FLOCCULATION, FLOC BREAKUP AND GRAIN-SIZE COMPOSITION OF SUSPENDED SEDIMENTS IN TIDAL WATERS OF THE SOUTHERN NORTH SEA

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Introduction

Fine-grained particles eroded at a particular source will be transported in suspension over shorter or greater distances before being deposited in a temporary or permanent sediment sink. The sink may in time become a source in its own right, and the whole cycle starts again. This, in a nutshell, explains the fate of fine-grained sediments in tidal environments such as the southern North Sea. Such cyclical processes play an important role in the sediment budget of a tidal basin. In addition, the flux of suspended matter has a major impact on the health of an ecosystem, as it controls the net import or export of both vital and harmful substances affecting individual organisms. Fine-grained sediments are also involved in defining the morphodynamic behaviour of different structural elements of a tidal basin, e.g. the length, width and depth of tidal creeks and channels, or the size of salt marshes and mud flats.

This study focuses on the particle fraction in the sediment cycle which is transported in suspension. Besides quantifying suspended sediment concentrations over individual tidal cycles in different seasons, the surveys also include basic hydrodynamic investigations required for realistic estimates of total suspended sediment fluxes.

In a complementary study, Chang et al. (2004, this volume) highlight depositional and erosional processes involving the fine-grained sediment fraction in a mixed tidal flat environment situated close to the mainland shore. Together the two studies form the sedimentological component of the multi-disciplinary research programme “BioGeoChemistry of the Wadden Sea” at the University of Oldenburg, Germany.

Study area

The back-barrier tidal basin of the East Frisian island of Spiekeroog was chosen for this study because it is easily accessible, is representative of the mesotidal barrier-island coast of the southern North Sea, and because large datasets of its hydrology, sedimentology, and biology collected over past decades are available. Spiekeroog Island lies near the eastern end of a barrier-island chain stretching from Den Helder in The Netherlands to the Jade tidal channel in Germany (Fig. 1). The “East Frisian Islands” in the German sector comprise eight barrier islands occupying the upper mesotidal section of the tidal regime. The tidal basin of Spiekeroog Island covers an area of approx. 75 km^2. The tides are semidiurnal with a range of 2.6 to 2.8 m. Most of the tidal water exchange occurs through the Otzumer Balje inlet situated between the islands of Langeoog and Spiekeroog. Small exchanges of water also take place across the tidal watersheds between neighbouring tidal basins, caused mainly by wind forcing, but these have been ignored in this project. Freshwater is supplied by rain and through an artificial sluice outlet at Neuharlingersiel which drains freshwater from the hinterland.

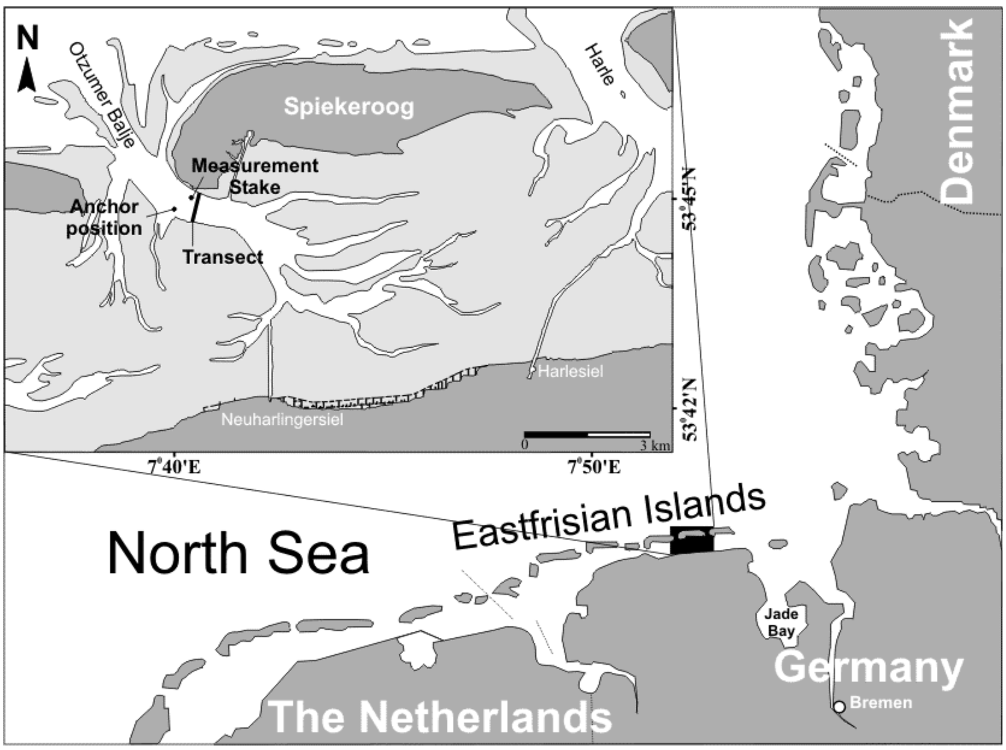

Fig. 1. Geographic location, intertidal physiography, and position of measuring stations in the Spiekeroog back-barrier tidal basin

Methods

Monthly measurement campaigns were carried out in the inner part of the Otzumer Balje (Fig. 1) in the course of which the water and material exchange of the eastern, i.e. the larger tidal catchment, was recorded. To obtain information on floc formation, transport and breakup, a combination of acoustic, optical and mechanical measurement techniques was used. Hydrodynamic parameters such as tidal current velocities and directions were recorded over the entire water column using an acoustic doppler current profiler (ADCP). A laser in-situ scattering and transmissiometry (LISST) system was used to determine particle size distributions of suspended sediments in the water column. Floc sizes in the range 2.5 to 500 µm were estimated by optical diffraction, and suspended sediment concentration was calculated on the basis of optical transmission (Agrawal and Pottsmith 2000). Bulk samples of suspended sediment were obtained by means of a flow-volume-controlled pump centrifuge. This allowed both direct calculation of suspended sediment concentrations and grain-size analyses of the dispersed pump samples in the laboratory using a Sedigraph. The in-situ measurements were used to calibrate the acoustic and optical instruments which were deployed in different modes depending on the weather conditions and the time of day.

For hourly sampling over an entire tidal cycle, at the anchor position the LISST and the pump-centrifuge system were deployed simultaneously onboard the research vessel *Senckenberg*. At the same time, ADCP measurements were carried out along a cross-channel transect from a motorboat. With the LISST, suspended sediment concentrations and particle size distributions were measured at different water depths, whereas the pump samples were obtained at a fixed depth of 1 m below sea surface. In bad weather conditions and during the night, both the ADCP and the LISST were deployed from the ship, measurements being made at 5-min intervals at a depth of 1 m below sea surface over an entire tidal cycle in each case.

Data files of LISST and ADCP were processed by software of Sequoia and RDI. For further analysis and combination of the datasets, we used Matlab routines and MS Excel. Pump samples were desalinated and split by sieving into sand and mud fractions. Organic matter (OM) content was estimated gravimetrically by loss on ignition at 480 °C. Particle sizes were measured by means of a Sedigraph for the mud fraction, and a settling column for the sand fraction. Unfortunately the centrifuge became damaged due to rough weather conditions at sea, so that we could not obtain pump samples for each field campaign. We have currently introduced a new system to take large (300 l) samples of seawater in situ, and to separate the sediment by a centrifuge system on land.

Results

The suspended matter in coastal waters of the North Sea is mainly composed of mineral particles and organic matter. Total organic matter contents typically are 6-11%. This contribution varies seasonally, the higher values being recorded in spring and early summer.

The LISST data reveal significant variations of suspension parameters over the tidal cycle. Thus, the suspended sediment concentration reaches its lowest values about half an hour after slack water (Fig. 2). With values around 10 mg/l, the concentrations after low water slack are about 50% lower than after high water slack (about 20 mg/l). Maximum concentrations coincide with maximum current velocities, the higher values in this case being reached during the flood phase (45 mg/l) as compared to 35 mg/l at full ebb flow. Variations in the mean in-situ particle size, by contrast, show the exact opposite trend (Fig. 3), maximum mean particle sizes (300 µm) occurring half an hour after slack water, whereas minimum particle sizes (70 µm) are observed during peak flow conditions. In this case, there is no clear distinction of mean particle sizes between flood and ebb tidal phases.

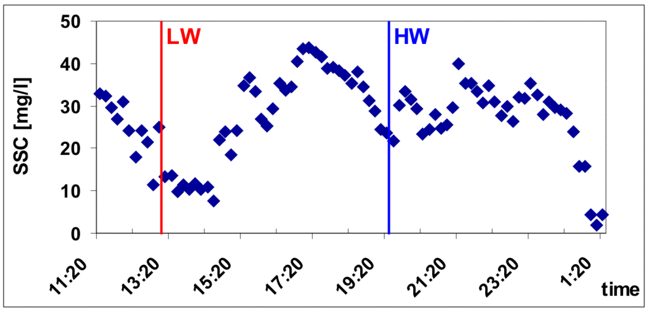

Fig. 2. Variation of suspended sediment concentrations (SSC) over a tidal cycle (data from January 2002, for explanations see text)

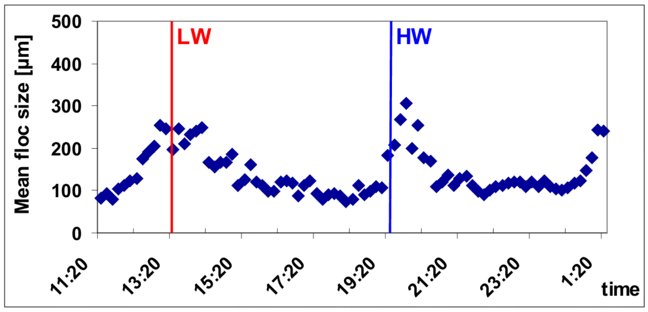

Fig. 3. Variation of mean in-situ particle sizes over a tidal cycle (data from January 2002, for explanations see text)

The ADCP data clearly show that the variations of suspended sediment parameters are dependent on the current velocity (Figs. 4 and 5), concentrations generally increasing with increasing current velocity, whereas mean particle sizes decrease with increasing current velocity. Both diagrams show a two-phase transport, the partition point occurring at a current velocity of 0.7 m/s. Thus, particle concentrations at first increase, reaching highest values (30 mg/l) at 0.7 m/s, remaining constant or decreasing slightly at higher velocities (Fig. 4). Mean particle sizes, by contrast, decrease from ca. 350 µm at low current velocities to about 250 µm at a velocity of 0.7 m/s, and thereafter remain almost constant (Fig. 5).

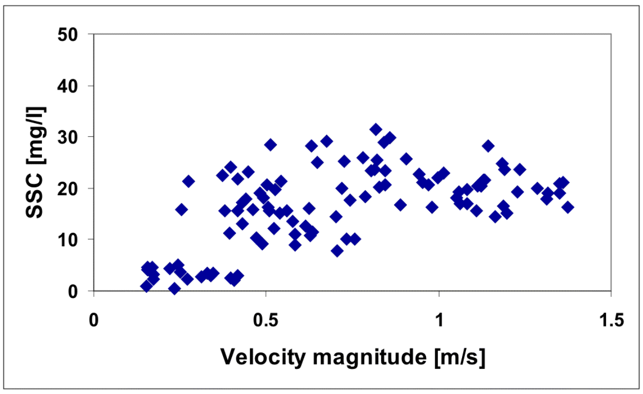

Fig. 4. Dependence of suspended sediment concentration (SSC) on current velocity (data from May 2002, for explanations see text)

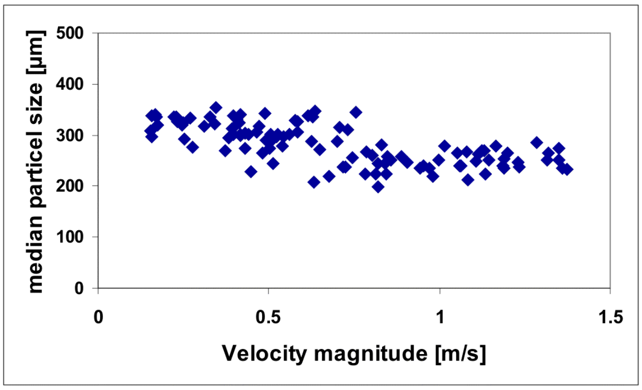

Fig. 5. Dependence of mean particle size on current velocity (data from May 2002, for explanations see text)

The LISST data indicate that at least 75% of the in-situ particle sizes are larger than 63 µm. Dispersed pump samples, on the other hand, show that less than 15% of the single-grain sizes are larger than 63 µm. This is illustrated in Fig. 6 which shows the relative size distributions of two samples obtained at the same time by the two methods. In this case, 97.86% of the single-grain sizes are smaller than 63 µm, the majority being even smaller than 25 µm. The volume distribution (size equivalent) of in-situ particles is truncated at 500 µm, this being the upper limit for the LISST instrument. This demonstrates that most of the suspended sediment consists of flocs and aggregates which reach diameters larger than 500 µm, and which consist of very small, single constituent particles. This is in agreement with other observations which have suggested that the flocs and aggregates predominantly consist of particles smaller than 8 µm. The large proportion of in-situ particles with diameters in the sand range contrasts sharply with the mere 2.14% of single sand grains measured in the dispersed pump samples. Thus, suspended sediments in the Wadden Sea are composed largely of complex aggregates which constantly change in size and concentration over individual tidal cycles.

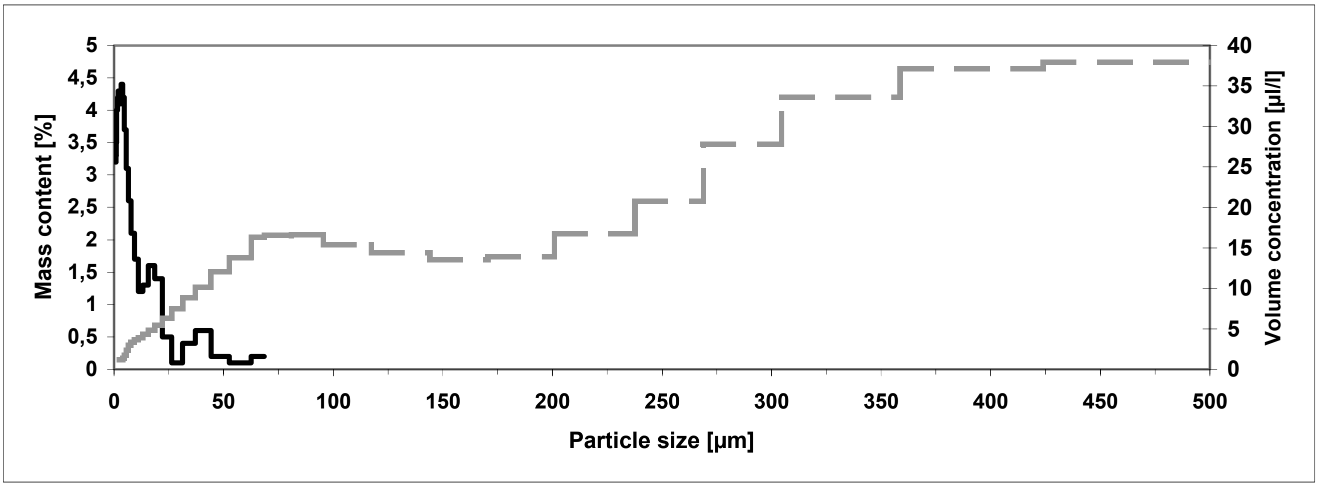

Fig. 6. Combination of particle size distributions obtained by LISST (*shaded dashed line*) and dispersed pump samples measured by a Sedigraph (*solid line*). Both datasets were collected simultaneously in January 2002 (sand content of the pump sample was merely 2.14%). The difference between the two curves shows that most of the suspended sediment is transported in the form of flocs. The truncations at both ends of the size spectra are caused by instrumental limitations

Discussion and conclusions

Field measurements show that suspended sediment in tidal environments is transported mainly in the form of fragile, highly changeable flocs. Thus, in-situ particle sizes measured by the LISST system can here be called “in-situ floc sizes” because the contribution of sand-size single grains can be neglected. In the study area, variations in suspended sediment concentration and mean in-situ floc sizes are dependent largely on current velocity. An impact of water temperature and the availability of biopolymers to floc formation and stability is obvious but has not been investigated in this paper.

The two-phase transport identified in this study can be interpreted as follows. Above a certain threshold, the increasing tidal current velocity resuspends increasingly more fine-grained sediments from the seabed until a velocity of 0.7 m/s is reached. Since the concentration remains constant above this velocity, it must be assumed that all of the locally available resuspendable material has been mobilised. Furthermore, the contribution of suspended material from the tidal flats is much larger than from the channel beds. Since the currents in the channels reach higher velocities than on the tidal flats, this second transport phase can also be seen as a constant uniform supply of material from the tidal flats.

The quasi-stable in-situ floc sizes at velocities above 0.7 m/s can be explained by high internal binding forces which are able to resist the external shear forces once a certain minimum size is reached. Since the data presented here were collected in May, i.e. at a time of maximum bioactivity, it is considered that biopolymers may play a major role in this floc behaviour. The larger flocs observed at lower current velocities are thus interpreted as representing macroflocs formed by aggregation of quasi-stable smaller flocs.

It is also evident that the LISST system used in this study is unable to correctly record floc sizes larger than 500 µm in diameter due to instrument-specific limitations. To solve this problem, attempts are currently underway to integrate data collected by another research group using different measurement and analytical techniques, such as digital floc image analysis (Lunau et al. 2003).

Outlook

A recently installed measurement pole in the Otzumer Balje will be equipped with an upward-looking ADCP for continuous measurements of current velocities and directions, and suspended sediment concentrations through the water column. At the same time, the instrument will provide directional wave data. The pole will be used to mount the LISST at various heights above the bottom for the collection of longer time-series data of in-situ particle sizes.

This approach will, in particular, provide data at times of stormy weather when ship-based observations are not possible. It should then be possible to pin down the events in the course of which the postulated export of fine-grained material from the tidal basin is taking place (Bartholomä et al. 2000; Bartholdy and Anthony 1998).

References

Agrawal YC, Pottsmith HC (2000) Instruments for particle size and settling velocity observations in sediment transport. Mar Geol 168: 89-114

Bartholdy J, Anthony D (1998) Tidal dynamics and seasonal dependent import and export of fine grained sediment through a backbarrier tidal channel of the Danish Wadden Sea. In: Alexander CR, Davis RA, Henry VJ (eds) Tidalites: processes and products. SEPM Spec Publ 61: 43-52

Bartholomä A, Flemming BW, Delafontaine MT (2000) Mass balancing the seasonal turnover of mud and sand in the vicinity of an intertidal mussel bank in the Wadden Sea (southern North Sea). In: Flemming BW, Delafontaine MT, Liebezeit G (eds) Muddy coast dynamics and resource management. Elsevier, Amsterdam, pp 85-106

Chang TS, Flemming BW, Bartholomä A (2004) Distinction between sortable silt and aggregated particles in muddy intertidal sediments of the southern North Sea. In: Flemming BW, Hartmann D, Delafontaine MT (eds) From particle size to sediment dynamics. Abstr Vol Int Workshop 15-18 April 2004, Hanse Inst Adv Study, Delmenhorst, Germany. Terramare Res Rep 13 (this volume)

Lunau M, Rink B, Grossart H-P, Simon M (2003) How to sample marine microaggregates in shallow and turbid environments? - problems and solutions. Terramare Res Rep 12: 85-88