (TPM), (b) particulate organic matter (POM), (c) particulate organic carbon (POC), (d) particulate inorganic matter (PIM), (e) particulate organic nitrogen (PON) and (f) plant pigment (PP) values in suspended material. Vertical bars correspond to the standard errors.

The carbonate percentage in trapped material was relatively low in the sheltered near-shore station (59%: station 1) and high near the reef (83%: station 5) with medium values (*c.* 75%) in intermediate stations. C/N ratios ranged from 19 to 30 according to the sampling sites, with a mean of 26. These values were higher than suspended particle ratios. The sedimented material percentage (sedimented material per m^2 *vs.* overlying water particle content) was roughly 20% for organic and mineral materials (Table 5). This percentage was about half for PON and plant pigments. The mean pheopigment percentage in total sedimented plant material was relatively high (54%).

TABLE 4. Classification of mean monthly values for suspended and sedimented particles

	Suspended material												Sedimented material											
TPM	May	Oct	Sep	Dec	Aug	Nov	Jul	Jun	Mar	Jan	Feb	Apr	Oct	Jul	Aug	Sep	Jan	Nov	Dec	May	Mar	Apr	Jun	Feb
POM	Dec	Aug	Jul	May	Oct	Sep	Jan	Nov	Mar	Jun	Feb	Apr	Oct	Jul	Aug	Sep	Jan	Nov	Dec	May	Mar	Apr	Jun	Feb
PIM	May	Oct	Sep	Jun	Mar	Dec	Aug	Nov	Jul	Feb	Jan	Apr	Oct	Jul	Aug	Sep	Jan	Nov	Dec	May	Mar	Apr	Jun	Feb
POC	Aug	Oct	Feb	Jul	Jan	Nov	Mar	Sep	Apr	Dec	May	Jun	Oct	Aug	Jan	Sep	Nov	Dec	Jul	Apr	May	Mar	Jun	Feb
PON	Aug	May	Mar	Jul	Sep	Apr	Oct	Jan	Feb	Nov	Jun	Dec	Sep	Oct	Dec	Aug	Jul	Jan	Nov	Jun	May	Mar	Apr	Feb
PP	Aug	Sep	Oct	Nov	Dec	Jan	Jul	Feb	Jun	Mar	Apr	May	Aug	Jul	Sep	Dec	Oct	Jan	Apr	Feb	Nov	May	Jun	Mar
Chl*a*	Aug	Nov	Sep	Dec	Oct	Jan	Jul	Feb	Jun	Mar	Apr	May	Aug	Jul	Sep	Dec	Apr	Jan	Oct	May	Nov	Feb	Jun	Mar
Pheo	Jul	Sep	Oct	May	Jan	Aug	Dec	Nov	Feb	Mar	Jun	Apr	Aug	Oct	Jul	Dec	Sep	Jan	Apr	Feb	Jun	Mar	Nov	May
Σ ranks	33	35	36	40	46	49	54	59	61	65	67	80	23	26	28	29	41	42	59	65	67	80	81	84
Month	Aug	Sep	Oct	Jul	Nov	Jan	Dec	May	Mar	Feb	Jun	Apr	Aug	Oct	Jul	Sep	Jan	Dec	Nov	Apr	May	Mar	Jun	Feb

Newman & Keuls test, $P<0{\cdot}05$.
Mean values increase from left to right. Figures jointly underlined indicate no significant difference. The last two lines indicate the classification for months obtained by summing of ranks for the eight parameters. A rank from 1 to 12 was attributed to each monthly value and ranks were averaged to non-significantly different means. Three homogeneous groups of months are defined. For abbreviations see Table 2.

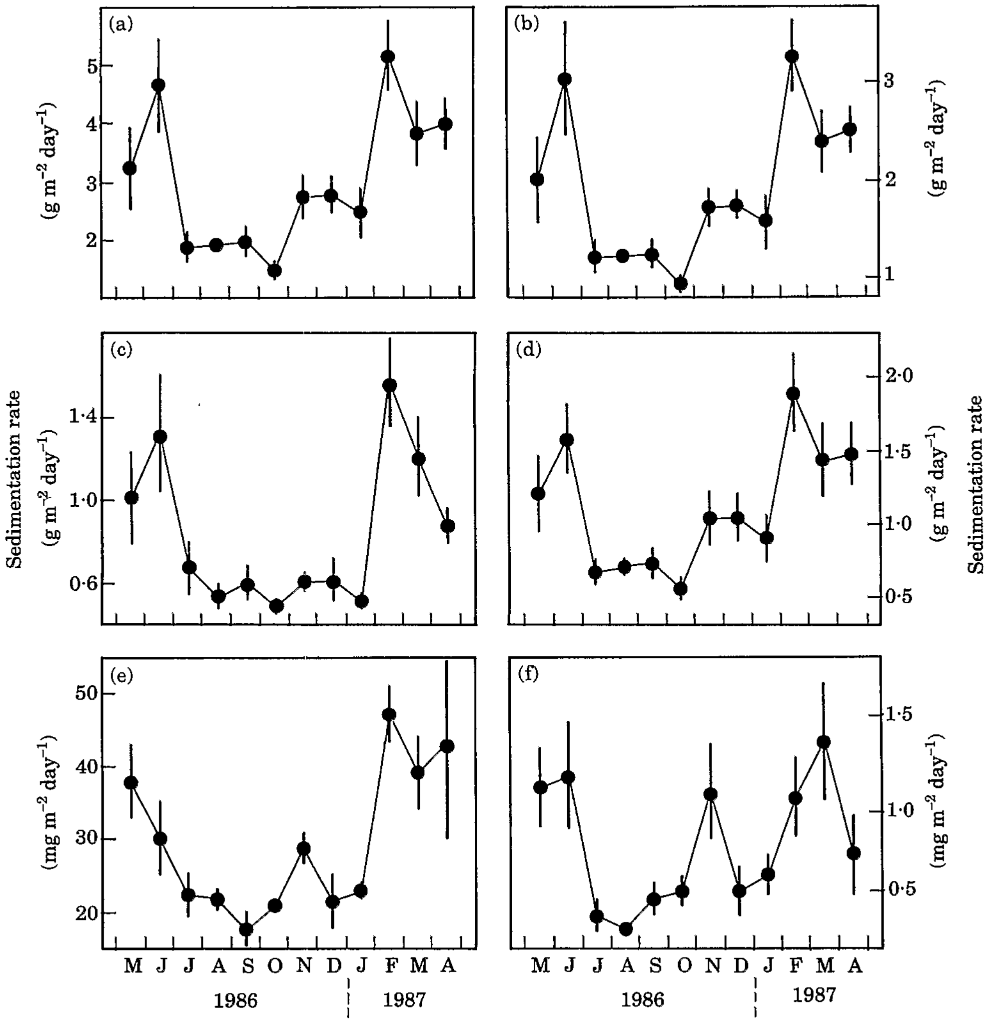

Figure 3. Monthly evolution of mean (a) total particulate matter (TPM), (b) particulate organic matter (POM), (c) particulate organic carbon (POC), (d) particulate inorganic matter (PIM), (e) particulate inorganic nitrogen (PON) and (f) plant pigment (PP) values in sedimented material. Vertical bars correspond to the standard errors.

Discussion

The near-surface TPM concentration gradient in the seston increased from the barrier reef to the shore. This feature is mainly due to a clear gradient of inorganic material which is more than twice as high in stations associated with muddy bottoms (stations 1 and 2) as in the near-reef site (station 5). It corresponds to an obvious turbidity gradient in the lagoon, linked to a terrigenous influence. Differences between coastal and near-reef POC concentrations are less marked. The mean POC concentration (222 mg C m^{-3}), close to French Polynesia Tikehau atoll value (192 mg C m^{-3}), is in the upper range of values recorded in tropical coastal waters (Charpy & Charpy-Roubaud, 1991). The general distribution of chlorophyll *a* in seston is similar to

TABLE 5. Percentage of daily sedimented material corresponding to the ratio of sedimented material per m^2 to the particle content of the overlying water column

	Station					
	1	2	3	4	5	Mean
TPM	20·20	13·11	21·03	14·22	24·50	18·61
POM	22·14	13·60	25·60	14·67	25·80	20·36
PIM	16·41	12·06	16·70	13·26	22·53	16·19
POC	33·86	21·08	27·92	17·93	30·10	26·18
PON	11·66	6·17	13·22	6·54	11·27	9·77
PP	10·70	11·34	9·88	9·24	8·94	10·02

For abbreviations see Table 2.

Rougerie's (1985) results with a maximum near the shore and rather homogeneous values around 0·3 mg m^{-3} in the external part of the lagoon.

The mean net POC sedimentation rate for the south-west lagoon of New Caledonia (0·756 g C m^{-2} day^{-1}) is significantly higher than those reported for Kaneohe Bay, Hawaii (0·49 g C m^{-2} day^{-1}; Taguchi, 1982), Tuamoto atoll lagoon, French Polynesia (0·350 g C m^{-2} day^{-1}; Charpy & Charpy-Roubaud, 1991) and Davies Reef, Great Barrier Reef (0·09–0·141 g C m^{-2} day^{-1}; Hansen *et al.*, 1992). However, a daily deposition rate of *c.* 1·5 g C m^{-2} day^{-1} has been measured by Koop and Larkum (1987) at One Tree Island, Great Barrier Reef. This last value falls among the highest daily vertical fluxes recorded in the literature (see Bhosle *et al.*, 1989, for a review) but the authors admit that it is mainly due to the resuspension process.

The mean sedimentation rate of total pigments (0·83 mg m^{-2} day^{-1}) is closely related to the results of Taguchi (1982) in Kaneohe Bay (0·95 mg m^{-2} day^{-1}). This would lead to a calculated settling velocity of 0·6 m day^{-1}, similar to the deposition rate for nanoplankton measured in tropical waters by Takahashi and Bienfang (1983) and to chlorophyll *a* velocity in Tikehau lagoon (Charpy & Charpy-Roubaud, 1991). No extensive pelagic primary production study has been conducted in the south-west lagoon of New Caledonia so far, and data are only available for one site corresponding to station 2 of the present study. The mean value calculated every 5 m from 0 to 30 m depth at five periods using ^{14}C, is 460 ± 165 mg C m^{-2} day^{-1} (Dandonneau, pers. comm.). Sedimentation of plant material at the same station estimated assuming a C/photosynthetic pigments ratio of 40 (derived from a review by Banse, 1977) is 56 mg C m^{-2} day^{-1}. It accounts for about 12% of the daily primary production. Therefore, only a small fraction of the primary production reaches the bottom. This view contrasts with the general field data reported on coastal waters. For comparison, Suess (1980) reports that about 30–80% POC primary production sedimented in coastal waters. At station 2, POC sedimentation rate is 2·5 times the primary production. If we exclude the direct pumping of energy from the water column by filter feeders, the contribution from pelagic primary production to the benthic compartment is thus relatively low.

Resuspension of benthic sediments is a general phenomenon observed even in the deep-sea (Drake & Cacchione, 1986; Crassous *et al.*, 1991) and the physics of the process has been recognized (Bennett, 1987; Demers *et al.*, 1987; Sanford, 1992). In the shallow coastal water environment, resuspension is a major process hindering true sedimentation and causing the sedimented carbon at the water–sediment interface to return quickly to the water column. The process is first linked to currents and starts at current velocities as low as 10 cm s^{-1} (de Jonge & van den Bergs, 1987). At station 2, the deepest of our sampling sites (Table 1), we often observed a 3–5 m bottom nepheloid layer during calm weather conditions. In the coastal environment, resuspension is also wave-induced. New Caledonian lagoons are exposed to relatively intense trade-winds, often over 25 knots, inducing relatively rough sea conditions. We established a significant relationship between wind intensity during the few days preceding our sampling and sediment resuspension collected in the traps. Resuspension allows newly sedimented material to be transported. Sedimentation is therefore a dynamic process which is difficult to assess using static traps. Resuspension, however, mainly affects inorganic material and its influence on POC calculation is only 10–20% in the lagoon. This value is consistent with Bloesch and Uehlinger's (1986) findings in a freshwater lake environment. Gasith's (1975) equation is based on POM concentrations in the seston and the sediment, and presumes an absence of resuspension signal in the surface waters and a similar composition of the upper 1 cm of sediment and of resuspended particles. Resuspension may affect surface waters. We believe, however, that the signal is low because of the high percentage of organic matter in seston compared to sedimented material. The resuspended sediment fraction in the content of the trap, set 2 m above the substrate, only consists of fine fractions, with an organic matter percentage probably greater than global sediment content. Our resuspension reckonings are underestimated in these circumstances. In fact, mineralization of organic matter in the lagoon is primarily a pelagic process.

The contribution of PIM to lagoon sedimentation is very low. The net sedimentation of PIM represents on average 400 g m^{-2} $year^{-1}$ (1·099 g m^{-2} day^{-1}). Based on measured density (2·5) and average porosity (46·4%) of the sediment it may be calculated that the sediment layer increases by 0·34 mm $year^{-1}$. According to the reef-to-coast gradient already mentioned, the lowest PIM sedimentation rate is observed near the reef formations (0·22–0·28 mm $year^{-1}$), the highest being found in coastal areas (0·42 mm $year^{-1}$). This PIM was mainly of terrigenous origin, as indicated by the relatively low carbonate content of the sedimented material, confirming the low contribution of terrigenous input to the lagoon sedimentation in New Caledonia. Terrigenous particles are almost absent from the sandy fraction (>0·063 mm) except in the near-shore areas. This terrigenous influence is consequently detectable only on the fine fraction (mud), whose non-carbonated material (terrigenous and siliclastic) may reach 10% near the reef and up to 80% in the bays. Most of the terrigenous inputs are trapped at the level of deltas and mangroves. Only a minute part, mainly fine particles (<0·063 mm), reaches the lagoon. This part, which is easily resuspended because of the size of its particles, is then rapidly scattered by wave action (Baltzer & Trescases, 1971; Launay, 1972). In addition, tidal currents probably carry most of it out of the lagoon through the passes.

The C/N ratio of particulate matter may give some insight into the proximate composition and origin of the material: low ratios (3 to 7 by weight) have been reported for phytoplankton whereas high ratios may result from influx of terrigenous material or from increased detrital organic matter (Banse, 1974; Slawyk *et al.*, 1978). Our values, however, are close to McMahon and Patching's (1984) findings which rarely fall below 10. The high mean C/N (weight) ratio of the trapped material (25·2) suggests terrestrial origin for sedimented particles rather than plankton-derived organic matter. This value, close to Koop and Larkum's (1987) findings at One Tree Island, indicates that the sedimented material mostly consisted of refractory organic matter.

Mineralization of particulate organic matter in the water column is the main nitrogen release pathway and, unlike carbon, particulate matter input is not a major nitrogen source for the benthos. Benthic nitrogen requirements are thus linked to considerable nutrient recycling in the sediment or at the water–sediment interface where nitrogen fluxes are low (Boucher & Clavier, 1990) but the nitrogen demand is high (Boucher *et al.*, 1994). The rapid benthic mineralization process occurs in the top sediment layers corresponding to the oxygenated zone and the amount of particulate-originated nitrogen reverted to the water column is probably very low.

The magnitude of recent organic deposition can exert a major influence on the magnitude of sediment–water exchange rates with a very rapid response (Kelly & Nixon, 1984; Graf, 1987). POM fluxes are different in the three bottom types described in the south-west lagoon (Chardy *et al.*, 1988) but the accumulated organic matter level is similar (Chardy & Clavier, 1988*a*; Garrigue *et al.*, 1992). This sediment organic matter content, however, is mainly the refractory fraction remaining after consumption of more labile compounds and is not the main food supply of the benthic system (Kelly & Nixon, 1984). The benthic energy demand, assessed by aerobic metabolism measurements expressed as carbon equivalents, was estimated to be 0·36, 0·74 and 0·57 $g\,C\,m^{-2}\,day^{-1}$ for mud deposits, grey sand bottoms and white sand bottoms, respectively (Boucher & Clavier, 1990). These values correspond to 34, 136 and 96% of the organic carbon sedimented, suggesting different fates for organic matter. They do not take the chemical oxygen demand of the sediment into account, however, and these percentages must be considered as maxima. Particulate matter originated carbon flux is high at mud deposit sites compared with bottom energy requirements. As the accumulated organic matter is roughly constant in the lagoon, mud deposits are likely to export organic matter to the other parts of the lagoon. This tendency to export should be enhanced by benthic primary production, which represents a potential further energy input. Intense resuspension of particles observed in this bottom type makes the export process easier. On the contrary, the energy demand for the grey sand bottoms is higher than POC input from the water column. Other carbon sources, such as benthic primary production and organic matter input from the other parts of the lagoon are expected. A similar deficit was observed for nitrogen by Boucher *et al.* (in press) for this part of the lagoon. POC flux at the near-reef white sand bottom sites is almost equal to metabolic requirements. As part of the sedimented material is refractory, it is difficult to determine the carbon budget of this zone. Estimates of benthic primary production are necessary to assess the carbon budget of the three bottom types.

Seasonality has been demonstrated to be a marked feature of coral reefs (Kinsey, 1985). A temporal pattern of sedimentation has been described in the lagoon with about three-fold variations throughout the year. The sedimentation pattern is related to suspended particle concentrations with a maximum in February, during the warm season. In New Caledonia, highest temperatures (26·5 °C) were recorded in February (Rougerie, 1985). This period also corresponds to the maximum river runoff associated with the major rainfall season (Bauduin & Brunel, 1981). At the opposite end, lowest sedimentation rates in August coincide with low temperatures (*c.* 21 °C) and lowest river runoff. Such an annual cycle of deposition was not observed by Hansen *et al.* (1992) in

Davies Reef lagoon located far from shore. In New Caledonia, the seasonality effect is probably increased by material carried along by rivers towards the lagoon, denoting a major terrestrial influence.

As pointed out by Bhosle *et al.* (1989), sedimentation rates measured by traps include both net (autochthonous) and secondary (allochthonous) sedimentation. In the south-west lagoon of New Caledonia, secondary sedimentation is an important process and originates both from the coast and the barrier reef. Our results suggest a predominant terrestrial influence, but hydrodynamic studies are required for further interpretation of the process.

References

Baltzer, F. & Trescases, J. J. 1971 Première estimation du bilan de l'altération, de l'érosion et de la sédimentation, sur péridotites, sous le climat tropical de la Nouvelle-Calédonie. *Comptes Rendus de l'Académie des Sciences, Paris* **273**, 2034–2037.

Banse, K. 1974 On the interpretation of data for the carbon-to-nitrogen ratio of phytoplankton. *Limnology and Oceanography* **19**, 695–699.

Banse, K. 1977 Determining the carbon-to-chlorphyll ratio of natural phytoplankton. *Marine Biology* **41**, 199–212.

Bauduin, D. & Brunel, J. P. 1981 Hydrologie. In *Atlas de la Nouvelle-Calédonie et Dépendances*. ORSTOM, Paris, pl. 12.

Bennett, J. R. 1987 The physics of sediment transport, resuspension, and deposition. *Hydrobiologia* **149**, 5–12.

Bhosle, N. B., Sawant, S. S., Sankaran, P. D. & Wagh, A. B. 1989 Sedimentation of particulate material in stratified and nonstratified water columns in the Bombay High area of the Arabian Sea. *Marine Ecology Progress Series* **57**, 225–236.

Bloesch, J. & Uehlinger, U. 1986 Horizontal sedimentation differences in a eutrophic Swiss lake. *Limnology and Oceanography* **31**, 1094–1109.

Blomquist, S. & Kofoed, K. 1981 Sediment trapping. A subaquatic in situ experiment. *Limnology and Oceanography* **26**, 585–590.

Boto, K. G. & Bunt, J. S. 1981 Tidal export of particulate organic matter from a northern Australian mangrove system. *Estuarine, Coastal and Shelf Science* **13**, 247–255.

Boucher, G. & Clavier, J. 1990 Contribution of benthic biomass to overall metabolism in New Caledonia lagoon sediments. *Marine Ecology Progress Series* **64**, 271–280.

Boucher, G., Clavier, J. & Garrigue, C. 1994 Estimation of bottom ammonium affinity in New Caledonia lagoon. *Coral Reefs* **13**, 13–19.

Chardy, P. & Clavier, J. 1988*a* Biomass and trophic structure of the macrobenthos in the south-west lagoon of New Caledonia. *Marine Biology* **99**, 195–202.

Chardy, P. & Clavier, J. 1988*b* An attempt to estimate the carbon budget for the south-west lagoon of New Caledonia. *Proceedings of the 6th International Coral Reef Symposium, Townsville, Australia* **2**, 541–546.

Chardy, P., Chevillon, C. & Clavier, J. 1988 Major benthic communities in the south-west lagoon of New Caledonia. *Coral Reefs* **7**, 69–75.

Charpy, L. & Charpy-Roubaud, C. 1991 Particulate organic matter fluxes in a Tuamotu atoll lagoon (French Polynesia). *Marine Ecology Progress Series* **71**, 53–63.

Crassous, P., Khripounoff, A., La Rosa, J. & Miquel, J. C. 1991 Remises en suspension sédimentaires observées en Méditerranée par 2000 m de profondeur à l'aide de pièges à particules. *Oceanologica Acta* **14**, 115–121.

Demers, S., Therriault, J. C., Bourget, E. & Bah, A. 1987 Resuspension in the shallow sublittoral zone of a macrotidal estuarine environment: wind influence. *Limnology and Oceanography* **32**, 327–339.

Douillet, P., Bargibant, G., Hoffschir, C., Laboute, P., Menou, J. L., Panche, J. Y. & Tirard, P. 1989 Mesures de courant, de marée de vent dans le lagon sud-ouest de Nouvelle-Calédonie. 1ère partie: octobre 1988 à juillet 1989. *ORSTOM: Nouméa. Rapports Scientifiques et Techniques. Sciences de la Mer. Biologie Marine* **53**, 1–250.

Drake, D. E. & Cacchione, D. A. 1986 Field observations of bed shear and sediment resuspension on continental shelves, Alaska and California. *Continental Shelf Research* **6**, 415–429.

Gardner, W. D. 1980a Sediment trap dynamics and calibration: a laboratory evaluation. *Journal of Marine Research* **38**, 17–39.

Gardner, W. D. 1980b Field assessment of sediment traps. *Journal of Marine Research* **38**, 41–52.

Garrigue, C., Clavier, J., Boucher, G., Gerard, P. & Menou, J. L. 1992 Flux d'oxygène et de gaz carbonique à l'interface eau-sédiment dans le lagon sud-ouest de Nouvelle-Calédonie. Méthodes et recueil des données. *ORSTOM: Nouméa. Rapports Scientifiques et Techniques. Sciences de la Mer. Biologie Marine* **62,** 1–21.

Gasith, A. 1975 Tripton sedimentation in eutrophic lakes: simple correction for the resuspended matter. *Internationale Vereinigung für Theoretische und Angewandte Limnologie Verhandlungen* **19,** 116–122.

Graf, G. 1987 Benthic energy flow during a simulated autumn bloom sedimentation. *Marine Ecology Progress Series* **39,** 23–29.

Grebmeier, J. M. & McRoy, P. C. 1989 Pelagic–benthic coupling on the shelf of the northern Bering and Chukchi seas. III. Benthic food supply and carbon cycling. *Marine Ecology Progress Series* **53,** 79–91.

Hansen, J. A., Klumpp, D. W., Alongi, D. M., Dayton, P. K. & Riddle, M. J. 1992 Detrital pathways in a coral reef lagoon. *Marine Biology* **113,** 363–372.

Hargrave, B. T. & Burns, N. M. 1979 Assessment of sediment trap collection efficiency. *Limnology and Oceanography* **24,** 1124–1136.

Hartley, H. O. 1962 Analysis of variance. In *Mathematical Methods for Digital Computers* (Ralston, A. & Wilf, H. S., eds). John Wiley, New York, pp. 221–230.

Hartwig, E. O. 1976 Nutrient cycling between the water column and a marine sediment. I. Organic carbon. *Marine Biology* **34,** 285–295.

Jarrige, F., Radok, R., Krause, G. & Rual, P. 1975 Courants dans le lagon de Nouméa. *ORSTOM: Nouméa, HLIO Adelaide, FUA Publication,* 1–5.

de Jonge, V. N. & van den Bergs, J. 1987 Experiments on the resuspension of estuarine sediments containing benthic diatoms. *Estuarine, Coastal and Shelf Science* **24,** 725–740.

Jørgensen, B. B. 1983 Processes at the sediment–water interface. In *The Major Biogeochemical Cycles and Their Interactions* (Bolin, B. & Cook, R., eds). John Wiley, New York, pp. 477–509.

Kelly, J. R. & Nixon, S. W. 1984 Experimental studies of the effect of organic deposition on the metabolism of a coastal marine bottom community. *Marine Ecology Progress Series* **17,** 157–169.

Kinsey, D. W. 1985 Metabolism, calcification and carbon production I. Systems level studies. *Proceedings of the 5th International Coral Reef Symposium, Tahiti, French Polynesia* **4,** 505–526.

Koop, K. & Larkum, A. W. D. 1987 Deposition of organic material in a coral reef lagoon, One Tree Island, Great Barrier Reef. *Estuarine, Coastal and Shelf Science* **25,** 1–9.

Launay, J. 1972 La sédimentation en baie de Dumbéa (côte ouest, Nouvelle-Calédonie). *Cahiers ORSTOM, Série Géologie, Nouméa* **4,** 25–51.

McMahon, T. & Patching, J. W. 1984 Fluxes of organic carbon in a fjord on the west coast of Ireland. *Estuarine, Coastal and Shelf Science* **19,** 205–215.

Mills, E. L. 1975 Benthic organisms and the structure of marine ecosystems. *Journal of the Fisheries Research Board of Canada* **32,** 1657–1663.

Parsons, T. R. 1966 The determination of photosynthetic pigments in sea-water. A survey of methods. *Monographs on Oceanic Methods, Unesco* **1,** 19–36.

Rougerie, F. 1985 The New-Caledonian south-west lagoon: circulation, hydrological specificity and productivity. *Proceedings of the 5th International Coral Reef Congress, Tahiti, French Polynesia* **6,** 17–22.

Sanford, L. P. 1992 New sedimentation, resuspension, and burial. *Limnology and Oceanography* **37,** 1164–1178.

Slawyk, G., Collos, Y., Minas, M. & Grall, J. R. 1978 On the relationship between carbon-to-nitrogen composition ratios of the particulate matter and growth rate of marine phytoplankton from the north-west African upwelling. *Journal of Experimental Marine Biology and Ecology* **23,** 119–131.

Smetacek, V. 1984 The supply of food to the benthos. In *Flow of Energy and Materials in Marine Ecosystems* (Fasham, M. J., ed.). Plenum Press, New York, pp. 517–547.

Smith, K. L. 1987 Food energy supply and demand: a discrepancy between particulate organic carbon and sediment community oxygen consumption in the deep ocean. *Limnology and Oceanography* **32,** 201–220.

Suess, E. 1980 Particulate organic carbon flux in the ocean-surface productivity and oxygen utilization. *Nature* **288,** 260–263.

Taguchi, S. 1982 Sedimentation of newly produced particulate organic matter in a subtropical inlet, Kaneohe Bay, Hawaii. *Estuarine, Coastal and Shelf Science* **14,** 533–544.

Taguchi, S. & Hargrave, B. T. 1978 Loss rates of suspended material sedimented in a marine bay. *Journal of the Fisheries Research Board of Canada* **35,** 1614–1620.

Takahashi, M. & Bienfang, P. K. 1983 Size structure of phytoplankton biomass and photosynthesis in subtropical Hawaiian waters. *Marine Biology* **76,** 203–211.

Youakim, S. & Reiswig, H. M. 1984 The distribution and flux of particulate matter in the Bideford estuary, Prince Edward Island, Canada. *Estuarine, Coastal and Shelf Science* **18,** 511–525.