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In-situ observation of aggregate dynamics in a tidal channel using acoustics, laser diffraction and optics

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ABSTRACT

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To describe the dynamics of aggregates in a tidal channel, in situ measurements of current velocity, turbulence, backscatter intensity, particle size distribution and suspended matter concentration have been carried out throughout half a tidal cycle. The dynamics of suspended particle matter are shown: Distinct turbidity clouds due to temporal increases in total concentration are detected by all sensors but acoustic methods seem to underestimate the amount of SPM when large aggregates are present. We compare two different approaches for the in-situ analysis of particle size distributions: A laser diffraction method (Sequoia LISST 100) and image analysis of in-situ photography. Both instruments are limited due to their resolution and technical properties. Applied in combination, the two methods reveal the broad range of particle sizes ranging from a few microns to millimetre size.

ADDITIONAL INDEX WORDS: *LISST, ADV, ADCP, suspended particle matter, flocs, tidal channel, Jade Bay*

INTRODUCTION

The understanding of suspended particle matter (SPM) dynamics in the marine environment such as coastal seas, estuaries and rivers has been greatly improved by the application of modern measuring techniques. The shortcomings of the laborious procedure of repeated mechanical collection of water samples and their subsequent analysis for the description of suspended matter transport processes have in recent years been largely overcome by in situ optical and acoustic methods, which allow quasi-continuous, autonomous, and less intrusive measurements of SPM and the transporting hydrodynamic environment (THORNE and HANES, 2002).

Optical methods include transmission or backscatter sensors, the signals of which can be calibrated to reflect the concentration of suspended matter in the water. Acoustic methods, on the other hand, are non-intrusive, highly resolving and much less susceptible to biological fouling compared to optical methods (DOWNING 2006; BUNT *et al.* 1999). Acoustic devices, e.g., acoustic Doppler current profiles (ADCP), derive properties of suspended matter based on the echo intensity of high-frequency sound pulses. However, these narrow-band frequency devices are not capable of differentiating between changes in concentration and changes in particle-size distribution (DEINES 1999). Their application thus requires thorough and repeated calibration with water samples, particularly in environments with fluctuating grain-size distributions or unstable aggregates (flocs).

In tidal environments, a high variability in the dimensions of particle aggregates is often observed. Thus, in shallow and turbid aquatic systems, aggregates composed of inorganic and organic particles between 5 and 1500 µm in size are the main component of SPM (ZIMMERMANN and KAUSCH 1996; CRUMP and BAROSS 2000; SIMON *et al*. 2002).

Although the composition, aggregation and disaggregation processes and the role of the hydrodynamic environment and microbial colonisation have been studied in fair detail (MANNING and DYER 2002; FUGATE and FRIEDRICH 2003; LUNAU *et al*., 2002, 2006), the fate of aggregates in the cycling of matter as well as decomposition processes are far from being understood, let alone from being predictable. Since the methods mentioned above describe the bulk characteristics rather than the dynamics of individual aggregates, other methods have been developed to allow a more quantitative description of SPM dynamics. Aside from the shortcomings already mentioned, mechanical sampling or continuous pumping of water is not advisable for the purpose of subsequent particle-size analysis because aggregates are inevitably broken down in the course of the sampling procedure.

Recently, laser in-situ scattering and transmissiometry (LISST) was introduced as a promising means to assess dynamics and size structure of particles directly in the water. To date, a number of LISST studies have been carried out in a variety of environments, but comparisons between different systems have yielded ambiguous results (TRAYKOVSKI *et al*. 1999; MIKKELSEN and PEJRUP 2001; MCCANDLISS *et al*. 2002; FUGATE and FRIEDRICH 2002). The performance of LISST thus needs further attention.

Other optical systems commonly used in the open sea, e.g., in-situ video observation or high-resolution photography (HONJO *et al*. 1984; ASPER1987; COSTELLO *et al*. 1989; LAMPITT *et al*. 1993; RATMEYER and WEFER 1996), are limited by high turbidity and

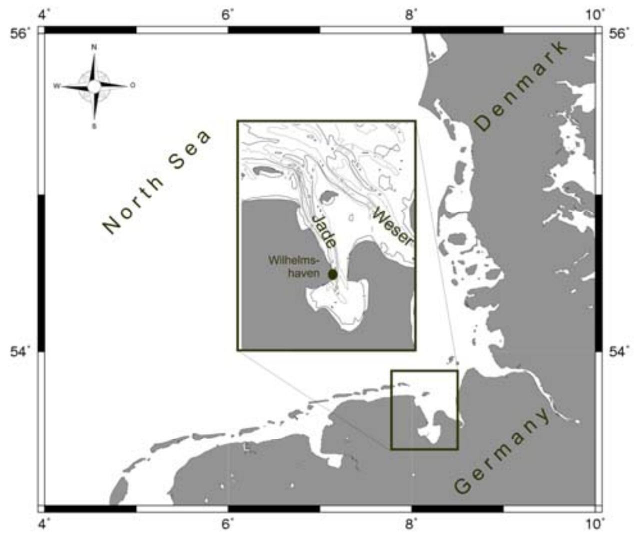

Figure 1. Study area: Jade tidal channel in the German Bight

current velocities. To overcome this, a number of advanced optical systems for the specific application in turbid environments have been developed (van Leussen and Cornelisse 1993; Milligan 1995; Eisma, 1991; Knowles and Wells 1996; Syvitski and Hutton 1996; Lunau *et al*. 2004). In this paper we introduce a newly developed optical system for the in-situ photography of aggregates and their subsequent image analysis. The data were collected in a tidal channel of the German Wadden Sea and the study incorporates a comprehensive description of SPM dynamics based on two acoustic sensors, in-situ particle size analysis and in-situ photography. We compare the performance of the devices in terms of bulk SPM characteristics and particle-size distribution.

STUDY AREA

The study was carried out from aboard FK Senckenberg at an anchoring position in the inner Jade estuary near Wilhelmshaven, Germany (Figure 1). The area is characterised by semidiurnal upper meso- to lower macrotidal conditions with a tidal range of 3.8 m during spring and 2.6 m during neap tides. The data were gathered during a measuring campaign from low water slack to high water slack on 10th April, 2006 between 16h00 and 22h00 MEST. The wind was 10 to 15 knots from N-NW but due to the sheltered location, surface waves were below 1 metre in height with a mean period of 4 seconds.

METHODS

Acoustic Doppler Current Profiler (ADCP)

Today ADCPs are commonly deployed for measuring vertical current velocity profiles. By making use of the Doppler Effect, ADCPs derive horizontal (x- and y-axes) and vertical (z-axis) current velocities as a function of depth in a defined number of depth cells. This acoustic method is based on the proportionality between the frequency shift of outgoing and reflected pulses as measured by four transducers and the celerity of the ensonified scatterers. Besides current velocity in three dimensions, the instrument also provides information on the corresponding acoustic intensity of the backscattered signal. For this study, a direct reading 1200 kHz RDI Rio Grande Workhorse ADCP was mounted downward looking along the side of the anchored vessel. The vertical resolution was set to 0.25 m depth cells (bins) with an average sampling frequency of 0.5 Hz. In this case, only the data of the acoustic beam directed towards the other instruments was taken into consideration.

Acoustic Doppler Velocimeter (ADV)

At a position approximately 1.5 m below the head of the ADCP, a 16 MHz Sontek MicroADV was mounted in order to measure high-frequency velocity oscillations. The ADV determines acoustic backscatter intensity and the instantaneous three-dimensional velocity for a very small sampling volume (0.09 cm^3) five centimetres below the sensor. In this study, the device was set to sample at 20 Hz. From this, one-minute running averages were calculated to distinguish between local turbulence and mean velocities.

Laser In-Situ Scattering and Transmissometry (LISST)

A Sequoia LISST-100 type C instrument was deployed from the anchored vessel at a fixed depth. The device measures the size distribution of SPM in the range of 2.5 to 500 µm. The measuring principle is based on small-angle forward scattering of laser light. The light scattering is detected by 32 logarithmically-scaled ring detectors, the spacing of which determine the size ranges of the scatterers (Agrawal and Pottsmith, 2000).Thus, within the measuring range, light scattered at angles larger or smaller than the angles covered by the ring detectors is not recorded. However, particles smaller than 2.5 µm or larger than 500 µm can still scatter light onto the ring detectors, as each particle creates its own diffraction pattern. Therefore, if smaller or larger particles are present, excess scatter will occur on the first and last rings. Upon inversion of the diffraction pattern, this results in an overestimation of particle volume in the smallest and/or largest size bins (Agrawal and Pottsmith, 2000). This is typically seen as a rising head/tail in the size spectrum (Mikkelsen, 2002). The SPM volume concentration is calculated by adding up the volumetric concentrations of all size classes. In addition, the percent optical transmission of the laser beam is recorded as an indicator of water turbidity. In our case, the instrument was set to output-averaged values of three samples at 0.1 Hz.

Digital In-Situ Documentation of Suspended Aggregates by Laser illumination (DISDAL)

A newly developed photographic device was designed, constructed and deployed to take in-situ digital photographs of suspended aggregates which were subsequently analysed by means of image processing. Three-dimensional distortion effects were avoided by using planar laser illumination. DISDAL is composed of a digital camera (Sony DSC F 828), a red diode laser (λ = 658 nm, 50 mW, HB-Laser Components, Schwaebisch-Gmuend, Germany) and an autonomous controller for both instruments, all fitted into a water-proof PE-housing. The laser beam is expanded to 1 x 60 mm by a semiplanar lens (Schott, Mainz, Germany). The beam is deflected by a prism and illuminates a defined area of water (48.9 x 36.7 mm) which continuously flows through a 150 x 150 mm PE-tube. The channel is always oriented towards the current by a fin.

In this study, one photograph per minute was taken at a resolution of 15 µm per pixel. For the subsequent image analyses, only the red channel of each image was extracted and the resulting 8–bit single–channel images were cropped on all sides to a size of

28.0 x 15.7 mm to exclude out-of-focus rim areas. Segmentation was based on a global colour threshold which was derived by visual inspection of representative image series. These were derived by k-means clustering of images based on the intensity distribution. Image processing and analysis was implemented in MATLAB (The MathWorks, Natick, Massachusetts, USA). Due to the diffuse structure of marine aggregates and variation in light intensity, it is not possible to assure accurate, automatic and objective edge detection. Thus, taking into account the dependency of the derived size distributions on the chosen threshold value the results must be interpreted with some care, particularly in the small particle-size ranges. Relative SPM concentrations were calculated by the summation of the total area of all detected aggregates at particular points in time.

Direct water sampling

Bulk water samples were taken at 15 minute intervals using a HYDROBIOS (Kiel, Germany) water sampler. On each occasion, two litres of water were taken close to the LISST and the DISDAL devices. The samples were filtered, the filters dried and weighed to derive the bulk SPM concentration for each sample after subtraction of the filter weight.

RESULTS

SPM concentration

Time series of current velocity and backscatter intensity as measured by ADV, ADCP acoustic backscatter, the total particle volume concentration as measured by the LISST, and the total area of aggregates detected by DISDAL are plotted in Figure 2 along with SPM concentration derived from water samples.

The survey covered a six-hour flood tidal period. The depth-averaged current velocities during that time interval slowly accelerated after low-water slack, to oscillate around a mean value of approximately 0.75 m/s for three hours. The total SPM concentration, as derived by direct samples at 15 minute intervals, shows a fluctuating signal rising from about 40 mg/l to 90 mg/l at the highest current velocities. Two samples, one at 20h45 and the other at 21h00, yielded very high concentration values of around 200 mg/l. Higher-frequency SPM dynamics was approximated on the basis of other measured parameters: Thus, the acoustic backscatter intensity obtained for a depth profile by the ADCP and for a small sampling volume by the ADV can be related to the concentration of suspended particles. However, the problem of absolute conversion is far from trivial and involves frequent calibration with water samples, but is usually still only valid for the specific campaign (DEINES, 1999; LEE and HANES, 1995). As the focus of this study was not set to absolute quantities, further conversion was omitted. Relative SPM concentrations were also calculated from LISST and DISDAL data as the total sum of all observed particle volumes, or rather all areas for each point in time. As a matter of course, the different sensors detected different magnitudes and characteristics of SPM dynamics, in spite of the fact that they monitored the same environment. However, all the devices show a similar large-scale tidal signal of SPM, i.e. the SPM concentration increased with a time lag of more than two hours after the accelerating tidal currents. Velocity oscillations of higher frequency show similar patterns as the SPM concentration signals, but no statistically significant correlation could be identified.

Turbidity clouds appear as distinct SPM concentration maxima during the rising tide. They stand out in the time-series of all four instruments, e.g., at 17h25 and 17h45. Later peaks, appearing at 19h15 and 20h00 in the LISST and the DISDAL time-series, are less pronounced in the acoustic data. The major event, as already seen in the direct samples and in the DISDAL series (20h45), also stands out in the LISST measurements, but is accompanied by a temporal instrument failure due to the exceedance of the transmissivity threshold. These events are recorded as zero values in the LISST time-series. Note that the DISDAL total particle area values go back to almost zero at times of low acoustic backscatter intensity. By contrast, the total volumetric concentration observed by LISST does not drop below a background concentration of about 150 µl/l, corresponding to a measured concentration value of 35 mg/l.

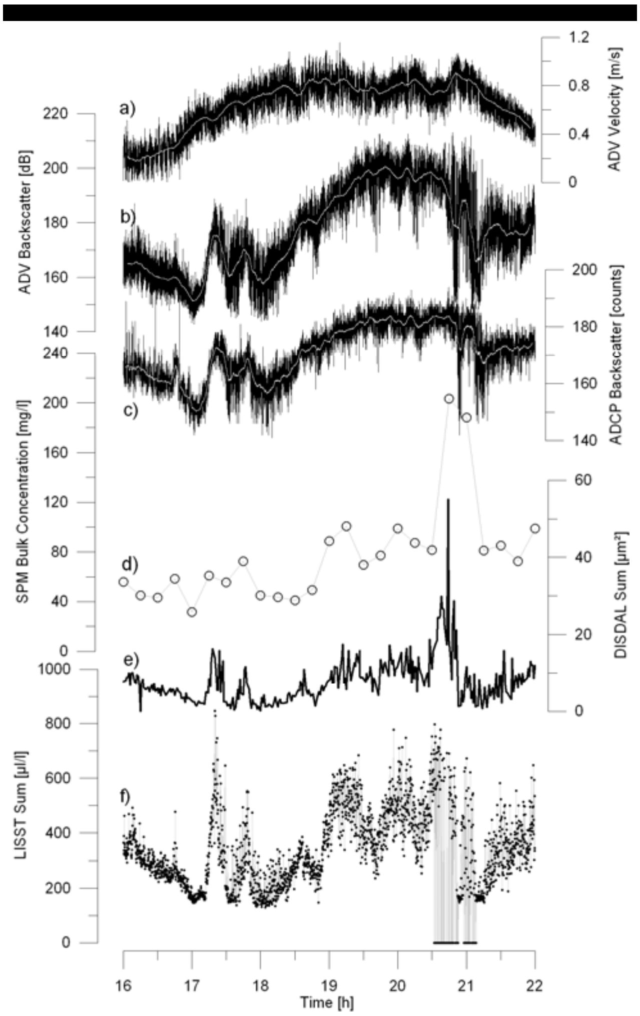

Figure 2. Time series of a) ADV current velocities, b) ADV backscatter intensity, c) ADCP backscatter intensity, d) Bulk concentration, e) DISDAL total particle area, and f) LISST total particle volume. The white lines show one minute running averages.

Particle-size distributions

Whereas the time-series of acoustic backscatter, total particle volumes and particle areas describe bulk characteristics of SPM as recorded in the sample volume of the respective sensors, further differentiation into particle-size classes is illustrated in Figure 3. It

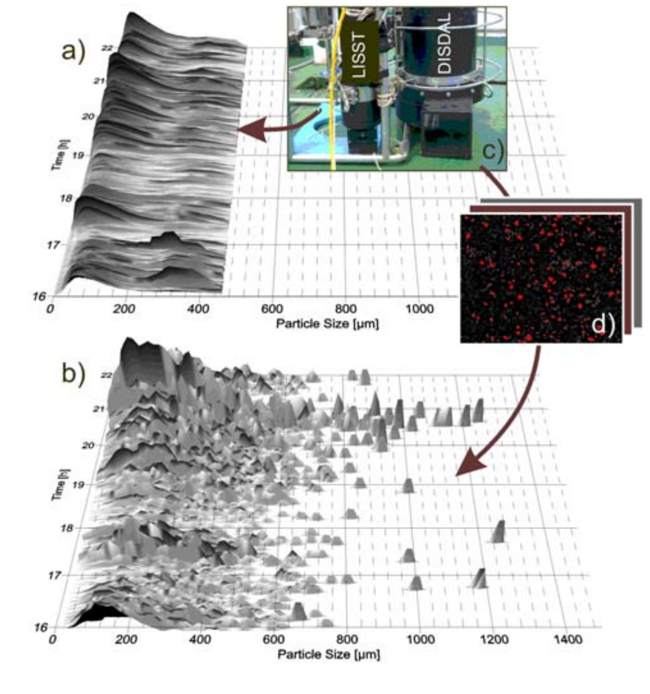

Figure 3. Temporal variation in absolute particle size distributions as derived from (a) LISST and (b) DISDAL in-situ photographs and image processing. The photos show (c) LISST and DISDAL mounted into an instrument frame and (d) a DISDAL image of SPM.

should be noted that, due to the complex shape of the aggregates, a conversion from particle areas (as derived from DISDAL) to volumes (as derived from LISST) - or vice versa - was not attempted.

Figure 3a shows the variation of particle-size distribution over time as obtained from DISDAL digital image analysis of in-situ photos. The total particle area has been sorted into size classes of 15 µm width. The detected particle equivalent diameters range from the lower limit of resolution (15 µm) to 1300 µm. Due to the narrow size classes, and the inhomogeneous distribution of the particles, the distributions are very incoherent. Nevertheless, a main mode below 200 µm is present over the whole measuring period. The largest particles are generally smaller than 700-800 µm, but larger isolated ones of up to 1300 µm also occur. Whereas most of the peaks in the SPM concentration can be related to variations in the total amount of suspended matter (not changing the distribution), the major event at 20h45 is clearly associated with an accumulation of larger particles.

LISST particle-size distributions, which are based on volumetric concentrations, are plotted in Figure 3b. Here, the size range of 2.5 – 462 µm is covered in logarithmically scaled classes. This implies that particle sizes smaller than 100 µm are better resolved than those measured by DISDAL, but larger particles are grouped into larger classes. LISST particle-size distributions are less variable in time. The main mode of the distributions is at about 100 µm during the first hour of measurement, and then drops to around 60 to 80 µm for the remaining time. This main mode is frequently accompanied by a second mode at about 350 µm which appears every few minutes. Also, the peaks in SPM concentration can be related to variations in the total amount of suspended matter without changing the shape of the distribution.

DISCUSSION

A broad range of size classes is present in the water column. Particles of a few microns and up to 1.3 mm in size were detected by in-situ observation. Careful interpretation has allowed the identification of grains belonging to the very fine sand fraction, which appears as an almost constant mode around 80 µm throughout the measuring period in the LISST signal. This material is evidently kept in suspension by local turbulence. This mode, however, does not appear in the DISDAL series, a feature which can be explained by the under-estimation of small particles due to the physical limit of resolution and uncertainties in edge detection: Small particles as observed at times of low turbidity are not at all detected by DISDAL, which then gives almost zero total aggregate areas.

Larger particles, as observed by both LISST and DISDAL, are interpreted here as flocs, i.e. marine aggregates composed of small mineral grains and organic components. These aggregates frequently appear as a secondary mode of approximately 350 µm in the LISST data. The performance of LISST with respect to the correct detection of aggregate dimensions cannot be assessed because the instrument is internally calibrated to express size in terms of a spherical standard which is more appropriate for the detection of sand grains. As a consequence, the LISST tends to over-estimate detected aggregate sizes. On the other hand, the observed mode at around 200 µm in the DISDAL data might be an under-estimation. Bearing in mind the effects of population statistics on modes when taking into account particle areas or volumes, we interpret the secondary mode in the LISST and the first main mode in the DISDAL data as the size signal of micro-aggregates somewhere in the range of 200 to 350 µm.

Further inspection of the DISDAL data reveals a substantial scatter in aggregate sizes. Largest flocs of 700 - 800 µm are frequently observed, while occasionally - e.g., during the 20h45 event - aggregates of up to 1300 µm may occur. It is important to note that aggregates larger than 350 µm seem not to seen by the LISST as discrete objects. This causes the particle distribution to show a rising tail. Since these contribute to the general turbidity of the water, the instrument fails during events with large particle concentrations.

CONCLUSIONS

Suspended Particulate Matter (SPM) is highly variable in marine waters, as shown here by the data from a tidal channel of Jade Bay, along the North Sea coast of Germany. In addition to an overall tidal signal, which also is resolved by repetitive mechanical sampling, modern technology allows the description of higher frequency dynamics in terms of concentration and size distribution. Although none of the approaches can be expected to measure true quantities, as various methodical shortcomings must be taken into account, the combination of different instruments reveals different aspects of SPM dynamics.

This study has shown that ADVs and ADCPs detect similar characteristics of SPM dynamics, a feature which has also been demonstrated by previous studies. It has also been shown that the acoustic signals are similar to the patterns observed in the measured SPM concentration, although pronounced turbidity clouds were not detected by these instruments.

The in-situ laser scatterometer LISST used in this study was able to resolve suspended particle sizes from 2.6 µm up to 460 µm. Here the data have been interpreted to show that a fraction of small aggregates or very fine sand (mode around 80 µm) remained in suspension throughout the measuring period. Larger mineral particles were not expected to occur. Thus, the interpretation of larger aggregates as detected by LISST must take into account the fact that these do not correspond to spheres in terms of laser scattering. The newly developed in-situ photographic device DISDAL has proven its applicability in tidal environments. Although the resolution is limited for the time being, the free definition of size classes allows the distinction of aggregates. Thus, the simultaneous deployment of a number of different in-situ devices has revealed the existence of particles ranging from grains a few microns in size to aggregates exceeding 1 mm in diameter.

Pronounced lag effects, single peaks in the SPM time-series unrelated to local velocities and a vertical distribution of suspended matter as observed in the ADCP acoustic backscatter profiles not shown here, indicate that the recorded suspended material was not brought into suspension at the measuring station but was transported there by the flood current.

It could also be shown that turbidity clouds can be caused by the temporal increase of all size classes, but also by sporadic accumulations of larger aggregates. Whereas the former events are detected by all sensors, acoustic methods seem to underestimate the amount of SPM when large aggregates are present.

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