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Suspended particulate matter dynamics and aggregate sizes in a high turbidity area

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Abstract

Measurements of aggregate size, suspended particulate matter (SPM) concentration and current velocity have been carried out in the Belgian coastal zone (southern North Sea). Two stations were situated in the coastal turbidity maximum zone; another station was located more offshore at the edge of this turbidity maximum. The data have been collected using a LISST 100, OBS sensors, water samples and a bottom mounted ADCP. Turbulence (Kolmogorov microscale) has been modelled for the same period using a 3D numerical model. The results show that the size of the aggregates is significantly smaller in the coastal turbidity maximum area. The processes responsible for the occurrence of smaller aggregate size in the coastal zone compared with the more offshore location are: the higher turbulence; the smaller time available for the aggregates to grow up to an equilibrium size; the higher deposition of mud, resulting in a break-up of the flocs and the lower availability of organic matter, which may limit the size of the flocs.

Keywords: SPM; aggregates; flocculation; Kolmogorov microscale; organic matter; coastal turbidity maximum; southern North Sea

1. Introduction

The aim of this paper is to present and discuss the results of measurements of suspended particle size and of suspended particulate matter (SPM) concentration in and just outside a high turbidity zone in the Belgian coastal waters (southern North Sea) and to discuss the possible processes, which control the size of flocs or aggregates and the SPM concentration dynamics. The names floc and aggregate are not well defined and often used interchangeably. In this study the definition of Van Leussen (1994) is followed, saying that an aggregate is a loosely packed structure containing lithogenic and organic substances; floc is a general term for an entity in which particles or groups of particles are bound together. It is well known that the SPM transport is affected by the formation and break-up of flocs (i.e. flocculation), because it may vary the settling velocity of the particles (Van Leussen, 1994). The settling velocity of cohesive sediments cannot be calculated directly from their particle size distribution, because due to size, form and density of the flocs, the settling velocity may not follow Stokes' law. SPM concentration and particle characteristics vary over time-scales ranging from tides, neap–spring cycles and seasons (Fettweis et al., 1998). The processes that determine flocculation are a function of the overall hydrodynamic and biological environment (Dyer, 1989) and also

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of the physical, chemical and biological characteristics of the particles, such as the SPM and organic matter concentration, the size, cohesiveness (clay) and form of the particles (Berlamont et al., 1993). Previous work (Van Leussen, 1994; Winterwerp, 1999) indicated that mainly turbulence and to a much lesser extent Brownian motion and differential settling are the responsible physical agents. Due to turbulence the particles will collide and may flocculate. Large turbulent motion results then in disruption of the aggregates. In tidal areas flocculation effects may vary in space and time as a result of turbulence stress history. The residence time of the flocs has furthermore to be sufficiently long (order of hours) such that the flocs can attain their equilibrium size (Winterwerp, 1999). This is particularly relevant at low turbulent levels, at small sediment concentration and/or very shallow water. Deposition and resuspension of fine-grained sediments may affect the size of the particles, e.g. by break-up of the aggregates during resuspension (Fugate and Friederichs, 2003) and/or changes in the structure of the aggregates due to consolidation. The occurrence of phytoplankton and its associated mucus finally is a crucial factor controlling the aggregate size, because these organic components can be large and sticky and can produce large aggregates if concentration is sufficient (Hamm, 2002).

The Belgian and southern Dutch coastal waters are an effective trap for fine-grained cohesive sediments, resulting in the formation of an area of high SPM concentration. Most of these suspended sediments originate from the English Channel and are transported into the North Sea through the Strait of Dover. The coastal turbidity maximum is for a greater part formed by the decreasing residual water transport in this area, which results in a congestion (longer residence time) of the suspended particles in this area (Fettweis and Van den Eynde, 2003). Accurate knowledge of the SPM transport system is especially important because of its effect on the economy (dredging and dumping), the environment and as such also for setting up a framework for a sustainable management of the area. Dredging and dumping in the Belgian coastal waters and harbours consist of about 10 millions tons of dry matter yearly, from which 70% is silt and clay. Comparison between the natural input of SPM and the quantities dredged and dumped at sea shows that an important part of the SPM is involved in the dredging/dumping cycle. The construction and extension of the Zeebrugge harbour and its connections to the open sea have to a great part created these efficient sinks and have thus changed the natural cohesive sediment system.

In this paper the results of measurements of SPM concentration, suspended particle size and current velocity are described at three stations. A three-dimensional (3D) hydrodynamic numerical model is used to simulate the currents, elevation and turbulent kinetic energy during the measurement periods. The main controls on floc size, which are turbulence, flocculation time and organic matter content, are discussed.

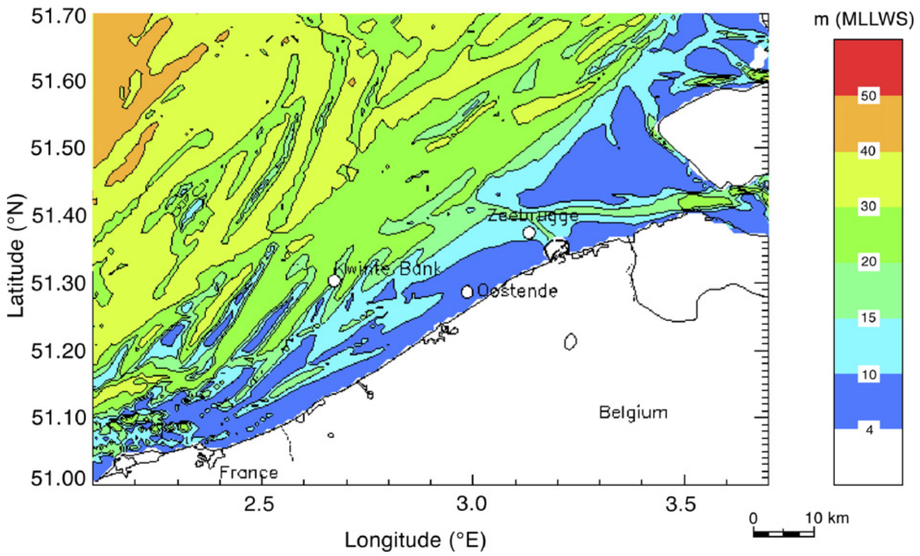

Fig. 1. Bathymetry of the southern North Sea (m MLLWS) as used in the OPTOS-BCS model. Indicated are the location of the measuring stations (Zeebrugge, Oostende and Kwinte Bank), the coordinates are latitude (°N) and longitude (°E).

2. Description of the study area

The study area is the Belgian coastal zone. Measurements have been made at three locations; one is situated on the Kwinte Bank, just outside or at the edge of the high turbidity zone and the other two are located in the coastal zone inside the high turbidity area, near Zeebrugge and near Oostende (Fig. 1). The Kwinte Bank is part of the Flemish Banks and is a tidal current ridge. In the coastal zone the depth is less than about 10 m below MLLWS (Mean Low Low Water Spring level), whereas on the Kwinte Bank the depth varies from 5 m below MLLWS up to 22 m below MLLWS in the swales (Fig. 1). The hydrodynamics in the area are mainly determined by tides. Because of the shallowness of the area waves may have an important influence on sediment transport. The high tidal amplitudes (mean spring amplitude at Oostende is 4.6 m, mean neap amplitude is 3.0 m) and tidal velocities (maximum > 1.0 m s^{-1}) result in generally well mixed waters. The winds are mainly from the southwest or the northeast. The significant wave height at about 20 km offshore is below 2.0 m 87% of the time.

The first studies on the fine-grained sediment dynamics in the area have been published by Van Mierlo (1899). Attention to this subject was drawn in the seventies (Nihoul, 1975; Gullentops et al., 1976; Eisma and Kalf, 1979) when the port of Zeebrugge was extended and the navigation channels deepened. Since then numerous studies have been published (an overview in Fettweis and Van den Eynde, 2003). The SPM concentration has a characteristic distribution in the Belgian–Dutch coastal zone (Fig. 2), which is due to the hydrodynamics, the prevailing winds, the input of suspended matter into the area mainly from the English Channel and the resuspension and/or erosion of (recent and old) fine-grained sediments. In the high turbidity area SPM concentrations of minimum 20–70 mg/l and maximum 100–600 mg/l have been measured (Fettweis and Van den Eynde, 2003). These variations are seasonal and on smaller time scales due to tides, neap–spring tidal cycles, storm events (erosion) and also wind influences in the Belgian coastal zone. During an offshore wind the coastal water with a high SPM concentration is pushed offshore, resulting in an increase of SPM concentration offshore (Lacroix et al., 2004).

The surface sediments in the coastal zone consist of medium to fine sand (Lanckneus et al., 2001) and between Oostende and Zeebrugge of mud (Fig. 3). Most of these fine-grained sediments have been deposited during the Holocene (Baeteman, 1999) and consist of consolidated slightly sandy mud (bulk density: ±1500–1800 kg/m^3), which is difficult to erode, intercalated with peat layers. The extension of the high turbidity zone corresponds well with the extension of these Holocene mud layers, but probably only a small part of the suspended matter in the area originates from erosion of these layers. The recent mud deposits are often related to the spring–neap tidal cycle: the mud which stays on the bottom during neap tide is gradually resuspended towards spring tide. In some specific areas and of

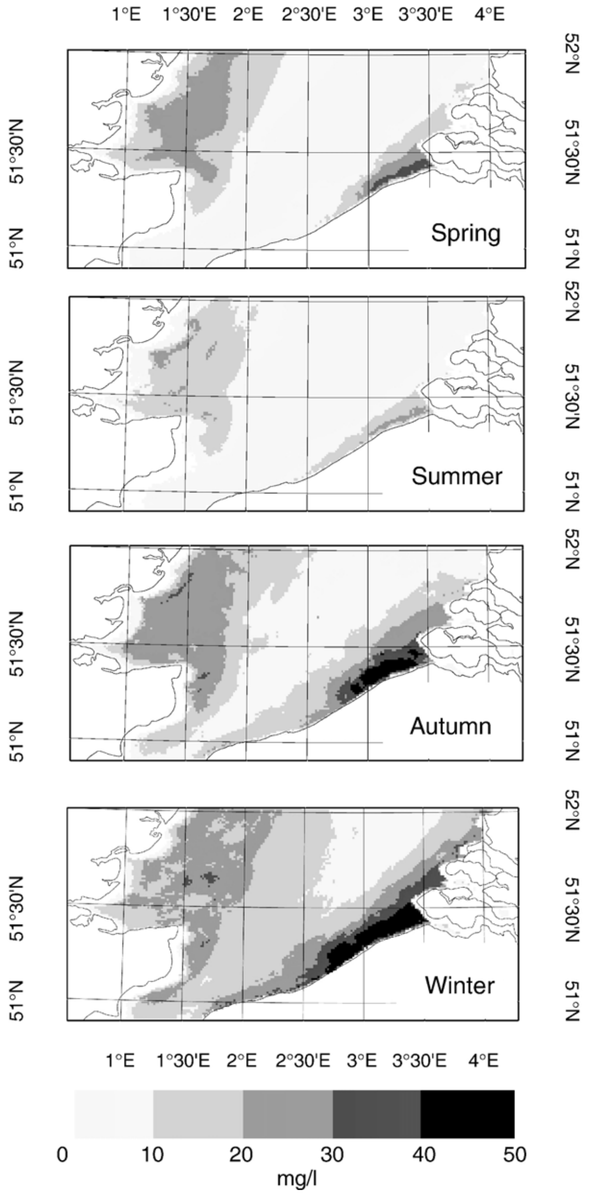

Fig. 2. Seasonal and depth averaged SPM concentration (mg/l) in the southern North Sea (between about 51°N–52°N latitude and 0.5°E–4.4°E longitude), derived from 370 SeaWiFS images (1997–2002) and corrected using in situ measurements of SPM concentration (Van den Eynde et al., 2006).

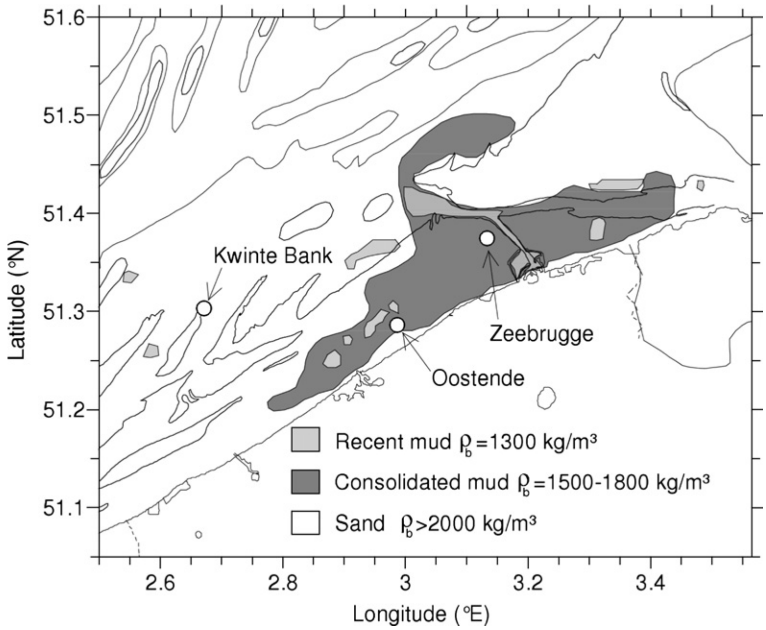

Fig. 3. Mud distribution in the Belgian coastal zone. The Holocene deposits correspond with the consolidated mud; they are covered with a thin ephemeral layer (0–20 cm) of fine sand. The density of the sediments was determined from box cores samples by gamma ray densitometry (Van Lancker et al., 2004).

course in the navigation channels and harbours durable deposits of unconsolidated mud occur (bulk density: ±1300 kg/m^3).

3. Methods

3.1. Measurements and instruments

The data, which are discussed here, were collected on 8 September 2003 at the Zeebrugge site on 11–12 June 2003, 23–30 June 2003 and 2–11 March 2004 at the Kwinte Bank site and on 8–15 July 2004 at the Oostende site. At the Zeebrugge site only one tidal cycle was monitored. At the other stations, long term measurements (7–10 days) were made using a multisensor benthic lander (tripod). At the Kwinte Bank a full tidal cycle was also monitored (Table 1).

During the tide measurements two conductivity–temperature–depth (CTD) recorders (Sea-Bird SBE09 and SBE19) together with optical backscatter sensors (OBS) and a laser in situ scattering and transmissometer 100C (LISST) of Sequoia Science were deployed from the R/V *Belgica*. The SBE09 CTD is integrated in a Sea-Bird SBE32 carousel sampling system (containing 12 10 l Niskin bottles) and was kept at about 3 m above bottom (mab), whereas the SBE19 measured at about 3 m below surface (mbs). Every 20 min a Niskin bottle was closed. The water samples were filtered on board using pre-weighted GFC filters and later on land dried and again weighted to obtain the SPM concentration. The OBS sensors and the transmissometer were calibrated with these SPM concentration data. On the tripod a SBE19 CTD system, 3 OBS sensors (at 0.5, 1 and 2 mab) and a LISST 100C (0.8 mab) were installed. A

Table 1
Inventory of the surveys at the three measuring stations (KB = Kwinte Bank, ZB = Zeebrugge, OE = Oostende)

Survey Nr	Station	Depth (m below MLLWS)	Measuring depth (m above bottom)	Date (dd/mm/yyyy)	Remarks
2003/15	KB	15.3	±3	11–12/06/2003	Offshore, tidal cycle
2003/17	KB	15.3	0.8	23–30/06/2003	Offshore, no ADCP, tripod
2003/22	ZB	11.7	±3	08–09/09/2003	Turb. max, tidal cycle
2004/05	KB	15.3	0.8	02–11/03/2004	Offshore, tripod
2004/15	OE	8.4	0.8	05–15/07/2004	Turb. max, tripod

The measuring depth is indicated for the LISST 100C instrument (turb. max. = coastal high turbidity area).

bottom mounted RDInstruments 1200 kHz Acoustic Current Doppler Profiler was deployed as close as possible to the tripod.

An OBS emits light and measures the amount which is scattered back. At moderate concentration the particle size cross sectional areas determines the amount of backscattered light and thus also the SPM concentration (Fugate and Friederichs, 2002). The output is proportional to the volume concentration and inversely proportional to the particle diameter and depends also on the colour of the suspended sediment (Sutherland et al., 2000). The relation between the output of the instrument and the total suspended matter concentration (filtration) is therefore – due to this dependence – not uniform if the particle size changes as a function of time, which occurs frequently in coastal zones and estuaries (Fugate and Friederichs, 2002).

The LISST 100C uses the laser diffraction technology to measure particle size distributions between 5 μm and 500 μm of the SPM and the transmission coefficient (Agrawal and Pottsmith, 2000). The transmissometer has similar properties as the OBS. The volume concentration is calculated using these measured parameters together with an empirical volume calibration constant and the assumption that the particles are spherical. The LISST works well in resolving uni-modal and multimodal silicate particle distributions, which are separated by at least 1 Φ (Traykovski et al., 1999). Gartner et al. (2001) have shown under laboratory conditions that the LISST underestimates mono-sized particles by about 10% and that this error tends to increase as particle size increased. This is partly due to the logarithmic spaced ring detectors of the instruments and large particles are thus not well represented. Aggregates are slightly flattened, because they are complex associations of lithogenic and organic particles (Van Leussen, 1994; Mikkelsen and Pejrup, 2001), which may thus influence the measured size distribution. It has been shown that diffraction patterns are formed by the aggregates and not by the primary particles from which the aggregates are built (Van Leussen, 1994) and that no multiple diffraction occurs in an aggregate (Agrawal and Pottsmith, 2000). Multiple diffraction results in a shift towards smaller size classes and can become important when the transmission is lower than 30% (Traykovski et al., 1999). The presence of particles coarser than the size range of the instrument changes the size distribution measured by the LISST. Traykovski et al. (1999) have shown that with the LISST 100C all particles larger then 250 μm are registered in the 500 μm class. The results of LISST measurements should therefore be interpreted as an index for comparing size distributions rather than relying on their exact values (Fugate and Friederichs, 2003).

3.2. Numerical model description

The currents, surface elevation and turbulent kinetic energy have been modelled for the measuring periods using an implementation of the 3D hydrodynamic model COHERENS to the Belgian continental shelf, termed hereafter OPTOS-BCS. A full description of the numerical model, including the details on numerical discretisation as well as a user's guide is given by Luyten et al. (1999). The source code of the standard version is available publicly on CD-ROM. The 3D model solves the continuity and momentum equations on a staggered sigma coordinate grid with an explicit mode-splitting treatment of the barotropic and baroclinic modes. OPTOS-BCS covers an area between 51°N and 51.92°N in latitude and between 2.08°E and 4.2°E in longitude. The horizontal resolution is 0.71′ (longitude) and 0.42′ (latitude), corresponding both to about 800 m. In the vertical 20 sigma levels have been implemented. Boundary conditions are water elevation and depth-averaged currents, these are provided by OPTOS-NOS, which is also based on the COHERENS code, but covering the whole of the North Sea and part of the English Channel. Meteorological surface forcing is from the forecasts of the UK Meteorological Office at Bracknell. The current velocities of OPTOS-BCS have been validated using about 400 h of ADCP current profiles collected during 12 campaigns from September 2002 on (Van Lancker et al., 2004). The validation exercise leads to the conclusion that the norm and the direction of the current profiles are satisfactory represented by the 3D hydrodynamic model. The RMSE of the norm of the currents is usually less than 15 cm/s and the relative error of the direction less than 15%.

The turbulence closure scheme used in OPTOS-BCS describes the turbulent energy dissipation (ε) as the product of a velocity (equal to the square root of the third power of the turbulent kinetic energy, k) and a length scale (mixing length, l), according to $\varepsilon=\varepsilon_0 k^{3/2}/l$. The turbulent kinetic energy is obtained by solving a transport equation whereas the mixing length is calculated by an algebraic formulation as suggested by Mellor and Yamada (1974).

4. Results

4.1. SPM concentration and particle size

The data of SPM concentration, current velocity, water depth and averaged particle size measured at the Zeebrugge site (survey 2003/22) together with the modelled Kolmogorov microscale are presented in Fig. 4. The site is situated in the high turbidity area;

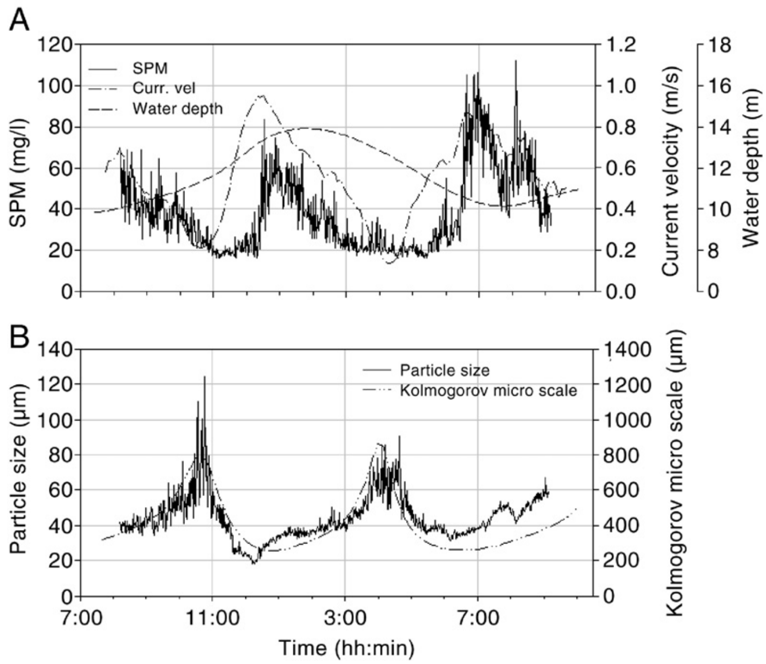

Fig. 4. Zeebrugge site, survey 2003/22. Through tide measurements from 8 September 2003 8h00 PM until 9 September 2003 9h00: (A) SPM concentration (mg/l), water depth (m) and vertical averaged current velocity (m/s) and (B) averaged particle size (μm) and Kolmogorov microscale of turbulence (μm, model result). Measurements have been taken at about 3 m above the bottom.

the bottom consists of Holocene mud covered with a small layer of 1–2 cm of fine muddy sand. The tide measurements take place between mean and spring tides. The average suspended particle size varies between 20 μm to 120 μm (mean value is 44 μm). The variation in particle size was inversely proportional to the current velocity: the biggest particles occur during slack water when the current velocity is about 0.2 m/s and the smallest during maximum currents. The particle size spectra have a uni-modal distribution. The SPM concentration has an inverse behaviour; the maxima are related to the maxima in current velocity. The SPM concentration has its minimum (±20 mg/l) around minimum current velocity; the increase in concentration occurs suddenly when the currents have reached almost its maximum value and reaches about 110 mg/l. These values of SPM concentration are rather low (average is 35 mg/l) and typical for calm weather during summer. The occurrence of a time lag in suspended sediment transport is well known (see e.g. Bass et al., 2002; Hoitink et al., 2003) and is due to the presence of a threshold for sediment movement. It is also related to the fact that the re-suspended mud needs a certain time before it is distributed over the water column.

The Oostende site (survey 2004/15) is also situated in the turbidity maximum area, regions of fresh mud deposits have been observed in the vicinity of the deployment (Fig. 3). During the measurements the concentration was high (maximum >300 mg/l, average ±70 mg/l) and the average particle size small (65 μm).

In Figs. 5 and 6 results of the Kwinte Bank site are presented. This area is situated outside the coastal turbidity maximum and the bottom consists of medium sand. The data in Figs. 5 and 6 cover both periods from about neap tide until about spring tide. Similar tidal variations as at Zeebrugge are observed during survey 2004/05 (Fig. 5). The comparison between both sites should be interpreted with care, because the measurements have not been carried out during the same period and have been measured at different heights above the bottom, but one can observe that the average particle size is about 3 times bigger (122 μm) and the SPM concentration (only) about 30% smaller (average: 26 mg/l; minimum: 9 mg/l; maximum: 250 mg/l) on the Kwinte Bank in comparison to Zeebrugge. The SPM concentrations measured on the Kwinte Bank during survey 2004/05 were surprisingly high; at previous surveys (2003/15 and 2003/17) SPM concentrations were always below 10 mg/l, see Table 2 and Fig. 6. However, the averaged particle sizes during the measurements, were only a little larger (158 μm and 198 μm, respectively) with respect to the survey 2004/05 but significantly larger than those of the coastal measurements (surveys 2003/22 and 2004/15). The particle size

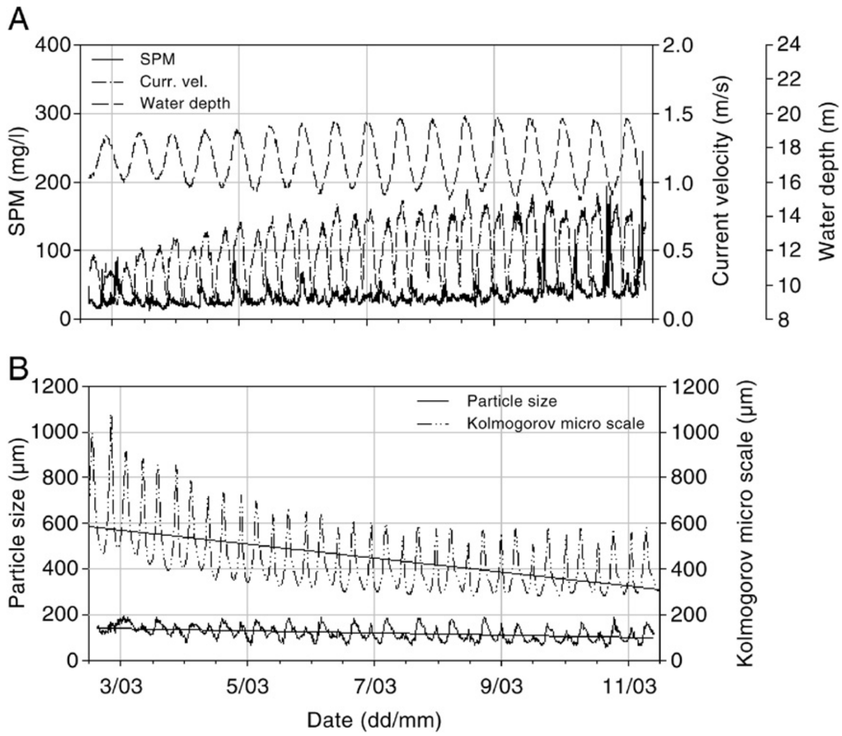

Fig. 5. Kwinte Bank site, tripod measurements of 2–11 March 2004 (survey 2004/05): (A) SPM concentration (mg/l), water depth (m) and vertical averaged current velocity (m/s) and (B) averaged particle size (µm) and Kolmogorov microscale of turbulence (µm, model result). Measurements have been taken at 0.8 m above the bottom (LISST) and 1 m above the bottom (OBS). The slope of the regression line for particle size is −7.13 and for Kolmogorov microscale −20.12.

spectra on the Kwinte Bank have a bi-modal distribution and have often a maximum in the 500 µm class of the LISST, the reported values of the aggregate sizes are thus expected to be lower than the real values.

The data of both tripod deployments on the Kwinte Bank (2003/17 and 2004/05) clearly indicate that the particles measured by the LISST were aggregates and not mineral grains, because a significant decrease in particle size from neap tide towards spring tide can be observed. For sand particles the opposite would have been expected.

4.2. Effective density of the aggregates

The effective density of the aggregates has been estimated for the data of the Kwinte Bank (26–27 July 2003) and the Zeebrugge surveys (8–9 September 2003) by dividing SPM concentration obtained through filtering with the volume concentration of the LISST data similar as presented by Mikkelsen and Pejrup (2001). The results show that the effective density (dry weight per m^3) on the Kwinte Bank is generally smaller (200–800 kg/m^3) than at the Zeebrugge site (400–1800 kg/m^3), but also that the values are relatively high. Typical values of the effective density of aggregates are 50–300 kg/m^3 as reported by Dyer (1989) and Van Leussen (1994). Although the accuracy of our results is limited because of the LISST (see above), the data give an indication that in the coastal zone (Zeebrugge) the aggregates are denser and thus contain more lithogenic constituents than on the Kwinte Bank.

5. Discussion

An interesting result of the measurements is that the particle size of the flocs in the coastal turbidity maximum zone was smaller (average: 44–65 µm) and the effective density higher, than more offshore at a site situated near the edge of the turbidity maximum (average: 122–198 µm). One possible reason could be that the data were collected at different heights above the bottom, because closer to the water surface bigger and/or less dense aggregates are expected. However, the tidal particle size data of the Kwinte Bank (2003/15), which were measured at about 3 m above the bottom, are of the same order of magnitude as those of the tripod measurements collected two weeks later (2003/17) at 0.8 m above the bottom. Both aggregate sizes are clearly larger then the coastal ones.

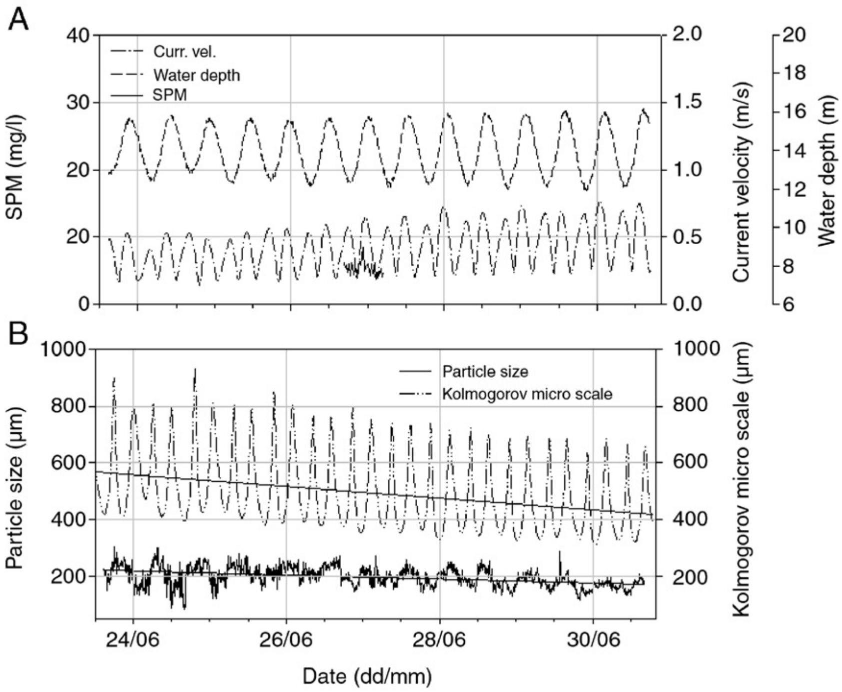

Fig. 6. Kwinte Bank site, tripod measurements of 23–30 June 2003 (2003/17): (A) SPM concentration (mg/l) during one tidal cycle on 26–27 June, water depth (m) and vertical averaged current velocity (m/s; model result) and (B) averaged particle size (μm) and Kolmogorov microscale (μm; model result). Measurements have been taken at 0.8 m above the bottom (LISST) and 3 m above the bottom (SPM concentration through water samples and filtration). The slope of the regression line for particle size is −5.12 and for Kolmogorov microscale −30.38.

Why do different particle sizes occur at sites which are close to each other? The coastal zone and the Kwinte Bank have already been described, the major sedimentological parameters are summarised in Table 2. The clay mineral composition of the SPM is similar at the three sites, indicating that differences in hydrodynamics, turbulence, aggregation time and organic matter content together with possibly bottom sediments in these three sites are responsible for the observed variations; this will be examined below.

5.1. Turbulence

The floc size can be linked to turbulence energy. The largest turbulent eddies break-up into smaller eddies through a cascade of turbulence and are finally dissipated

Table 2
The sedimentological and mineralogical characteristics of the suspended particulate matter and the sediments on the bottom at the three measuring stations

Survey Nr	2003/22	2004/15	2003/15	2003/17	2004/05
Station	Zeebrugge	Oostende	Kwinte Bank Offshore		
	Coastal zone (high turbidity area)				
Suspension					
Average SPM concentration (mg/l)	35	70	<10	<10	26
Average aggregate size (μm)	44	65	158	198	122
Effective density (kg/m^3)	400–1800	–	200–800	–	–
Clay mineral content (%)	ill. (53), smec. (21), kaol. (26)	ill. (52), smec. (25), kaol. (23)	ill. (58), smec. (20), kaol. (22)		
Bottom sediment					
Mud content (%)	65		<1		
D50 (μm)	30		±200		

Clay mineral analysis has been performed by Fontaine (2004), ill. = illite, smec = smectite, kaol = kaolinite.
The SPM concentrations on survey 2003/17 have been measured through water sampling and filtration.

at small isotropic eddies due to molecular kinematic viscosity. The length scale of these small eddies is called the Kolmogorov microscale (λ_k). Assuming that turbulent kinetic energy production is equal to dissipation this microscale can be calculated as:

$$\lambda_k = (v^3/\varepsilon)^{1/4}$$

where v is the kinematic viscosity, which is set to 10^{-6} m^2/s in the model, and ε is the turbulent energy dissipation (m^2/s^3). The size of the floc is limited by the Kolmogorov microscale (Van Leussen, 1994). OPTOS-BCS is used to compute the Kolmogorov microscale for the surveys on the Kwinte Bank (2003/17, 2004/05) and at Zeebrugge (2003/22). The influence of turbulence on the particle size is clear: current velocity varies inversely proportional with the λ_k; during high current velocities (small microscales) the particles are small and vice versa. Furthermore the Kolmogorov microscale and the particle size follow both the same long term variation, as is indicated by the linear regression lines in Figs. 5B and 6B. In Fig. 7 the simulated Kolmogorov microscales at the Kwinte Bank and the Zeebrugge station for the period covered by survey 2004/05 are shown. The figures also show – besides the fact that tides are the major control on particle size at both stations – that the maxima in turbulence (minima in λ_k) are higher (smaller) at Zeebrugge than on the Kwinte Bank, meaning that turbulence can limit the particle size to a greater degree at Zeebrugge and that the aggregates may become larger on the Kwinte Bank.

5.2. Aggregation time

The aggregation time of particles in the turbulent water column controls the size of the flocs and a dynamic equilibrium between floc size and residence time may develop depending on concentration and velocity gradient. When the residence time of the settling flocs is too small, the flocs cannot attain their equilibrium size. In the coastal area, the maxima/minima in current velocities are larger/smaller than further offshore. This will result in higher velocity gradients and in more stress exerted on the flocs and thus a reduction of the time needed for the aggregates to reach equilibrium size. This could also explain the result that the Kolmogorov microscales at Zeebrugge are about three to six times bigger than the LISST measured particle sizes (Figs. 5 and 6), other studies mention a smaller factor (Van Leussen, 1994; Fugate and Friederichs, 2003). These bigger differences are probably also caused by the measurement instrument (LISST) and the fact that turbulent kinetic energy has been modelled and not measured, but they indicate that the available time for aggregation is smaller at Zeebrugge than at the Kwinte Bank station. The fact that the flocs are smaller may also be due to a higher fragility of the flocs in the coastal zone, because they have a higher effective density and are thus built up of less sticky biological matter.

5.3. Deposition and resuspension

The results of a previous numerical modelling study (Fettweis and Van den Eynde, 2003) have shown that in the coastal area during an important part of a tidal cycle

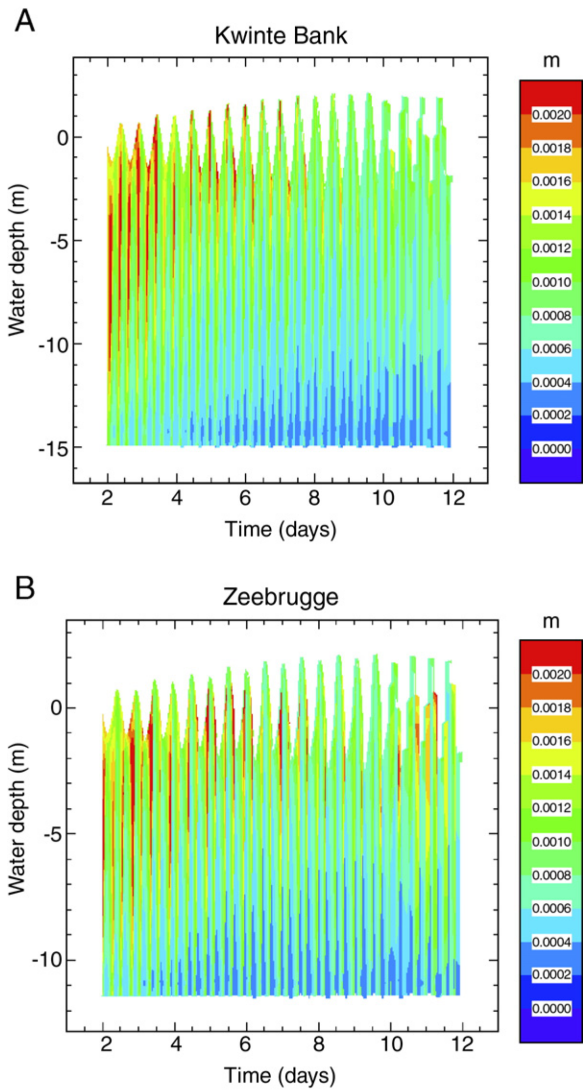

Fig. 7. Kolmogorov microscales (m) for the period 2–11 March 2004 at the (A) Kwinte Bank and (B) Zeebrugge stations (both model results). The water depth is relative to mean sea level, which is about 2.2 m above MLLWS level.

the bottom stress is lower than the critical erosion stress value (set as 0.5 Pa). This is thus a potential sedimentation area. On the sand banks, the maximum bottom shear stresses are lower and the minimum higher resulting in smaller velocity gradients. The very low mud content on the bed in this area (Table 2) can be explained by the fact that during most of the tidal cycle the bottom stress is higher than the critical bottom stress for erosion of mud. Deposition and resuspension of aggregates may result in a break-up of the structure, depending on biological aggregation strength (Fugate and Friederichs, 2003). The aggregates of the coastal zone are more easily deposited and resuspended (lower minimum and higher maximum currents), have possibly lower organic matter content (see below) and will therefore break-up more easily than the aggregates of the Kwinte Bank. This could explain the smaller minimum floc sizes at Zeebrugge (2003/22) and Oostende (2004/15) (about 20 μm) compared to the Kwinte Bank (50–100 μm).

5.4. Organic matter

The formation of macroflocs is possible when phytoplankton is present and in the absence of it the aggregation efficiency will be lower and the floc size significantly smaller (Ziervogel, 2003). Organic matter concentration has not been measured during the surveys. Data of particulate organic carbon (POC) and SPM concentrations over the period 1999–2003, both measured at the same locations on the Belgian continental shelf have therefore been downloaded from the BMDC database (http://www.mumm.ac.be/datacentre). An arithmetic mean has been calculated in those points where minimum 10 values are available. The POC and SPM concentration have the same distribution with a maximum between Oostende and the mouth of the Westerschelde and a decreasing concentration towards offshore. The mean POC concentration varied between 0.4–2.7 mg/l and the mean SPM concentration between 7–85 mg/l. The availability of organic matter (Fig. 8), which is represented by the ratio of the POC concentration with respect to the SPM concentration (POC/SPM) is indicating that more than 6% of the SPM consists of POC on the Kwinte Bank whereas in the high turbidity zone the lithogenic particles are more predominant and POC represents about 3–4% of the SPM. Hamm (2002) confirms that lithogenic particles aggregate efficiently with POC and that the aggregates can become large if concentration of phytoplankton and its associated mucus are sufficient. If lithogenic particles predominate then intermediate sizes can be expected, because the sticky organic matter will be saturated by less cohesive clay minerals or other lithogenic particles. The fact that variations in POC availability exist between the high and low turbidity zones offers an additional explanation for the smaller floc sizes in the coastal zone, where the turbidity is usually high and also an explanation for the differences in mean aggregate sizes of the three Kwinte Bank surveys (2003/15, 2003/17 and 2004/05). During survey

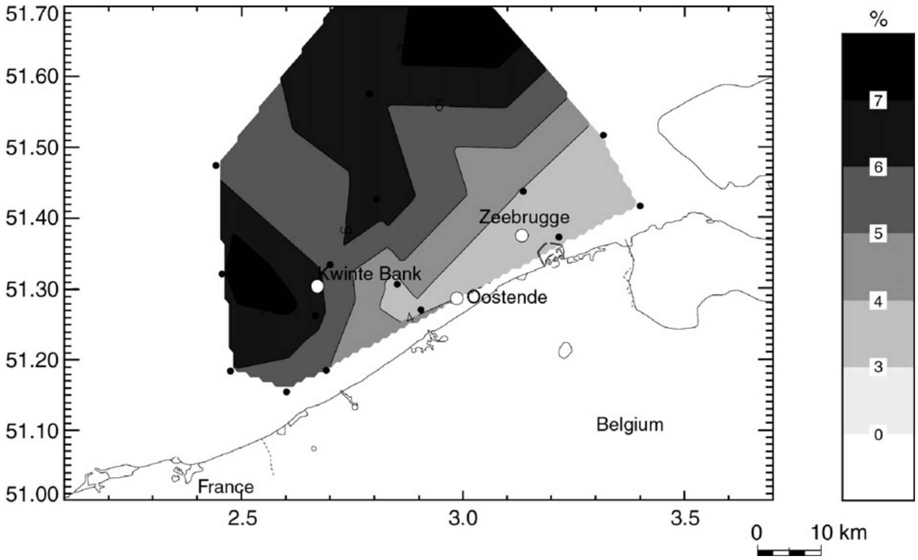

Fig. 8. Relative availability of POC with respect to SPM (in %). The map has been constructed using the arithmetic mean of minimum 10 samples per point of POC and SPM concentrations (1997–2004). The black points are the POC/SPM sample points, the white points are the measurement location on the Kwinte Bank (2003/15, 2003/17, 2004/05), at Oostende (2004/15) and at Zeebrugge (2003/22).

2004/05 the aggregate size was up to 60% smaller than during the other surveys, but the SPM concentration was significantly higher than during the other surveys.

6. Conclusions

The processes responsible for the occurrence of differences in floc size in the coastal turbidity maximum area (Zeebrugge, Oostende) and in a station situated more offshore at the edge of the turbidity maximum (Kwinte Bank) have been examined using measurements and numerical model results. The main conclusions are:

1. The hydrodynamics and thus the turbulence are stronger in the coastal zone. Therefore the maximum size of the aggregates is smaller in the coastal turbidity maximum zone than more offshore.
2. The effective density of the flocs is generally smaller on the Kwinte Bank site (offshore) than at the Zeebrugge site (turbidity maximum). This gives an indication that in the coastal zone (Zeebrugge) the flocs contain more lithogenic constituents than on the Kwinte Bank.
3. The time necessary to make larger aggregates is smaller at Zeebrugge than at the Kwinte Bank.
4. In the coastal zone the maximum bottom stresses are higher and the minimum lower than more offshore. This explains the fact that mud can be more easily deposited and resuspended in the coastal zone. During these processes the fragile aggregates may easily be destroyed.
5. The availability of organic matter (POC) with respect to SPM is smaller in the turbidity maximum area. The organic matter is more quickly saturated there by the less cohesive lithogenic fraction and the growth of the aggregates is limited.
6. The extension of the turbidity maximum in the Dutch/Belgian coastal zone is – beside external influences – also regulated by the size of the flocs, because important local differences in settling velocity of the flocs may occur. Organic matter availability could therefore be an important parameter in numerical mud transport models in order to simulate the settling velocity of the flocs.

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