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Effects of tidal currents on chlorophyll *a* content of sandy sediments in the southern North Sea

M. I. Jenness[1] and G. C. A. Duineveld[2]

[1] Davis and Elkins College, Elkins, West Virginia, USA
[2] Netherlands Institute for Sea Research, Postbox 59, Den Burg, Texel, The Netherlands

ABSTRACT: Observations of high growth rates among benthic species living on sandy bottoms in turbulent areas of the southern North Sea suggested the hypothesis that transient deposition of suspended organic matter during period of slack current might provide a food source for these animals. Over a 24 h period, changes in chlorophyll levels in the water, on the sediment surface, and in 3 sediment layers were measured. The results not only confirmed the hypothesis, but also revealed that with each tidal cycle, high levels of chlorophyll were alternately being buried in the sediment (to a depth of 5 cm) and then resuspended. Laboratory experiments suggest that the mechanism by which this occurs is related to the formation of sand ripples on the sediment surface. Various implication of these findings are discussed.

INTRODUCTION

Turbulent shallow-sea and coastal waters are usually zones of high productivity as a result of nutrients being mixed throughout the water column. One consequence of this turbulence, however, is that very little of this productivity becomes incorporated into the sediments of these zones. For the southern North Sea, it has been postulated that the products of primary production in excess of those consumed in the pelagic system, are transported to less turbulent zones where they ultimately settle (Creutzberg and Postma, 1979; Creutzberg, 1983; Creutzberg et al., 1984).

In the turbulent areas of the southern North Sea, benthic macrofauna are apt to be less abundant and not as diverse as in more stable regions. Those species which do occur are usually either suspension feeders or surface deposit feeders (e.g. the bivalves *Ensis* spp., *Tellina fabula, Donax vittatus* and the polychaetes *Spio filicornis, Spiophanes bombyx, Magelona papillicornis, Lanice conchilega*). However, several subsurface deposit feeders are also known to occur in this region (e.g. the polychaetes *Scoloplos armiger, Chaetozone setosa, Ophelia limacina* and the echinoderm *Echinocardium cordatum*). *E. cordatum* not only frequents these areas, but has recently also been found to have higher growth rates in these areas than in more stable regions where the bottom sediments contain considerably higher levels of organic matter (Duineveld and Jenness, 1984). One possible explanation for this observation is that *E. cordatum* may in fact be a facultative filter feeder. Preliminary tests by the present authors on pumping rates by these animals do not, however, support this hypothesis. A more likely explanation seems to be that transient deposition of organic matter occurring during periods of slack tidal currents provides a food source for this species. Our observations support the findings of Gislen (1924) and Buchanan (1966) that this species is certainly capable of feeding from surface deposited material. The objective of the present study was to determine whether in fact this deposition does occur.

METHODS

An established sampling station (Lat. 53° N, Long. 4° E) in the southern North Sea (depth: 26 m) was used for this study. Bottom sediments are comprised mostly of coarse sand and broken shells (median particle size: 245 μm). Sediments are characterized by a very low mud content (0.12 % of particles < 50 μm), a low biomass value (3.6 g AFDW m^{-2}) (Creutzberg et al. 1984), and a low organic content (0.5 mg C g^{-1} sediment) (van Megen, pers. comm.). Maximum surface tidal velocity at this site, as reported by Creutzberg, is

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1.4 knots. At the time of sampling, this North Sea area was experiencing a heavy bloom of the alga *Phaeocystis* sp.

The ship was anchored over this site on 16 May 1984 for 24 h. Each hour, current velocity was measured and a 1 l sample of sea water taken with a Nansen bottle at 1 m above sea floor Simultaneously, a sample of bottom sediments, with it's overlying water, was collected using a Reineck's box-corer. From the intact core, 2 sub-samples were made with a 3.3 cm diameter tube-corer to a depth of 10 cm. The tubes were swirled to resuspend any recently deposited algae or organic matter into the overlying water. These water samples, as well as the sea water sample, were filtered over glass microfiber filters to which a small amount of $MgCO_3$ had been added. The cores were divided into 3 segments (0 to 1 cm, 1 to 5 cm, 5 to 10 cm). All filters and sediment samples were immediately frozen for transport back to the laboratory.

Chlorophyll *a* was extracted from the samples in 90 % acetone using an ultrasonic disintegrator. Chlorophyll *a* levels were determined by fluorescence with a Turner 111 fluorometer and expressed as µg chlorophyll *a* l^{-1} water for water samples, and per g sediment for sediment samples. Chlorophyll *a* values for the sediment surface were obtained by substracting the values for the seawater samples from the values for the overlying water in the tube-core samples.

RESULTS

Results are graphically presented in Fig. 1. Due to equipment difficulties, reliable values were not obtained for the first 4 sample periods. Therefore, the results shown represent only 20 sampling periods rather than the 24 originally planned.

In Fig. 1a, the current speeds have been converted to indicate the velocity at 0.15 m above the sediment surface. The formula of van Veen (1936) for calculating tidal velocity profiles was used for this purpose. The resulting graph illustrates that 2 peak periods of current velocity occurred at 1800 h and at 0600 h, with lesser peaks occurring at 0100 h and at 1300 h. The 2 higher peaks are associated with north-flowing (flood) currents and the lower peaks with south-flowing (ebb) currents, indicating a net flow to the north. This agrees with the results of Ramster (1965), who also reported a net current flow to the north for this region of the North Sea.

Levels of chlorophyll *a* in seawater at 1 m above the sea floor are shown in Fig. 1b. Again, 2 major peaks are obvious with values roughly twice those of the trough values. No secondary peaks were observed. Each of the 2 peaks is associated with, and occurs ca

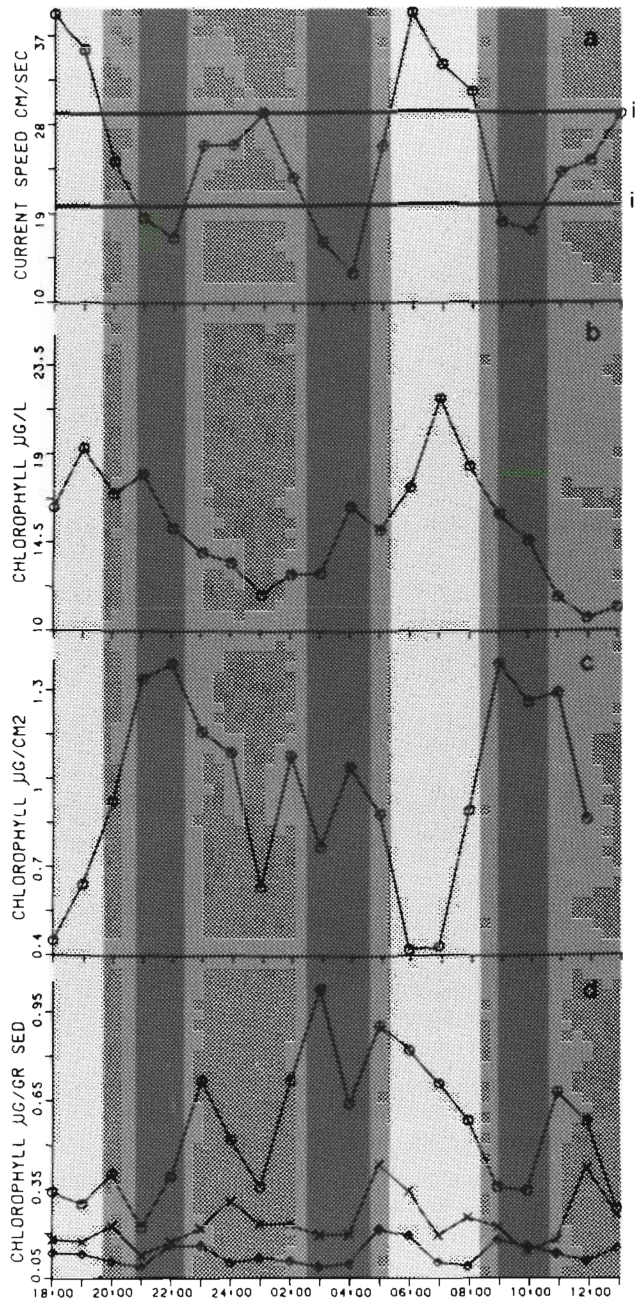

Fig. 1. (a) Changes in current speed at 0.15 m above sediment surface over 20 h. Lines designated *i* and *ii* represent respectively minimum erosion speed and critical sedimentation speed. (b) Changes in chlorophyll *a* content (µg l^{-1}) of seawater collected at 1 m above sea floor (c) Changes in levels of chlorophyll *a* (µg cm^{-2}) deposited on sediment surface. (d) Changes in chlorophyll *a* content (µg g^{-1} sediment) of 3 sediment levels: circles: 0 to 1 cm; crosses: 1 to 5 cm; squares: 5 to 10 cm. Variations in density of vertical stippling differentiate between periods of erosion, transport and sedimentation

1 h after, a major peak in current velocity This delay is thought to represent the time lag necessary before maximum erosion of the sediment occurs. The troughs

of chlorophyll *a* levels coincide with peaks of ebb current velocity. The range of these chlorophyll values (10 to 22 $\mu g\ l^{-1}$) are equivalent to those reported by Gieskes and Kraay (1977) and Creutzberg (1983) for late spring in the southern North Sea. According to Creutzberg, such high values occur in this region only during spring algal blooms.

The chlorophyll *a* values for the sediment surface (Fig. 1c) are somewhat erratic, probably as a result of non-uniform distribution coupled with the small surface area of each core (8.55 cm^2). To minimize this 'noise', while retaining any major shifts in chlorophyll *a* levels, each point plotted on the graph in Fig. 1c represents an average of the value measured at that time with the values measured at the times just before and just after that time. Chlorophyll *a* deposited on the surface of the sea floor has major peak values occurring at ca 4 h after flood current velocity peaks and minor peak values which occur 4 h after ebb current velocity peaks. All peaks of surface deposits coincide with troughs of current velocity, with the major peaks associated with the troughs immediately following peaks of flood current velocity. Conversely, the troughs of the surface sediment chlorophyll *a* values coincide with peaks in suspended algae (Fig. 1b).

Peak values of chlorophyll *a* in the top 1 cm of sediment occur at 6 h intervals, each ca 1 h after every minimum current-speed level (Fig. 1d). Unlike the surface-deposited chlorophyll *a*, however, the highest peak value of the buried chlorophyll *a* is associated with that current speed trough which follows the peak of ebb current velocity. Levels of chlorophyll *a* in sediments 1 to 5 cm deep more or less follow the levels in the top centimeter, although at about one-half the absolute values. Levels of chlorophyll *a* in 5 to 10 cm layer of sediment do not vary anywhere near as much as those in the upper layers, but there is evidence of some increase corresponding to the peaks seen in those layers.

DISCUSSION

Our results offer some intriguing insights into the effects of tidal currents on the distribution of algae at the water-sediment interface, at least at this site. Presumably, other suspended organic material and detritus follow similar patterns.

According to these results, algae are deposited on the sediment surface during periods of slack tidal current, thus providing a high-quality food source for epibenthic fauna and other surface-deposit feeders. In addition to this surface deposition, however, algae are also worked into the sediment to a depth of at least 5 cm. Most of this burying activity seems to occur after the peak of ebb current velocity, although minor peaks in the levels of buried chlorophyll *a* at 2300 h and 1100 h (Fig. 1d) indicate that some burying also occurs with a decrease in current velocity of the flood current peaks. These results were not anticipated, yet are also not inexplicable. Several laboratory experiments have been conducted by the authors using a circular current tank in which current velocity can be closely monitored. This apparatus has been described by Creutzberg and Postma (1979), who used it to determine the velocities at which various sediment types would settle. We found, when operated at a constant velocity of 20 cm s^{-1} at 15 cm above the sediment surface, that surface ripples formed. Algae introduced into the sys-

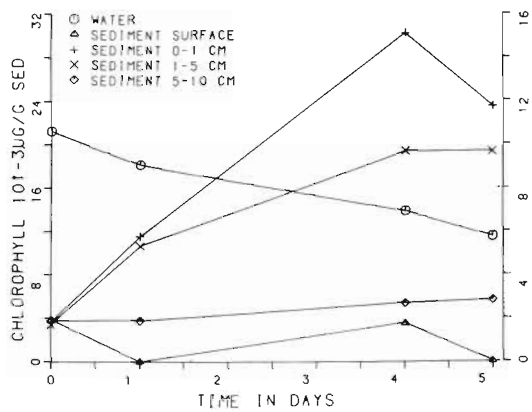

Fig. 2. Circular flow-chamber experiment: at 20 cm s^{-1}, algae become trapped in the top 5 cm sediment. Virtually no algae are buried deeper than 5 cm

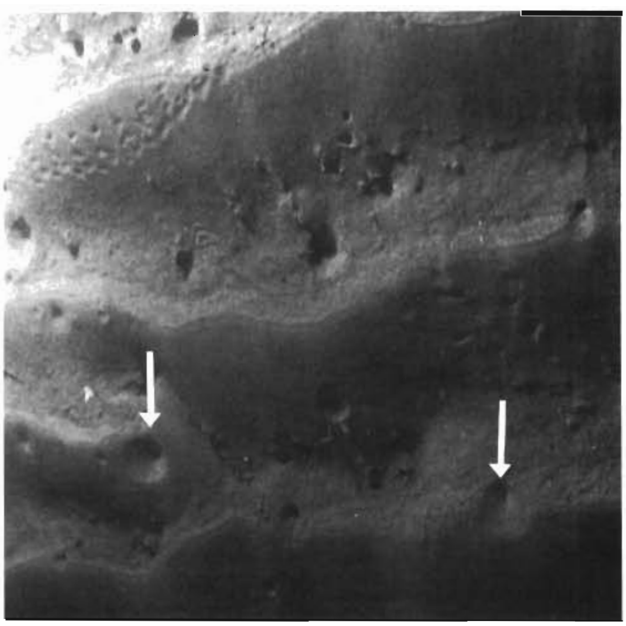

Fig. 3. Ripple formation on sandy bottom of southern North Sea. Arrows indicate the presence of respiration funnels. Laboratory observations would suggest that these were produced by *E. cordatum*. (Photo by Govert van Noort)

tem at this velocity soon became buried to a depth of 5 cm, even though, as a result of a constant current velocity of 20 cm s^{-1}, no surface deposit could be detected (Fig. 2).

It seems likely that this same mechanism could also be working in the North Sea. A photograph of the bottom (Fig. 3) from a nearby location (Lat. 53°33′ N, Long. 4°15′ E), taken on 22 Feb 1982 at a depth of 28 m, shows that ripples do indeed occur on these sandy bottoms. The surface current speed and median grain size of the sediment at the photo site are virtually identical to those at the site we sampled (Creutzberg et al., 1984). Moreover, calculations based on data from Postma (1967) showed that a current speed of at least 20 cm s^{-1} at 15 cm above the sediment surface is required to initiate ripple formation in sediments having a median grain size of 245 µm. Above a current speed of 29 cm s^{-1}, complete erosion of the sediment layer begins. When these values are superimposed on the graph of current speeds (Fig. 1a), the following observations can be made. At 1800 h and 0500 h, the current speed becomes sufficiently high for everything in the top 5 cm to become suspended. During the slack tides which follow, the sand sediments out first, followed by the lighter algae and other organic matter (Fig. 1b). This leaves algae deposited on the surface, which can be observed at times 2200 h and 0900 h (Fig. 1c). At the same time, suspended algae decreases (Fig. 1b). The ebb current velocities which follow are insufficient to erode the sediment, but are high enough to introduce ripple formation. Intuitively, one would think that if the current speed were sufficiently high to induce ripple formation, that it would also be high enough to resuspend the light-weight algae. Fig. 1b clearly shows, however, that no increase in suspended algae is associated with peak ebb current velocity. Since an increase in buried chlorophyll *a* values is associated with these current velocities, it is concluded that the formation of ripples effectively traps the algae previously deposited on the surface. Fig. 4 illustrates a mechanism by which ripples could effect this process. The zone of backflow in the trough of the ripple would tend to move algae and other low density particles towards the lee side of the ripple where they would tend to be buried by heavier sand particles descending from the crest of the ripple. This could also explain the 'noise' found in values for surface deposited algae observed at this time. The widely fluctuating values may represent the differences found between samples taken from the crest and from those taken from the troughs of ripples. The influence of this trapping process decreases with sediment depth, although the congruency of peaks at the deeper sediment levels (Fig 1d) reveal the extent to which this mechanism has an effect.

The amount of algae buried by this process is considerable. When expressed in terms of µg chlorophyll *a* l^{-1} of interstitial water (1 g sand contains 0.23 ml interstitial water) the range of values is from 400 to 3,500 µg l^{-1}. This represents a marked concentration of algae over that found in open seawater. These high concentrations form a potentially important food source for benthic organisms, particularly for subsurface deposit feeders and for interstitial meiofauna. Not only does this mechanism provide an abundant food supply to the sediment, it is also high quality food that is virtually completely exchanged with each tidal cycle.

Some important questions remain to be investigated. It is not known, for example, if the concentration and the quality of the available food delivered by this process is sufficient to produce the observed rates of growth in *Echinocardium cordatum*. The distinct skeletal ring formation observed by Duineveld and Jenness (1984) for this species shows very broad summer growth bands relative to winter growth bands. This suggests a seasonal food supply It is also not known how widely distributed over the southern North Sea this process of sedimentation might be. It is possible that it is only a local process. However, the wide distribution of fast-growing *E. cordatum* in this area would suggest that some form of this process occurs throughout the sandy bottom regions. If, in fact, this is a rather universal process, it could have a major influence on the study of bio-energetics in turbulent ecosystems, particularly in regard to the energy flow between

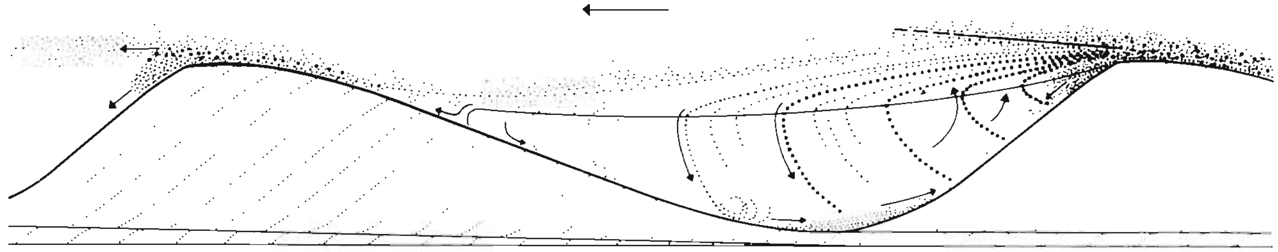

Fig. 4. Flow pattern and sedimentation processes on the lee side of a ripple. Particles accumulate at crest, from which heavier particles avalanche down the lee face. In the zone of backflow, lighter sediment particles are deposited at the toe of the lee slope. Shown are idealized path-lines of sediment grains. (After Jopling, 1967, as modified by Reineck and Singh, 1973)

the pelagic and the benthic systems. Also, the interpretation of past studies and the design of future studies on chlorophyll *a* levels in seawater could well be influenced by the fluctuating levels of chlorophyll *a* resulting from tidal currents.

Even with the influx of large amounts of high quality food into the sediment, as indicated by these results, the fact remains that the area sampled represents a highly stressed environment. This is reflected in the low diversity and abundance of the infauna. To exist here, an organism must be capable of tolerating a highly unstable and abrasive substrate as well as long periods with minimal food resources. For those species that can tolerate such conditions, however, the reward is a seasonal burst of high quality food which can be utilized effectively in rapid growth and also, according to Buchanan (1966), in high levels of reproduction by *Echinocardium cordatum*.

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