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Over time and space changing characteristics of estuarine suspended particles in the German Weser and Elbe estuaries

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ABSTRACT

Fine cohesive, suspended sediments appear in all estuarine environments in a predominately flocculated state. The transport and deposition of these flocs is influenced by their in-situ and primary particle size distribution. Especially the size of the inorganic particles influences the density and hence the settling velocity of the flocculated material. To describe both the changes in primary particle size of suspended particulate matter as well as the variability of floc sizes over time and space, the data of In-Situ Particle-Size Distributions (ISPSDs), Primary Particle Size Distributions (PPSDs) and Suspended Sediment Concentrations (SSCs) were collected. For this, Laser In-Situ Scattering and Transmissiometry (LISST) measurements as well as the water samples were collected in the German Elbe and Weser estuaries, covering seasonal variability of the SSC.

The data of the ISPSDs show that the inorganic and organic Suspended Particulate Matter (SPM), as found in the Elbe and Weser estuaries, mostly appears in a flocculated state. The substrate for organic matter is mainly imported from the seaside and transported into the estuaries as indicated by an upstream decrease of the amount of fine particles. In winter, when the freshwater discharge is high, different PPSDs are found in the case of the Elbe estuary in the Turbidity Maximum Zone (TMZ) as well as in the landward and in the seaward sections close to the TMZ. In summer, the distance between the seaward and the landward section is too low to obtain an individual PPSD within the Elbe TMZ.

A missing correlation between the PPSD and ISPSD shows that the inorganic constituents do not have an influence on the in-situ floc size. Although flocs aggregate and disaggregate over a tidal cycle and with changing SSC, they do not change their PPSD. The microflocs are therefore strong enough to withstand further breakage into their inorganic constituents.

1. Introduction

In tidal estuarine environments fine cohesive sediments, supplied from rivers and the sea, are mainly transported in suspension. They are quite often organized in so called 'flocs' or 'aggregates' (e.g. Eisma, 1986; Fugate and Friedrichs, 2003; Uncles et al., 2006). Flocculation is a consequence of particles sticking together as they are brought into contact with each other (Whitehouse et al., 2000). Processes whereby particles are brought together are multifarious (Winterwerp, 2002). The most relevant ones are Brownian motion (Eisma, 1986), differential settling and turbulent shear (Eisma, 1986; Whitehouse et al., 2000). The probability of collision is increased under conditions of turbulent flow (Eisma, 1986; Whitehouse et al., 2000) as well as under increased SSCs (Chen et al., 1994; Eisma, 1986; Manning et al., 2006; Whitehouse et al., 2000). To allow the formation of flocs (Chen et al., 1994; Eisma, 1986; Whitehouse et al., 2000), the brought together particles have to either be cohesive, e.g. on the base of electrochemical attraction (van Olphen, 1991; Whitehouse et al., 2000; Winterwerp and van Kesteren, 2004). As an alternative, sticky organic substances could be responsible for flocs such as extracellular polysaccharides (EPS) mainly produced by bacteria and micro algae (Eisma, 1986).

Electro-chemical forces of suspended cohesive sediments can be strongly influenced by the addition of salts. A negative particle charge is compensated by adding positively charged ions to the surrounding water. This process, known as salt flocculation, has been demonstrated by laboratory experiments (e.g. Thill et al., 2001). In the past salt was thought to cause particle flocculation within the zone of brackish water of estuaries (van der Lee, 2001) where riverine freshwater and salty seawater mix. Up to now, salt flocculation has only been shown for colloid ironhydroxydes, humates and associated substances <1 μm (Sholkovitz, 1976; Sholkovitz et al., 1978). In the case of salt flocculation for particles >1 μm no evidence has yet been found (Eisma, 1986; Eisma et al., 1980). In contrast, an increased amount of small flocs at the salt water – fresh water contact have been observed and interpreted as de-flocculation (Eisma, 1986; Puls et al., 1988).

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Organic matter, such as bacterial polysaccharides, algae and higher plants serves as a "glue" by providing fibrous structures around the inorganic particles (Fennessy et al., 1994). However, knowing that biological activity significantly depends on temperature, the strength of biological effects may differ on seasonal scales. Thus, concurring with Eisma (1986) and Eisma et al. (1991, 1994) that more intensive biological activity in spring and summer leads to stronger inter-particle bindings than in winter. The most effective inorganic particle size (substrate size) for organic matter has been reported to be 8 μm (Chang et al., 2007).

Krone (1963) (summarized by Mikes, 2011) described with his conceptual aggregation model that each floc is built from flocs of the next lower order. Single inorganic grains or so called "primary particles" (mostly with mineral components of quartz, feldspars and carbonates) represent the zero order "flocs". These inorganic grains together with organic matter form 'flocs of low order', also known as microflocs. They are mostly irregular shaped (Eisma, 1986) and are considered to be sufficiently dense and strong enough to withstand disaggregation (Chen et al., 1994; Manning et al., 2006). The only way to break up microflocs in their inorganic constituents is by the artificial use of ultrasonic and/or by the removal of organic matter (Eisma, 1986). The maximum size limit for microflocs is proposed to be between 100 μm (van Leussen, 1999), 125 μm (Eisma, 1986), 150 μm (Dyer et al., 1996) and 160 μm (Manning et al., 2006). Larger particles with a porous and fragile structure are known as macroflocs. Eisma (1986) described macroflocs or 'higher order flocs' as somewhat irregularly shaped and more or less rounded, but in some cases they are elongated and curved, almost sickle-shaped. Maximum sizes of up to 600 μm (surface water) and 800 μm (bottom water) are known from sampling in the Elbe around slack water (Chen et al., 1994). Macroflocs with diameters of even up to 3–4 mm were observed in the Gironde estuary (Eisma, 1986). However, these large flocs are fairly loose bound and can easily break up under turbulent conditions (Whitehouse et al., 2000). In this work, flocs <125 μm are proposed as microflocs and particles larger than 125 μm as macroflocs, similar to the work of Eisma (1986).

The floc size distribution varies in dependency of the number of aggregation and disaggregation of single particles and particle agglomerations, respectively (Chen et al., 1994). Size variation over space and time can be related to tidal induced flow and turbulence (Winterwerp, 2011). In many cases, largest flocs occur around slack water when fluid shear is small (e.g. Eisma et al., 1994; Fugate and Friedrichs, 2003; Uncles et al., 2006). With increasing current velocity floc size tends to decrease (Chen et al., 1994; Eisma et al., 1994), and with the approach of the next slack water phase, when current intensity diminishes, floc sizes again begin to increase rapidly (Chen et al., 1994). Besides this general tendency in floc size variation, more voluminous flocs can occasionally be found during the flood or ebb current, when high SSCs result in an increased particle collision frequency (Chen et al., 1994; Eisma, 1986; Manning et al., 2006; Whitehouse et al., 2000).

So far, the PPSD of the flocs has been poorly quantified, especially on spatial and temporal scales. Mikkelsen et al. (2006) for example, simply assume in their study in the Adriatic Sea, that all particles <36 μm represent the primary particles. Size analyses of the inorganic fraction were not separately done in their studies. Nevertheless, the size quantification of the inorganic particles is important because they increase the density and hence the settling velocity of flocs by orders of magnitude (van Leussen, 1988). The following studies show that partially a relation between primary particle size and floc size does exist. Kranck (1981) proposed a linear relationship between inorganic particle size (after ashing and de-flocculation) and in-situ sizes when total SSC is high, often in response to changes in current speed. In contrast, van Leussen (1999) describes an increase of primary particle size while microfloc size (in this case < 100 μm) increases only at the seaward boundary of the Ems estuary where mucopolysaccharides are mobilized.

A problem occurring with studies about flocculation processes is the susceptibility of flocs concerning physical disturbance, especially during sampling. The work of Bale and Morris (2007) illustrates how prone flocs are with respect to physical disruption during sampling. Here, the "real" in-situ size (87–188 μm) differs in comparison to pumped samples (10–20 μm) and primary particles (considerably smaller). To get undisturbed floc sizes it is important to use in-situ techniques which do not physically disturb the fragile flocs. Laser In-Situ Scattering Techniques (LISST, Sequoia® Scientific Inc.) have been proved to be very useful for correct identification of in-situ particle size distributions (Agrawal and Pottsmith, 2000; Mikkelsen and Pejrup, 2001; Mikkelsen et al., 2005; Traykovski et al., 1999).

The objective of this paper is to describe both, undisturbed ISPSDs measured with a LISST and the size distribution of their inorganic constituents, the primary particles. Furthermore, the ISPSD and the PPSD, are necessary to know for quantifying the transport and deposition of fine cohesive sediments. To know the size of the inorganic particles is very important because it influences the density and hence the settling velocity of flocculated material. Time series measurements are necessary to describe the variability of flocculation and changes in PPSD on different spatial and temporal scales as well as under different hydrodynamic conditions. The in-situ particle size measurements were collected during several tidal cycles of the summer and winter season. They took place in the Elbe and Weser estuary which differ in their hydrodynamics (e.g. tidal dominance, freshwater discharge; see chapter 'regional setting').

2. Regional settings

The meso- to macro-tidal coastal plain estuaries of the Weser and Elbe rivers are located along the southern North Sea coast of Germany (Fig. 1). The tidally influenced parts, which extend from the open North Sea to the weir at Bremen in the case of the Weser and up to Geesthacht in the case of the Elbe, are about 120 and 160 km long, respectively (Table 1). The geometry of the upper estuarine section of the Weser (upstream of Bremerhaven) and the Elbe (upstream of Cuxhaven) is channel-like, whereas the lower estuarine sections are funnel-shaped. Morphology of both rivers is strongly influenced by human activities such as repeated deepening, ongoing maintenance and constructional work in and along the navigation channel. The sustained navigable depth in the channel-like section of the Weser is currently 9 m (Schrottke et al., 2006), and 14.4 m in the Elbe (Kerner, 2007) at low-spring tide. As a consequence of man-induced changes in river geometry over the last decades, the tidal range has substantially increased in both estuaries (Table 1). Today, the mean tidal range in the Weser varies from 3.6 m in Bremerhaven to 4 m in Bremen (Grabemann and Krause, 2001), while for the Elbe it currently amounts to 3 m in Cuxhaven, 2.7 m in Glückstadt and 3.5 m in Hamburg (Kerner, 2007).

Both estuaries are characterized by semidiurnal tides but differ in morphology, tidal dominance, river run-off and mixing despite their geographical proximity (Table 1). The long-term, mean annual freshwater discharge of the ebb-dominated Weser (Grabemann and Krause, 1989) is 326 m^3/s and 713 m^3/s (NLWKN, 2009; NLWKN, 2011) in the flood-dominated Elbe (Svenson et al., 2011). The mean current velocity in the Weser amounts to 1-1.3 m/s with maximum values of 2.6 m/s being achieved during the ebb-tidal phase (BfG, 1992). In the main navigation channel of the Elbe mean current velocities range around 0.9 m/s with maximum current velocities of up to 2.2 m/s (long-term measurements November 2005–November 2010 at Rhinplate North (surface), WSV Database – Portal Tideelbe).

The Weser estuary is a partially mixed (Grabemann et al., 1997; Winterwerp and Kranenburg, 2002) and the Elbe partially to well mixed system depending on the freshwater discharge (Kappenberg and Fanger, 2007). Both rivers exhibit a well-developed TMZ (Postma and Kalle, 1955; Wellershaus, 1981) which are characterized by significant higher SSCs than up- and downstream of the TMZ