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Long-term ferry-based observations of the suspended sediment fluxes through the Marsdiep inlet using acoustic Doppler current profilers

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Abstract

Long-term measurements with a hull mounted acoustic Doppler current profiler (ADCP) under the ferry, crossing the Marsdiep inlet between the mainland and the island of Texel (the Netherlands), were used to determine the volume flux and the flux of suspended particulate matter (SPM) through this inlet for the period 2003-2005. Profiles of the SPM concentration were estimated from profiles of the acoustic backscatter intensity in which the shift between the low and high turbulent regime is taken into account. Calibration constants and tuning parameters were estimated by using data collected during 7 different 13 hour anchor stations. The residual (water) volume flux through the inlet appears to vary strongly on a variety of time scales from daily to inter-annual. A regression analysis indicates that the daily residual volume transports correlate well with the daily mean wind component from the south; the latter likely drives the residual flow along the coast of Holland. The observed residual SPM transport of 7 to 11 Mton/yr is dominated by the correlation between tidal velocity and SPM concentration variations. This leads to an import as currents and SPM concentrations during flood were higher than those during ebb, a process generally known as tidal asymmetry. Our analysis has shown that regular observations with a ferry mounted ADCP is an effective method to monitor the volume and SPM transport processes in an estuary.

Keywords: Suspended Particulate Matter, Acoustic Doppler Current Profiler, long-term time-series

1. Introduction

The Wadden Sea, on the list of the UNESCO world heritage site since 2009, is known for its rich biological diversity. It is located in the southeastern part of the North Sea and stretches 500 km along the Dutch, German and Danish coast. It is an intertidal area consisting of a collection of (weakly) connected estuaries behind a series of barrier islands. The Dutch part of the Wadden Sea is the largest nature reserve in the Netherlands and a marine protected area. The Marsdiep inlet between the mainland of the Netherlands and the island of Texel is the major tidal inlet connecting the North Sea to the western Dutch Wadden Sea (Fig. 1). The inlet is 4.5 km wide and

has a maximum depth of about 30 m. Studies in this area have focussed primarily on the hydrodynamics and to a lesser extent on sediment transport. The (water) volume transport through the Marsdiep inlet is semi-diurnal, dominated by motion at the M2 and S2 tidal frequencies, which have amplitudes of $6.6 \cdot 10^4$ and $1.8 \cdot 10^4$ m³/s, respectively, and are responsible for a distinct spring-neap tidal cycle (Buijsman and Ridderinkhof, 2007a). Maximum current velocities can be of about 1.8 m/s. Tidal asymmetry is depended on the location in the Marsdiep: the southern two thirds of the Marsdiep inlet is flood dominant due to interaction of the M2 and the M4 overtide, whereas the northern part close to the island of Texel is ebb dominant.

Interaction between tidal currents and the bathymetry leads to a horizontal anti-clockwise residual circulation in the Marsdiep, which was first observed by Zimmerman (1976b). These results were confirmed by numerical model simulations (Ridderinkhof, 1988) and ferry-based current observations (Buijsman and Ridderinkhof, 2007a). The tidally driven residual transport is a small fraction of the tidal amplitude, between $1 \cdot 10^3$ to $3 \cdot 10^3$ m³/s, and directed from the Marsdiep towards the North Sea (Ridderinkhof et al., 2002; Elias et al., 2006). The residual flow is fed by a throughflow from the Vlie inlet via the Wadden Sea to the Marsdiep inlet. This is attributed to a larger tidal range in the Vlie inlet compared to that of the Marsdiep inlet by and phase difference between the arrival of the tidal wave in both inlets (1.7 hours) Ridderinkhof (1988). Base on observations, Buijsman and Ridderinkhof (2007b) suggest that the transport from the Vlie to the Marsdiep is predominantly forced by the local wind stress and to a lesser extent by tidal stresses between the two inlets.

The Marsdiep basin and inlet form a tidal estuary. Fresh water is discharged at the sluices in the enclosure dike near Den Oever and Kornwerderzand. The daily mean discharge is about 400 m³/s (Postma, 1954), which is 13 to 40% of the residual transport through the Marsdiep inlet. Estimates for the flushing time-scale of fresh water discharged at Den Oever and leaving the Marsdiep inlet are in the range of 13 - 15 tidal periods (Postma, 1954; Zimmerman, 1976a). This corresponds well to the time-lag of 5.5 days, or 11 tidal cycles, observed between the time-series of the discharge at Den Oever and the salinity measured in the Marsdiep inlet (van Aken, 2008). Recently, evidence of stratification is found in multiple observations of solitary internal waves in the inlet, of which some could directly be related with density fronts (Groeskamp et al., 2011). Although tidal currents are strong and mixing is often enhanced by local wind stress, the Marsdiep estuary is not always well-mixed, contrary to what is suggested by Zimmerman (1976a).

The suspended particulate matter (SPM) transport to the Wadden Sea is important, because SPM consists (for a small part) of organic nutrients and is therefore a source for primary production. However, SPM also absorbs light, thereby hindering photosynthesis (van Beusekom et al., 2001) and may be a source for pollutants, which can bind to SPM (Burchard et al., 2008). Being a marine protected area, human interference to the Wadden Sea ecological system must be kept to a minimum. However, results from a numerical model suggest a substantial decrease in the SPM concentration in the Dutch coastal zone due to the extension of the harbor of Rotterdam and consequently a decreased SPM flux into the Wadden Sea (van Ledden, 2005). Uncertainties in the results were estimated to be as much as 50 %, due to shortcomings in the model.

Current estimates for the SPM flux into the Wadden Sea are based on deposition rates, which vary significantly between different studies and/or different basins from values less than 1 to over 10 mm/yr. Eisma (1993) suggests that sedimentation equals subsidence, being 1.2 to 2.8 mm/yr. The German part of the Wadden Sea is assumed to act as a sink for SPM of $3 \cdot 10^6$ ton/yr (Puls et al., 1997), similar to the estimate for the entire Wadden Sea of $3.5 \cdot 10^6$ ton/yr (Postma, 1981). The sedimentation rate associated with the latter budget is 0.27 mm/yr (Burchard

et al., 2008). Core dating in the Sylt-Rømø Bight leads to a yearly mean sediment deposition of $5.8 \cdot 10^4$ ton/yr (Pejrup et al., 1997), equivalent to a sedimentation rate of less than 1 mm/yr. However, rates of 5 – 12 mm/yr were also measured in the Sylt-Rømø Bight (Andersen et al., 2000; Andersen and Pejrup, 2001). Net deposition estimates for the extremely turbid Dollard area are in the order of 1-2 mm/y (up to 8 mm/yr) (Haas and Eisma, 1993). Modeling efforts using a setup for the western Dutch Wadden Sea in the Delft3D model showed a net deposition of 0 – 3 mm over the tidal flats for the modeled year of 1998 (Borsje et al., 2008).

Numerous processes that can cause a (counterintuitive) net SPM transport from the North Sea to the Wadden Sea, thus from low to high concentration, have been proposed in the past. They are summarized in the introduction of the paper by Burchard et al. (2008), being: settling lag and scour lag (Postma, 1954; Straaten and Kuenen, 1958; Postma, 1961; Bartholdy, 2000), tidal asymmetry (Groen, 1967; Dronkers, 1986a,b), flocculation (Pejrup, 1988; Dyer, 1994) and Stokes' drift (Dyer, 1988, 1994; Stanev et al., 2007). Burchard et al. (2008) add the effect of the density driven circulation to this list.

Many methods to study SPM concentrations and fluxes in the coastal ocean have a number of shortcomings. Given the high spatial variability of the suspended matter concentrations, observations from fixed platforms are only representative for a limited region. Similarly, the high temporal variability limits the applicability of remotely sensed data, even if cloud-cover would not hinder the availability of useful images (Puls et al., 1997; Eleveld et al., 2008). Satellite and low frequency in-situ measurements are nevertheless biased towards good weather conditions and satellite measurements are inherently bound to the sea surface and cannot provide information on the SPM profiles even if sophisticated extrapolations are used (Fettweis and Nechad, 2011). To overcome (part of) these problems, studies were performed in which observations from measurement poles were assimilated into numerical model simulations (Stanev et al., 2003; Burchard et al., 2008).

This paper aims to determine the long-term average SPM transport through a major tidal inlet based on *in situ* measurements. For this purpose unique data from a hull-mounted Acoustic Doppler Current Profiler (ADCP) beneath the ferry Schulpengat, recorded for several years, on a high frequency, will be used. The velocity as well as the SPM concentration are determined simultaneously, the latter by calibrating the acoustic backscatter intensity as demonstrated in Merckelbach (2006). These measurements are performed throughout the entire water column, over the entire width of the channel. They have sufficiently high frequency to solve tidal variability and are long enough to provide a reasonable estimate for the long-term average SPM flux. Also the variability of the SPM flux on tidal to seasonal time-scales is established in the period between 2003 and 2005, well before the activities associated with the extension of the harbor of Rotterdam started. Numerical modeling studies have suggested that the extension has influence on density driven coastal current, which leads to a decrease of the SPM concentration along the coast of Holland. The latter may have an indirect effect on the SPM flux through the Marsdiep inlet. Using the data for the period 2003 to 2005, therefore will provide an estimate of the long-term residual SPM flux through the Marsdiep inlet and its variability in the 'undisturbed' situation and can be used for later reference.

2. Data

2.1. Ferry data

The Marsdiep inlet is the Southwesternmost inlet between the southern North Sea and the Wadden Sea (Fig. 1). Since 1998, measurements have been performed with an ADCP mounted

underneath the hull of the ferry Schulpengat of the company Texels Eigen Stoomboot Onderne-
ming (TESO). Northward ship tracks are on average located further west than the tracks going
south due to the company's protocol. The ferry crosses the 4.5 km wide Marsdiep inlet in ap-
proximately 15 minutes. Every 30 minutes a crossing takes place between 6:00 (7:00 on Sundays
and holidays) and 22:00 local time. Emergency ambulance transportation introduces deviations
from the planning and extra crossings and additional data when they occur during night.

We present the long-term SPM flux through the Marsdiep inlet using ADCP data from 2003
to 2005. The acoustic backscatter intensity is used to estimate the SPM concentration profiles
and thus an SPM flux can be determined by additionally using the velocity profiles. In 2003, a
1.0-MHz Nortek ADCP was mounted beneath the ferry Schulpengat. It used bottom tracking to
determine the ship's velocity as compared to differential GPS that was used prior to 2002 (e.g.
in Buijsman and Ridderinkhof (2007a,b)). In the second half of 2004 the ADCP was replaced
by another 1.0-MHz Nortek with similar specifications. In 2003, an *in situ* calibration was per-
formed for heading and speed scaling by sailing along a transect up and down the Texelstroom
and assuming that the mean current remains constant between successive passes. This calibration
procedure was not repeated after the replacement. Therefore, regular operations of the ferry had
to be used for calibration.

The ADCP is mounted beneath the ferry at a depth of 4.3 m below the sea surface. The bin
size and blanking distance of the ADCP are 0.99 and 1.01 m, respectively. The three sound beams
are at an angle of 25° with respect to the vertical. Depth estimates are determined by locating the
hard reflections at the bottom, which appear as local maxima in the acoustic backscatter intensity.
The processing of the ferry data follows a similar procedure as in Buijsman and Ridderinkhof
(2007a) (BR2007 in the rest of this paper). BR2007 describe the temporal and spatial distribution
of tidal currents in the Marsdiep inlet after gridding the data on 18 horizontal grid cells located
parallel to the main current. Assuming that SPM concentrations are spatially more variable than
tidal currents, we choose to grid the data onto 50 horizontal grid cells (Fig. 2). With a sampling
frequency of about 1 Hz, this leads to an average number of 17 ± 4 profiles per grid cell.

2.2. Calibration data

Deriving SPM concentration profiles from acoustic backscatter intensity requires additional
calibration measurements, which were taken aboard the RV Navicula for a period of 13 hours on
several different occasions, while being anchored near the tracks of the ferry. The calibration
procedure to determine the SPM concentration follows four successive steps. The first step
consists of recording vertical optical backscatter (OBS, Seapoint) profiles every 20 minutes by
lowering it on a CTD frame. Meanwhile, another OBS, fixed in a dark chamber onboard, is
calibrated for SPM concentration using filtration of water samples. Step two takes place either
before or after the 13-hours calibration cruise. In this step, the onboard OBS is mounted in the
CTD-frame, facing the same direction as the OBS already fixed in the frame. Subsequently, the
frame is lowered to a certain depth, where it is kept for a few hours. The OBS on the frame is then
calibrated *in situ* using a linear fit between the measurements of both OBSs. SPM concentration
profiles are determined from the calibrations in the first two steps. Thirdly, these optically derived
SPM profiles are used to calibrate profiles of the acoustic backscatter intensity measured by the
ADCP mounted below the Navicula. A detailed description of the instrumentation and step 2
and 3 of the procedure can be found in Merckelbach (2006) (M2006) and Merckelbach and
Ridderinkhof (2006) (MR2006). For the fourth and final step, the backscatter intensity data of the
ADCP beneath the Navicula are interpolated on the same vertical grid as the ADCP data collected
with the ferry. The backscatter intensity data of the ADCPs beneath both vessels are averaged

Figure 1: Lower right: Map of the Netherlands in which the area of interest is indicated by the square. Upper right: map of the location of the approximate envelope of the tracks of the ferry Schulpengat in the Marsdiep inlet. Axis are in the Dutch national reference grid: the Rijksdriehoekstelsel.

Figure 2: Map of the Marsdiep inlet. Dashed is the envelope of the north- and southward going tracks of the ferry, dots show the location of the grid points and drawn are lines between the grid cells parallel to the main current direction.

for the period that the ferry is located within the same horizontal grid cell as the Navicula. A comparison between both data sets for the entire duration of the 13-hours calibration provides the calibration of the ADCP backscatter intensity beneath the ferry.

Besides that, the intensity of the acoustic backscatter is a function of the grain size distribution. Not the in-situ floc size, but the distribution of the primary constituents is important (Fugate and Friedrichs, 2002) as already mentioned in MR2006. Grain size distributions were determined from water samples using the laser particle sizer Coulter LS (Loizeau et al., 1994). During the 13-hours calibration station of the Navicula, every hour samples were taken 1 m above the bottom for analysis of the grain size distribution. After the cruise, all samples are placed in a dark refrigerator at 7°C for several days to allow the sediment to settle on the bottom. Subsequently, the samples are reduced to 120 ml by carefully siphoning the top part of the water column. A linear relationship exists between the obscuration of the reduced sample and the SPM concentration and therefore OBS value measured with the OBS in the dark chamber onboard. The obscuration of the reduced sample should be in the optimal range between 7 and 13 %. In this range the SPM concentration of the reduced sample is low enough for the Coulter LS laser to penetrate the sample, while it contains enough particles within all size classes. Therefore, the total volume of the sample taken on board (thus before reduction) was roughly based on the OBS value measured in the dark chamber and turned out to be between 200 and 1000 ml.

The entire calibration routine has been developed over the past several years, which has led to great improvements in the results. In the current paper we focus on the data for the years 2003 to 2005 in which both the data recorded by the ADCP beneath the ferry as well as the calibration data are of good quality.

3. Estimating suspended sediment concentration from acoustic backscatter

3.1. Theory

The total acoustic scattering cross-section, σ , is related to the backscatter intensity, N_c , which is recorded by the ADCP in counts. After subtracting a certain threshold value, N_t , the backscatter intensity can be derived by multiplying $(N_c - N_t)$ with a conversion factor, K in dB. The total acoustic cross-section is then given by:

$$\sigma = k_t 10^{(K(N_c - N_t)/10)} r^2 e^{4\alpha r} \quad (1)$$

In this relation k_t is a device dependent calibration constant and r the distance from the transducer to the bin. The term r^2 accounts for the geometric spreading of the sound beams and the last term in this equation is a correction for attenuation of the sound waves by water, dissolved minerals and suspended particles, in which α is the acoustic attenuation factor.

Thorne and Hanes (2002) make the assumption that scatterers are randomly distributed. Under strong turbulent conditions, this assumption may not hold. MR2006 and M2006 have shown that the Kolmogorov wavelength can become of the same size or even smaller than the wavelength of the sound wave, $l = 1.5$ mm, in the Marsdiep inlet due to the strong vertical shear and the resulting high turbulent intensity. In that case, small scale turbulent eddies of the Kolmogorov length scale disturb the background vertical SPM concentration profile such that sediment particles cluster in a "coherent" fashion. Wave crests of the reflected sound merge together and the random phase model no longer holds. MR2006 have derived a relation between the acoustic backscatter intensity and the SPM concentration for the turbulent regime, leading to the following set of equations:

$$\sigma = \frac{25}{48} \frac{k^4}{\pi \rho_s} \frac{\langle a_s^6 \rangle}{\langle a_s^3 \rangle} c \quad k \geq \frac{k_\eta}{2} \quad (2a)$$

$$\sigma = \frac{25}{64} \frac{k^4}{\pi^2 \rho_s^2} A \frac{\langle a_s^6 \rangle}{\langle a_s^3 \rangle} \alpha_c \beta \left(\kappa z \frac{h-z}{h} \right)^{\frac{2}{3}} (2k)^{-\frac{5}{3}} \left(\frac{dc}{dz} \right)^2 \quad k < \frac{k_\eta}{2} \quad (2b)$$

Equation 2a describes the commonly used linear or classical model and is complemented with Eq. 2b for the turbulent regime. The most important parameters are the wavenumber of the sound, k and the Kolmogorov wavenumber, k_η . Other parameters are the Von Karman constant, $\kappa = 0.4$, the total water depth, h , and the vertical coordinate, z , with $z = 0$ being the bottom and $z = h$ the sea surface and A represents the horizontal surface area of the acoustic bin. The radius of the sediment particles is given by a_s and the brackets $\langle \cdot \rangle$ indicate the ensemble average.

The Kolmogorov wavenumber is defined as $k_\eta = 2\pi/\eta$, in which the Kolmogorov length scale, $\eta = (\nu^3/\epsilon)^{1/4}$ with ν being the kinematic viscosity and ϵ the dissipation rate of turbulent kinetic energy. A common parameterization is used to estimate ϵ :

$$\epsilon = \frac{u_*^3}{h\kappa} \frac{(h-z)}{z} \quad (3)$$

which is slightly different from the parameterization used in MR2006 and M2006, who assume in first order a vertically constant dissipation rate of turbulent kinetic energy, ϵ . The friction velocity, u_* , is estimated from the depth-averaged velocity divided by 20, $\overline{U}/20$ with an estimated delay frequency of $1/\alpha_t = 15$ minutes:

$$\frac{du_*(t)}{dt} = \alpha_t \left(\frac{\overline{U(t)}}{20} - u_*(t) \right) \quad (4)$$

Equations 3 and 4 state that the switch between the classical Eq. 2a and turbulent Eq. 2b regimes are essentially determined by the depth-averaged current, $\overline{U}$. MR2006 give a detailed derivation of the equations and a description of the parameters.

4. Calibration

4.1. Velocity

The velocity data obtained with an ADCP on a moving platform is subject to errors introduced by heading offsets, errors due to the tilt of the ADCP beams, alignment and the mounting angle. From 2003 onwards, the ship's velocity was determined using the bottom tracking (BT) instead of differential GPS (as in BR2007). Using the BT derived ship's velocity to correct the ADCP velocities reduces the errors as the bottom tracking velocity is measured with the same device and in the same reference frame as the profiles themselves. The bottom track corrected velocity data, however, showed a discontinuity in the eastward and the northward component of the water velocity coincident with the replacement of the ADCP in 2004. Apparently, the new ADCP was slightly rotated, when it was mounted at the beginning of the second period. Moreover, the sound speed was likely incorrect as it is based on a given value of the salinity, which was set to $S = 32.2$ in the first and $S = 27.2$ in the second period. Rotating the BT velocities over an angle, α and scaling them with a factor β leads to the following equations for the true ship's velocity:

Figure 3: a) Angle, α between the GPS and bottom tracking (BT) derived ship velocity and b) Scaling, β , between the GPS and the BT derived ship velocity. Gray dots show the despiked results for each day and the black line is long term average, which is the median over a certain period in panel a and the 14-day running mean in panel b.

$$u = \beta(u_{bt} \cos \alpha - v_{bt} \sin \alpha) \quad (5a)$$

$$v = \beta(u_{bt} \sin \alpha + v_{bt} \cos \alpha) \quad (5b)$$

In which (u, v) is true ship's velocity and (u_{bt}, v_{bt}) the ship's velocity based on bottom tracking. The BT velocities are then least squares fitted to the ship velocity based on GPS measurements for each day of data separately.

Three different periods can be identified from figure 3. The first period lasts until April 15, 2004; the date on which the first ADCP broke down. During this period the mounting angle appeared to be $\alpha = -1.8^\circ$, which is different zero even though the ADCP was calibrated. On August 13, 2004, the new ADCP was installed and the mounting angle appeared to be $\alpha = +3.9^\circ$. On March 20, 2005 a sudden decrease in backscatter intensity in one of the beams was observed associated with a small increase in the angle to $\alpha = 4.3^\circ$.

A remarkable change is observed in the velocity scaling on April 14, 2004 from values generally larger than one to values generally smaller than one (Figure 3). This change occurred simultaneously with a firmware update and could be associated with a change in the salinity setting leading to an artificial increase in the sound speed. The 14-day running mean value for β is used in the scaling and that leads to a maximum correction of 1.5% of the velocity.

The first processing of the ADCP data is already performed in the device and by the computer programme collecting the data; velocities in the beam direction are rotated into earth coordinates corrected for the ship's speed using bottom tracking. Water velocities are therefore subjected to the same rotation angle α and scaling factor β as the ship's velocity derived with bottom tracking. Thus 5 has also been used to correct the water velocities.

4.2. SPM calibration

The grain size distribution is an important parameter in the theoretical model by MR2006 through the factors $\frac{\langle a_s^6 \rangle}{\langle a_s^3 \rangle}$ and $\frac{\langle a_s^6 \rangle}{\langle a_s^3 \rangle \langle a_s^3 \rangle}$. A cutoff diameter of $200 \mu m$ was used in the calculation

Figure 4: a) Mean grain size diameter and the factors $\frac{\langle a_s^6 \rangle}{\langle a_s^3 \rangle}$ and $\frac{\langle a_s^6 \rangle}{\langle a_s^3 \rangle \langle a_s^3 \rangle}$ averaged over the near bottom samples taken approximately every hour during the different 13-hours calibration cruises as a function of day of the year. Error bars indicate the standard deviation of the 14 samples taken during each calibration cruise.

of $\langle a_s^n \rangle$, to exclude sand grains that may have unintentionally been incorporated in the sample when the Niskin bottle was closed near the bottom. The mean and standard deviation of the grain size diameter and the factors $\frac{\langle a_s^6 \rangle}{\langle a_s^3 \rangle}$ and $\frac{\langle a_s^6 \rangle}{\langle a_s^3 \rangle \langle a_s^3 \rangle}$ were calculated for each calibration cruise, based on hourly samples taken near the bottom. The results are displayed in Figure 4 as a function of day of the year. Variations (indicated by errorbars) during a calibration cruise could not be linked to the tidal cycle and no annual cycle was observed. The mean grain size diameter over all calibration cruises is $31.7 \mu\text{m}$ and the mean values of both factors are $\frac{\langle a_s^6 \rangle}{\langle a_s^3 \rangle} = 1.55 \times 10^{-13} \text{ m}^3$ and $\frac{\langle a_s^6 \rangle}{\langle a_s^3 \rangle \langle a_s^3 \rangle} = 5.43 \times 10^3$. As these factors appear to be relatively constant the latter values are used in the rest of this paper. Both values are an order of magnitude smaller than those given by MR2006, which may be related to their different way of sampling. However, the SPM concentration is insensitive to this difference, since the ratio of both numbers is the same and will be compensated for by a much larger device dependent constant, k_i in equation 1.

4.3. Calibration of the ADCP derived SPM concentrations beneath the Navicula

The field data collected with the RV Navicula were used to determine the device dependent calibration constant of the ADCP under the Navicula, k_{Nav} . From Eq. 1 it is clear that the acoustic backscattering cross-section, σ , depends heavily on the counts threshold, N_t , or in other words that the device dependent calibration constant depends on the latter value. MR2006 already pointed out a systematic offset of 8 dB between two different instruments (their footnote 2). It was, however, not always recorded, which instrument was used. The 0.1 percentile of the backscatter values in the water column was taken to be the counts threshold, N_t , derived for each calibration cruise. A list of threshold values indicates that different instruments were used for the various calibration cruises (Table 1). The difference between the threshold value of the cruise on 2004-04-20 and 2004-06-03 is 20 Counts or 8.7 dB, similar to systematic offset found by MR2006.

The optically derived SPM concentration profiles have been bin-averaged on the same depths as the ADCP data. The ADCP data were time-averaged between 2 minutes before and 2 minutes after a CTD-cast. The top of the water column is influenced by bubbles generated at the surface or beneath the hull and the bottom part of the water column may be subjected to side-lobe interference. Therefore, only the relatively undisturbed data between 5.5 and 18 m were used. Note that, the exact numbers themselves are fairly arbitrary. Fig. 5 shows the acoustically derived SPM concentration using the classical regime only (2a) versus the optically derived SPM. A linear fit is made through data points for which the depth averaged velocity is less than $\bar{U} < 0.5$ m/s (black dots in Figure 5). This depth averaged velocity is well below the threshold at which the system shifts from the classical to the turbulent regime. For larger depth averaged velocities, $\bar{U} \geq 0.5$ m/s (red dots in Figure 5), the acoustically derived SPM concentrations are usually overestimated; these are very likely in the turbulent regime.

The device dependent constants for all calibration cruises, k_{Nav} and offsets, c_0 , are given in Table 1 with the coefficient of determination, R^2 , of the linear fit. The offset, c_0 , may possibly be caused by an excess of salt, if the filters are not rinsed thoroughly enough or systematic errors in the depth measurements of the CTD and ADCP. Besides that, a difference of 7 mg/l was found between two different methods to determine the SPM concentration of the exact same sample. The calibration constant of the ADCP is fairly constant: $k_{Nav} = 9.2 \cdot 10^{-10} \pm 7.0 \cdot 10^{-11}$, which supports our assumption that both the device dependent calibration constant and the factor $\frac{\langle a_s^6 \rangle}{\langle a_s^3 \rangle}$ from the grain size distribution are indeed constant. Gathering the data of all 7 calibration cruises together (not shown) leads to one device dependent constant of $k_{Nav} = 1.1 \cdot 10^{-9}$ ($R^2 = 0.76$), which is used in the rest of this paper.

Fig. 6 shows the relation between the acoustically derived SPM concentration and the optically derived one for the depth range between 5.5 and 18 m; 48 % of the data are in the classical (panel a) and 52 % are in the turbulent regime (panel b). To conclude, if we would only apply the classical relation to the data, half of the acoustically derived SPM concentrations would be (significantly) overestimated.

4.4. Calibration of the boundary condition

To derive an SPM concentration profile, $c(z)$, from acoustic backscatter intensity, a constant of integration is needed to solve (2b), if the entire water column is in the turbulent regime. In the latter equation the acoustic cross-section, σ , is derived from (1). In the calibration of the ADCP beneath the Navicula for SPM concentration, *in-situ* observations of the optically derived SPM concentration at a depth of $z=7.2$ m were used as a boundary condition, if necessary. However,

Figure 5: SPM concentration derived from acoustic backscatter using the classical regime only (equation 2a) versus the SPM concentration derived from OBS. Black (gray) triangles (dots) represent data for which the depth average velocity $\bar{U} < 0.5$ m/s ($\bar{U} \geq 0.5$ m/s). Drawn is the linear fit through the black triangles. The panels show the results for measurements on 2004-04-20 and 2004-06-03, respectively, and represent the worst and the best fit of all calibration cruises.

Figure 6: SPM concentration from ADCP versus the one from OBS for all observations taken between 5.5 and 18 m depth. Panel a) indicates data points that are in the classical and panel b) in the turbulent regime. The coefficient of determination, R^2 , of the combined data is 0.71.

cruise date	N_t (Counts)	k_{Nav}	c_0 (mg/L)	R^2
2003-04-24	64	$8.69 \cdot 10^{-10}$	-4.7	0.70
2003-09-17	59	$9.95 \cdot 10^{-10}$	-2.8	0.50
2003-11-05	61	$9.56 \cdot 10^{-10}$	-4.8	0.78
2004-04-20	62	$1.02 \cdot 10^{-9}$	0.0	0.54
2004-06-03	42	$8.39 \cdot 10^{-10}$	0.2	0.91
2005-05-23	35	$8.30 \cdot 10^{-10}$	-7.5	0.83
2005-11-23	58	$9.27 \cdot 10^{-10}$	-4.7	0.86

Table 1: Threshold value, N_t (Counts), device dependent calibration constant, k_{Nav} , and offset, c_0 , for the ADCP under the RV Navicula, as well as the R^2 of the linear fit between the ADCP and OBS derived SPM concentration and depth averaged velocities of $\overline{U} < 0.5$.

across the ferry transect no *in-situ* optically derived SPM observations are available. Therefore, we have derived a boundary condition empirically.

Clearly, the dissipation rate of turbulent energy, ϵ , is an important parameter in the theory to derive the SPM concentration from the acoustic backscatter intensity. Below a certain critical dissipation rate, ϵ_{crit} , in the classical regime, the SPM concentration can simply be derived from (2a). From figure 7a it appears that the SPM concentration may be related to the turbulent dissipation rate through a power law above a certain critical dissipation rate, ϵ_{crit} . Thus the following empirical relationship is tested with the observations made during the 13-hours surveys with the Navicula:

$$\frac{c_{OBS}}{c_{ADCP}} = C \quad \epsilon \leq \epsilon_{crit} \quad (6a)$$

$$\frac{c_{OBS}}{c_{ADCP}} = A \left(\frac{\epsilon}{\epsilon_{crit}} \right)^B \quad \epsilon > \epsilon_{crit} \quad (6b)$$

where A , B , C and ϵ_{crit} are the parameters to be determined. It is assumed that the ratio of the optically and acoustically derived SPM concentration is continuous in ϵ . This implies that $C = A$, leaving three unknowns, which are solved using a least squares method. The values obtained for A , B and ϵ_{crit} vary with depth (not shown). The parameters, $A(C)$, decrease with depth and is in the range of $A = 0.8$ to 1.2 for depths from $z = 6.2$ to 14.2 m. The power, B , of the fit decreases with increased depth and stabilizes at about $B \approx -1.2$ for depths larger than $z > 5.2$ m. The critical dissipation rate, ϵ_{crit} , increases with increasing depth. We select a depth of $z = 9.2$ m to apply the boundary condition as it is still in the top part of the water column, but only weakly influenced by disturbances at the surface. At this depth, the values for the constants are: $\epsilon_{crit} = 5.4 \cdot 10^{-6} \text{ m}^2/\text{s}^3$, $A = C = 1.1$, $B = -1.2$, leading to the fit displayed in Figure 7a. In section 4.3, the definition of the classical regime is based on a critical value of the depth-averaged velocity $\overline{U} < 0.5$ m/s, whereas in this section it is based on the critical dissipation rate, ϵ_{crit} . Even though the latter is related to the former (with a time delay), minor changes in the boundary between the classical and turbulent regime apparently lead to a value for A which is different from 1.

Figures 7b and c show two examples of time-series of the optically and acoustically derived SPM concentration using the best fit, of the data derived on 2004-04-20 and 2003-11-05, respectively. These represent the best and the worst fit. SPM concentrations in the classical regime

Figure 7: Top panel: Optically derived SPM concentration at $z = 9.3 m$ divided by the acoustically derived SPM concentration using the classical regime only (black dots). Drawn black lines are the best fit to the theory with $\epsilon_{crit} = 5.4 \cdot 10^{-6} m^2/s^3$, $A = C = 1.1$, $B = -1.2$. Bottom panel: examples of the optically derived SPM concentration (black) and acoustically derived SPM concentration by using the boundary condition (6); black triangles show data for which $\epsilon \leq \epsilon_{crit}$ and gray dots is for $\epsilon > \epsilon_{crit}$. The SPM concentrations are shown for calibration data on 2004-04-20 in (b) and 2003-11-05 in (c).

($\epsilon \leq \epsilon_{crit}$) are low and acoustically derived SPM concentrations (green) generally agree well with the optically derived ones (black). SPM concentrations in the turbulent regime ($\epsilon > \epsilon_{crit}$) are much higher. Absolute values of the ADCP derived SPM concentrations in the turbulent regime have the correct order of magnitude, but sometimes seem to be displaced in time, which is especially visible for the data on 2003-11-05. This may be caused by the delay time, $1/\alpha_T$, between the depth averaged velocity, $\bar{U}$, and the friction velocity, u_* , in (4), neither being constant nor exactly 15 minutes.

4.5. Calibration of the ADCP beneath the ferry

For the ferry data, the threshold value, N_t , is determined in a similar way as for the calibration data for each day and each beam separately. The median values are remarkably similar for both periods and for the individual beams. During the first period, the threshold values $N_t(1, 2, 3)=(49, 52, 47)$ Counts for beams 1, 2 and 3, respectively. In the following period the threshold values are $N_t(1, 2, 3)=(50, 45, 44)$ Counts. On March 20 (2005), backscatter intensities of beam 2 dropped significantly throughout the entire water column, when this particular transducer apparently was damaged. This is also reflected in a reduction of the threshold value, $N_t(2) = 20$ Counts. From this date, backscatter intensity data from beam 2 are left out of the estimation of the SPM concentration. Velocity profiles from this period, however, are still assumed to be unaffected as they do not depend on the backscatter intensity, but on the Doppler shift of the sound frequency.

The device dependent calibration constant for the ADCP under the ferry can now be determined by comparing the corrected backscatter intensities of the devices beneath the ferry and the Navicula at the instances when the ferry passes by the RV Navicula. Data in the top three bins of the ferry and bottom two bins of the Navicula are neglected. The gridded ferry data are used and the Navicula data were time-averaged for the period that the ferry was in the same horizontal grid cell as the Navicula (2). The acoustic cross-section of the data of the Navicula, σ_{Nav} , is interpolated to same depths as the data of the ADCP beneath the ferry. For all the calibration cruises individually, the associated device dependent, k_{Fer} is fairly constant, which validates the approach to estimate the threshold value, N_t . Gathering all calibration data together leads to a value of $k_{Fer} = 3.7 \cdot 10^{-9}$ with a relatively high coefficient of determination, $R^2 = 0.80$ (Figure 8).

5. Long-term volume- and SPM fluxes through the Marsdiep inlet

Volume fluxes and SPM fluxes through the Marsdiep inlet were calculated using velocities and SPM concentrations determined using the theory by Merckelbach (2006) after performing all steps in the calibration described above. SPM concentrations in the top four bins were generally unrealistically high, because of the presence of air bubbles beneath the hull. The boundary condition (section 4.4) was therefore applied to the acoustic backscatter data to a depth of $z = 9.3$ m below the ferry. Extremely high values were considered to be overestimates related to the application of the classical regime, where the system was in fact in the turbulent regime. To remove these data, the daily top 2% of the SPM concentrations were marked as outliers. Subsequently, a Rouse profile (Dyer, 1985) was least squares fitted to the remainder of the SPM data and these outliers as well as the SPM concentrations in the top 4 bins were replaced by applying the fit. The Rouse profile obeys the following equation:

$$c(z) = c_a \left(\frac{a}{a-h} \right)^B \left(\frac{h-z}{z} \right)^B, \quad B = \frac{w_s}{\kappa u_*} \quad (7)$$

Figure 8: Drawn is the linear relation between the corrected acoustic backscatter (dB) of the ADCP under the Ferry and the one of the Navicula. Data is used of all different calibration cruises except the one on 2004-06-03 as no ferry data were available at this date.

In which B is the Rouse parameter, w_s the settling velocity, a the reference height and c_a the concentration at $z = a$ and u_* the friction velocity from (4). The settling velocity can be estimated from Stokes law (Dyer, 1985):

$$w_s = \frac{2}{9} a^2 g \left(\frac{\rho_s - \rho}{\mu} \right) \quad (8)$$

where μ is the molecular dynamic viscosity.

This approach sometimes also led to extremely high concentrations in the bottom bin, which were subsequently removed by marking the the top 1% of the remaining SPM concentrations for each day as outliers.

Before performing a cross-sectional integration, the binned data were converted into 30 bottom-following sigma coordinates. In this conversion, the horizontal velocity was assumed to be zero at the bottom (no-slip boundary condition) and the SPM concentration was assumed to be constant from the deepest valid measurement downwards. In the top 6.3 meters, above the top bin of the ferry-mounted ADCP, it was assumed that the velocity remains constant. There, the mean velocity of the top five sigma levels was applied (similar as in BR2007a). The SPM concentration was assumed to go linearly to zero at the surface. Integration of the data across the inlet and over depth leads to estimates of the water volume transport, channel-mean SPM concentration and SPM flux for every crossing, and leads to values at 30-minute intervals assuming that the data is gathered quasi-synoptic as a crossing takes about 15 minutes. Note that profiles of the SPM flux were fairly constant over depth (not shown) as SPM concentration in the top (near the bottom) were relatively low (high) and velocities high (nearly zero). This suggests that the choice to fit the SPM data to the Rouse model is not really significant as long as the SPM profile is the inversely proportional to the velocity profile.

The amplitudes of the (water) volume transports are between about $5 \cdot 10^4$ and $10 \cdot 10^4 \text{ m}^3/\text{s}$ (Figure 9a), comparable to the values found by BR2007. The channel mean SPM concentrations were comparable in the period before and after the data gap in 2004 (Figure 9b), suggesting that the corrected backscatter intensity in both ADCPs was well-calibrated for SPM concentration. The spring-neap tidal cycle is evident in the observed SPM concentration and especially in the SPM flux (Figure 9c).

The semi-diurnal character and the spring-neap tidal cycle are clearly visible in the time-series of the volume transport of a typical month, September, 2003 in this case (Figure 10a). A considerable spring-neap tidal cycle was also present in the time series of the SPM concentration. During spring tide the maximum SPM concentration exceeds 60 mg/l, while it remains below about 35 mg/l during neap tide. However, also note differences between successive spring tides and neap tides. Moreover, during the winter months concentration seem to be higher and more in the order of 50 to 100 mg/l for neap and spring tides (Figure 9b).

The time series of the SPM flux shows behavior similar to those of the volume transport (Fig. 10c). The semi-diurnal and spring-neap tidal cycle could be observed and the diurnal inequality was also present; the second peak in the SPM flux was 92% of the first peak. The difference between the amplitudes during spring tide and neap tide was enhanced compared with that of the volume transport. During neap-tide the amplitude was about $2 \cdot 10^3 \text{ kgs}^{-1}$, while it was about twice this value during spring tide.

The daily cycle of the volume transport, SPM concentration and SPM flux for 15 September 2003 is shown in Figure 11, being a typical example. The volume transport displays a semi-diurnal cycle, while the SPM concentration has a quarter-diurnal signal as it peaks both during

Figure 9: a) Volume transport (m^3/s), b) transect averaged SPM concentration (kg/m^3) and c) SPM flux ($kg s^{-1}$) through the Marsdiep inlet.

Figure 10: a) Volume transport (m^3/s), b) transect averaged SPM concentration (kg/m^3) and c) SPM flux (kg s^{-1}) through the Marsdiep inlet zoomed in on September 2003.

Figure 11: a) Volume transport (m^3/s), b) transect averaged SPM concentration (kg/m^3) and c) SPM flux (kg s^{-1}) through the Marsdiep inlet zoomed in on 15 September 2003.

the flood and during the ebb phase of the tide. The increase of the SPM concentration occurs some time after slack tide, which suggests that there exists a critical erosion shear stress (de Swart and Zimmerman, 2009). A lag of about one hour can be recognized between the maximum (minimum) volume transport and the subsequent peak in the SPM concentration indicating that it takes a certain amount of time for the particles to get up into the water column. This is slightly longer than the lag of 0.16 to 0.36 hours found in the Frisian inlet between silt and current speed (van de Kreeke and Hibma (2005)). Furthermore, a lag can be observed between the slack tides and the minimum SPM concentration, which is due to the time necessary for particles to settle on the sea floor.

5.1. Long-term average transport, SPM concentration and SPM flux

The long-term mean values were not determined by taking the mean, because the data is not equally distributed over time (hardly any night-time data). Instead it is determined by applying a least squares harmonic analysis (LSHA) and taking the residual values. This was done using the T.Tide software to the entire time-series and the two periods separately (Pawlowicz et al., 2002). The residual volume transport, SPM concentration and SPM flux (Table 2) can be regarded as

good representations of the long-term averages. The prediction of the volume transport, using the significant frequencies, explained more than 95 % in the analysis of either period as the volume transport at any moment is largely determined by the tides. In general, the significant components were the high-frequency ones with periods less than a day. Only during the first period the lower frequency components such as Sa, MsF and MF were significant.

The residual volume transport is less than 6% of the amplitude of the dominant M2 tidal component. It is save to assume that the error in the velocity measurements does not have a tidal period as it is either randomly distributed or related to the velocity of the ferry. Therefore, most of the error will enter in the residual value as noise in a least squares harmonic analysis. Thus, the relative error in the residual transport is likely larger than the relative error in the tidal transport. The volume transport suggests a shift from a long-term average outflow from the Wadden Sea to the North Sea of $1.6 \cdot 10^3 \text{ m}^3/\text{s}$ in the first period to an inflow of $3.6 \cdot 10^3 \text{ m}^3/\text{s}$ in the second period. Daily values of the along-channel residual water transport are correlated with the daily mean 10-meter wind velocity at Den Helder airport the Kooy (Royal Dutch Meteorological Office, KNMI) and is found to be maximal for the wind vector from a direction of 186° (Fig. 12). Hence, near southerly (northerly) winds are correlated with a residual water transport towards (away from) the Wadden Sea. Southwesterly winds prevail in this region, but during first observation period northeasterly winds were observed more often than usual, leading to the change in direction of the mean volume transport between both periods. This has not been observed in previous studies using ferry-based observations in the Marsdiep inlet for the period 1998-2002 in Buijsman and Ridderinkhof (2007a,b).

It is strictly speaking not appropriate to apply a LSHA with tidal components to the time-series of the SPM concentration as it is not known beforehand that tides determine the variations in the SPM concentration. A LSHA analysis will provide the deterministic part of the signal, a residual value and the remainder is composed of a trend and noise (van de Kreeke and Hibma (2005)). The variability of the SPM concentration is only partially deterministic, which is reflected by the low percentage of predicted variance over the variance in the original time-series, which is 59%, 48% and 50% for the first, the second and the total time-series, respectively. The residual SPM concentration is between 24 and 25 mg/l and thus is similar for the two periods. The M2 and M4 tidal components always had the highest signal to noise ratio. The significance of the M4 tidal component reflects the doubling of the M2-frequency in the SPM concentration (Figure 11). The relative importance of the M2 tidal component is reflected in higher (lower) SPM concentrations during the flood (ebb) phase of the tide.

The long-term residual SPM flux was $3.0 \cdot 10^2 \text{ kgs}^{-1}$ for the entire period from 2003 to 2005 (2.3 and $3.6 \cdot 10^2 \text{ kg s}^{-1}$ in the first and the second period). This long-term residual SPM flux equals to about 7-11 Mton/yr. This is a substantial part of the estimated northward SPM flux along the North Sea coast of the Netherlands, which amounts to about 25 Mton/yr (de Kok, 2004). Low-pass filtering the time-series of the transport, channel mean SPM concentration and SPM flux did not reveal significant seasonal variability.

The SPM flux is positive, thus towards the Wadden Sea in both the first and the second period, whereas the water transport changes sign between the two periods. This indicates that other processes besides the advection of the long-term mean SPM concentration by the residual flow must be important in transporting SPM. The instantaneous longitudinal flux can be decomposed into six different terms, following Medeiros and Kjerfve (2005), who use a modified version of the decomposition performed by Hansen (1965) and Dronkers and van de Kreeke (1986) for the salt flux:

Figure 12: Daily residual volume transport versus the wind speed from a direction of 186° ; dots are individual data points and the drawn line is the least squares fit with $R^2 = 0.3$.

	Length Time Series	Transport	SPM	SPM Flux
	(days)	($\cdot 10^3 \text{ m}^3/\text{s}$)	(mg/l)	($\cdot 10^2 \text{ kg s}^{-1}$)
2003-2005	998	1.1	25	3.0
2003-2004	451	-1.6	24	2.3
2004-2005	547	3.6	25	3.6

Table 2: Long-term residual transport (m^3/s), SPM concentration(mg/l) and SPM flux ($\text{kgm}^{-2}\text{s}^{-1}$) through the Marsdiep inlet determined by a least squares harmonic analysis using 68 tidal components for the entire three year time series.

$$F(t) = \int_A \int u(y, z, t) c(y, z, t) dy dz \quad (9)$$

Here, u , is the eastward component of the velocity (m/s) and c the SPM concentration (kgm^{-3}) and $A(t)$ is the cross-sectional (wet) area of the inlet. Now, the instantaneous velocity and concentration are decomposed into a cross-sectional average value (over-bar) and a deviation from this average (prime).

$$u(y, z, t) = \bar{u}(t) + u'(y, z, t) \quad (10a)$$

$$c(y, z, t) = \bar{c}(t) + c'(y, z, t) \quad (10b)$$

Then the cross-sectional averages and the cross-sectional area, A , are decomposed into tidal residual terms, subscripted 0, and tidally varying terms, subscripted T:

$$\bar{u}(t) = u_0 + u_T(t) \quad (11a)$$

$$\bar{c}(t) = c_0 + c_T(t) \quad (11b)$$

$$A(t) = A_0 + A_T(t) \quad (11c)$$

Substituted into (9) and taking its residual leads to the following for the long-term residual flux:

$$F_0 = A_0 u_0 c_0 + (A_T u_T c_T)_0 \quad (12a)$$

$$+ u_0 (A_T c_T)_0 + c_0 (A_T u_T)_0 \quad (12b)$$

$$+ A_0 (u_T c_T)_0 + (\overline{A u' c'})_0 \quad (12c)$$

In our analysis we have used the residual value from a least squares harmonic analysis (using all significant tidal frequencies) instead of the average for all variables subscripted 0. The terms on the right-hand side of (12) are given in Table 3 for the entire period (2003-2005) and for the first (2003-2004) and second (2004-2005) period, separately. The tidal velocity concentration flux, $A_0 (u_T c_T)_0$, is the most dominant term and explains 70 to 90% of the total residual flux, F_0 . This term together with the tidal concentration flux and the tidal pumping flux form the non-local contribution to the flux. For the first and the second period, the next most dominant term is the residual advective flux, $A_0 u_0 c_0$, and has a contribution of about $\pm 20\%$. This term changes sign, however, leading to a small effect on the total SPM flux over the entire 3 year period (4%). The sign change of the residual eastward velocity, u_0 , is the cause for this, because the residual cross-section, A_0 , and the residual SPM concentration, c_0 , remain of similar size (and sign). Changes in residual eastward current are probably related to differences in the wind forcing as has been

		2003-2005	2003-2004	2004-2005
residual flux	F_0	299	229	362
residual advective flux	$A_0 u_0 c_0$	11	-48	63
tidal pumping flux	$(A_T u_T c_T)_0$	9	9	10
tidal concentration flux	$u_0 (A_T c_T)_0$	0	0	0
tidal wave flux	$c_0 (A_T u_T)_0$	27	27	27
tidal velocity-concentration flux	$A_0 (u_T c_T)_0$	242	210	270
cross-sectional shear dispersion	$(A u' c')_0$	10	31	-8

Table 3: Analysis of terms in equation 12 for the periods 2003-2005, 2003 - early 2004 and end 2004 - 2005 (kg/s).

discussed in relation to Fig. 12. Overall, the tidal wave flux, $c_0(A_T u_T)_0$, and the cross-sectional shear dispersion (or local flux), $(A u' c')_0$, are only contributing only less than 15%, which makes them relatively unimportant.

Focussing further on the dominant term, e.g. the tidal velocity-concentration flux, $A_0(u_T c_T)_0$, we observe that interactions between u_T and c_T only contribute if both contain a significant amplitude and a small phase difference at the same tidal frequency, e.g.:

$$A_0(u_T c_T)_0 = A_0 \sum_{i=1}^N u_i c_i \cos(\phi_{c,i} - \phi_{u,i}) \quad (13a)$$

where u_i and c_i are the amplitudes of the velocity and SPM concentration at the i -th tidal frequency and $\phi_{u,i}$, $\phi_{c,i}$, the phases. The largest contributions are from the M2 and S2 components, contributing 234 and 25 kg/s to the tidal velocity-concentration flux. At first glance, the M4 component seems to be important as well, because the SPM concentration has a significant contribution at this frequency. However, it actually causes an export of -3 kg/s, because the phase difference between the SPM concentration and the velocity is 97 degrees at this frequency. The tidally varying SPM concentration has a component on the M2 tidal frequency with an amplitude of 7.8 mg/l, which is comparable to the amplitude on the M4 tidal frequency, being 7.2 mg/l. The phase lag between the velocity and the SPM concentration on the M2 tidal frequency is only 22 degrees, or 47 minutes, which leads to a significant contribution in the flux. The fact that the SPM concentrations are higher during flood than during ebb introduces the M2 tidal frequency component in the harmonic analysis and of the SPM concentration and is the main cause for sediment transport from the North Sea to the Wadden Sea. Additional explanation on why the SPM flux is towards the Wadden Sea will be provided in the next section.

5.2. The SPM transport model by Groen (1967)

A nice illustration of the tidally dominated process causing SPM import into the Wadden Sea is given in Figure 13. Here the sectional averaged SPM concentration is shown against the sectional averaged velocity. Each dot in this figure represents a single transect with the channel mean velocity on the horizontal and the channel mean SPM concentration on the vertical axis, where positive (negative) velocities indicate flood (ebb) velocities directed from the North Sea (Wadden Sea) into the Wadden Sea (North Sea). The velocity was binned in steps of 0.1 m/s, where a distinction was made between increasing and decreasing velocities. The channel mean SPM concentration within the specified velocity bins were averaged and shown by the drawn lines; the dark gray line represents increasing and white line decreasing velocities. Note that

SPM concentrations increase with increasing speeds (the gray line on positive V-axis and the white line on the negative V-axis), but that highest SPM concentrations are only found, when the speeds are decreasing again (the white line on positive V-axis and the gray line on the negative V-axis). This confirms the phase delay of the SPM concentration relative to the tidal speed. During flood, maximum current speeds occur in the Marsdiep inlet, due to tidal asymmetry Buijsman and Ridderinkhof (2007a). Highest SPM concentrations also occur during the flood phase, leading to an excess SPM flux into the Wadden Sea.

6. Conclusions and discussion

Until now estimates of the SPM flux in the Wadden Sea were based on surface measurements (Postma, 1961, 1981; Eisma et al., 1987) or indirectly derived from deposition rates (Eisma, 1993). Both methods probably lack sufficient information to derive a reliable flux as surface SPM concentrations do not represent concentrations in the entire water column well. Moreover, SPM concentrations from model output strongly depend on boundary conditions, which are often not well calibrated against in-situ measurements, since these are generally not available throughout the total water depth for a significant period and under variable forcing- and meteorological conditions.

In this paper, SPM concentration profiles were determined from the acoustic backscatter intensity, recorded by the ADCP below the ferry crossing the Marsdiep inlet, using the method by Merckelbach (2006). Two major improvements are made to the method, namely a new empirical boundary condition to determine the SPM concentration near the surface in the turbulent regime and a new approach to determine the threshold value for the backscatter intensity. The latter approach has led to a constant value for the device dependent constant, k_t , even though different ADCPs have been used throughout the measurement period. This provides additional confidence in the method to derive SPM concentration profiles from acoustic backscatter intensity. Moreover, the SPM flux is easily determined, since velocity profiles are obviously also available from the ADCP measurements.

The residual volume transport displayed inter-annual change in direction from the first period from 2003-2004 (towards the North Sea) to the second period 2004-2005 (towards the Wadden Sea). These results differ from the model results by Ridderinkhof (1988). Without wind stress forcing, his model gives a residual transport from the Vlie inlet to the Marsdiep inlet driven by the tidal stress. BR2007 found a westward transport through the Marsdiep inlet of $-2.91 \cdot 10^3 \text{ m}^3/\text{s}$ for the earlier period between 1998-2002. However, they did not use bottom tracking to correct for the ships velocity in their ADCP measurement, which may lead to a less accurate transport estimate. In our study, the daily mean residual volume transport correlates with the daily mean wind speed component from 186° . This suggests that the long-term variation in the residual transport is probably due to significant differences in the meteorological forcing conditions of the along-shore current.

The main conclusion is that the long-term mean SPM flux based on well calibrated ADCP measurements is about 7 to 11 Mton/yr and indeed from the North Sea to the Wadden Sea and thus from low to high concentration. The dominant contribution to the residual flux is from the tidal velocity-concentration flux; it contributes more than 75%. The tidal speeds and the SPM concentration variations have $O(1)$ contributions to the amplitude and are almost in phase. Because of tidal asymmetry and the SPM concentrations being higher during flood, a net import of suspended sediment is generated. This was demonstrated by the dominant contribution of the correlation of the tidal varying velocity and SPM concentration on the M2 tidal frequency. The

Figure 13: SPM concentration against velocity. The black dots are the channel averaged SPM concentration against the channel mean eastward velocity for each transect for the years 2003 until 2005. The colored dots are the binned averaged concentrations for velocity bins of 0.05 m/s. In this, red represents increasing velocities, $du/dt > 0$, and yellow decreasing velocities, $du/dt < 0$. Positive (negative) velocities represent flood (ebb) velocities.

fit of the data to the Groen (1967) model for sediment flux provided additional evidence for this process. The advective residual flux of sediment is not negligible. It contributes about 21% to the residual flux from year to year, but only 4% of the 3-year average flux.

The long-term mean flux of SPM of 7 to 11 Mton/yr equally distributed over the Marsdiep backbarrier basin in the Wadden Sea would have caused a bottom rise of 4 to 6 mm/yr, given that the Marsdiep area is approximately 755 km² and the density of SPM is roughly $\rho_s = 2650$ kg/m³. In reality, sediment doesn't have a 100% packing and the bulk density is less, leading to larger bottom rise. Thus, this amount of sediment is well capable to prevent the Marsdiep basin from 'drowning' or 'filling up' as the relative sea level is rising at nearly the same pace of about 3.5 mm/year (consisting of 1.7 mm/yr subsidence and 1.8 mm/yr sea level rise, Hoeksema et al. (2004)). Moreover, part of the long-term mean flux through the Marsdiep inlet might leave the Wadden Sea through other inlets, possibly reducing the total net influx. Concluding, we can remark that monitoring the water velocity and SPM concentration with a ferry mounted ADCP is an adequate method to obtain reliable estimates of the transport of water and SPM as well as gaining insight into the dominant processes and sources of variability.

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Reviewers' comments:

Reviewer #1:

Ref: long-term ferry-based observations...

Nauw et al

1. This is a rather long paper (I don't know if there is a limit on the number of pages in NJSR). The fact is that if you want to get your message across, the shorter the paper the better. With regards to the present paper there are two messages to two different (informed) audiences. One message deals with the calibration of the backscatter signal the other with the long term volume fluxes, SPM and SPM fluxes. I strongly suggest to present these messages in two companion papers, each standing on its own. The paper on long term volume fluxes, SPM and SPM fluxes would include sections 1 , 2.1 , an expansion of the present section 5 and part of section 6. It is these sections which I have reviewed. The sections on calibration are beyond my area of expertise.

Response to reviewer comment No. 1:

We have chosen not to split the calibration and the results into two separate papers, because the calibration is more an application and extension of previous work by Merckelbach (2006) and Merckelbach and Ridderinkhof (2006).

Overall I am impressed with the data that is available and would make for an excellent paper. However in its present form I find especially Section 5 lacking in physical interpretation and reference to especially other studies in the Dutch Wadden Sea. In the following I have made some comments and suggestions.

2. P 2. Line 8 Marsdiep channel. Better Marsdiep Inlet.

Response to reviewer comment No. 2:

We have changed "channel" into "inlet" throughout the ms.

3. P 2. Line 21 In addition to the difference in tidal amplitude didn't the phase difference between Vlie and Marsdiep play a role as well?

Response to reviewer comment No. 3:

Indeed, the sentence has been altered into:

"This is attributed to a larger tidal range in the Vlie inlet compared to that of the Marsdiep inlet by and phase difference between the arrival of the tidal wave in both inlets (~1.7 hours, Ridderinkhof, 1988b)."

4. P3. Line 38. Be more specific. Mention that no measurements were made during the night (12-6 ?). During the day time you have measurements extending over 15 minutes every 30 minutes?

Response to reviewer comment No. 4:

*This sentence is removed here and additional information is given in section 2.1: "Ferry Data":
The ferry crosses the 4.5 km wide Marsdiep inlet in approximately 15 minutes. Every 30 minutes a crossing takes place between 6:00 (7:00 on Sundays and holidays) and 22:00 local time.*

5. P 4. Texel Inlet? Confusing for readers outside The Netherlands. Suggest you use either Marsdiep Inlet or Texel inlet.

Response to reviewer comment No. 5:

"Texel inlet" is changed into "Marsdiep inlet" throughout the manuscript.

6. P 17. Line 53. How well do the data conform to the Rouse profile? Present plots and R2 values.

Response to reviewer comment No. 6:

*Even though the request seems fair, it is not possible to show the results of fitting the Rouse profiles. They are performed for each gridcell of data and thus 50 profiles per transect and something like 32*50 profiles per day and 32*50*O(200) profiles per year, leading to 32*50*O(200)*3= O(10⁶) profiles. We can't imagine a way to properly display that in a single plot.*

We explain that our choice for fitting the SPM concentration to the Rouse profile is not significant for the estimation of the SPM flux.

We added the following:

"Note that profiles of the SPM flux were fairly constant over depth (not shown) as SPM concentration in the top (near the bottom) were relatively low (high) and velocities high (nearly zero). This suggests that the choice to fit the SPM data to the Rouse model is not really significant as long as the resulting SPM profile is the inversely proportional to the velocity profile."

7. P20. Lines 28-33. Be specific about what is plotted in Fig 12. Are those the 15 minute mean values ?

Response to reviewer comment No. 7:

The following sentence is added to the paragraph before line 28 on p20.:

Integration of the data across the inlet and over depth leads to estimates of the water volume transport, channel-mean SPM concentration and SPM flux for every crossing, and leads to values at 30-minute intervals assuming that the data is gathered quasi-synoptic as a crossing takes about 15 minutes.

8. P 20. Lines 37-40. Looking at Fig 12 b seem more like 50 mg/l for neap tide and 100 mg/l for spring tide. Value agree with observations in the nearby Frisian Inlet (van de Kreeke and Hibma, 2004).

Response to reviewer comment No. 8:

For the data of September 2003 in figure 13, the numbers of 35 mg/l and 60 mg/l for neap and spring tide seem appropriate.

We added:

Moreover, during the winter months concentration seem to be higher and more in the order of 50 to 100 mg/L for neap and spring tides (Figure 12).

9. P 20 Line 43. I believe you but daily inequality in SPM flux is not obvious from Fig 13c. Show this in a separate figure.

Response to reviewer comment No. 9:

We agree that the daily inequality is not obvious from the figure, but nevertheless it is in there. Therefore we changed this line into:

The semi-diurnal and spring-neap tidal cycle could be observed and the diurnal inequality was also present; the second peak in the SPM flux was 92% of the first peak.

10. P 20. Line 49-50. Lag between SPM and current speed. The existence of a critical shears stress implies that silt is eroded from the bottom. Not knowing the bottom composition of the Marsdiep inlet my guess would be that the silt in the inlet is derived from the North Sea and the Wadden Sea. The lag is simply the result of the time required to transport the silt upward in the water column. It might be of interest that in the Frisian Inlet using spectral analysis the lag between current speed and SPM was approximately 0.2 hours.

Response to reviewer comment No. 10:

The text is changed into:

"A lag of about one hour can be recognized between the maximum (minimum) volume transport and the subsequent peak in the SPM concentration indicating that it takes a certain amount of time for the particles to get up into the water column. This is slightly longer than the lag of 0.16 to 0.36 hours found in the Frisian inlet between silt and current speed (van de Kreeke and Hibma, 2005). Furthermore, a lag can

be observed between the slack tides and the minimum SPM concentration, which is due to the time necessary for particles to settle on the sea floor.”

11. P 23. Lines 43-45. Define "long-term residual values". Is this the long-term average or does it refer to the residuals in the harmonic analysis. To calculate the long term average you do not need a harmonic analysis. You use T_Tide and state “no frequencies were inferred”. That cannot be correct because T_Tide prescribes the astronomical frequencies.

Response to reviewer comment No. 11:

Indeed this refers to the residual of a harmonic analysis.

The lines are changed into:

“The long-term mean values were not determined by taking the mean, because the data is not equally distributed over time (hardly any night-time data). Instead it is determined by applying a least squares harmonic analysis (LSHA) and taking the residual values.”

If frequencies cannot be resolved because the timeseries are too short, but if the phase/amplitude relation with some other frequency, that can be resolved in analysis, is known; this ‘unresolvable’ frequency can be inferred (Pawlowicz, 2002). We removed “no frequencies were inferred” as it apparently only generates confusion and is irrelevant, because we have a long time-series.

12. P 23. Line 47. List the significant frequencies.

Response to reviewer comment No. 12:

We think it is not useful to list all 48/46/33 of the 68 components for each of the periods separately.

Instead, we added:

“In general, the components that are significant are high-frequency with periods less than a day.

Only during the first period the lower frequency components such as Sa, MsF and MF are significant.”

13. P 23 Line 51-52. "the relative error in the residual transport is likely larger than the relative error in the tidal transport". Be specific, explain why you expect it to be larger.

Response to reviewer comment No. 13:

Added:

“We can assume that error in the velocity measurements had no tidal frequency as it is either randomly distributed or related on the velocity of the ferry. Therefore, most of the error will enter in the residual value in a harmonic analysis.”

14. P 24. Line 40 Instead of the variable part, better the variation of the residual volume transport.

Response to reviewer comment No. 14:

Changed accordingly

15. P 24 Line 49. The harmonic analysis will give you the deterministic part of the signal, the remainder is trend and noise. For this see van de Kreeke and Hibma (2004)

Response to reviewer comment No. 15:

Agreed. The sentence is changed into:

A LSHA analysis will provide the deterministic part of the signal, a residual value and the remainder is composed of a trend and noise (van der Kreeke and Hibma, 2005). The variability of the SPM concentration is only partially deterministic, which is reflected by the low percentage of predicted variance over the variance in the original time-series, which is 59%, 48% and 50% for the first, the second and the total time-series, respectively.

16. P 25 Lines 30-55 and P 26 Lines 18-31. Decomposing longitudinal fluxes in contributions due to the residual velocity and tidal velocities has been around for quite a while notably for salt fluxes (Hansen, 1965, Fisher et al 1978 , Dronkers and van de Kreeke (1986). Like in the Marsdiep inlet, in most estuaries and inlets it is the tidal velocity-concentration flux that is dominant. What is lacking in the present paper is a physical explanation as to why this term is dominant.

Also you might want to expand this section and show what the contributions to the tidal velocity-concentration flux are of the M2 and M4 tidal variations

Response to reviewer comment No. 16:

The sentence: “The SPM flux is positive, thus towards the Wadden Sea in both the first and the second period, whereas the water transport changes sign between the two periods. This indicates that other processes besides the advection of the long-term mean SPM concentration by the residual flow must be important in transporting SPM.”, with which the paragraph started, was put there because (even though the analysis of the terms of the flux is already old), an explanation needed to be given as to why the residual advective transport is not dominant. This was question coming up over and over again by colleagues after presenting the results of the residual current changing sign with hardly any effect on the SPM flux.

The papers by Hansen (1965) and Dronkers and van de Kreeke (1986) are now also cited before the derivation of the equations:

“The instantaneous longitudinal flux can be decomposed into six different terms, following Medeiros and Kjerfve (2005), who use a modified version of the decomposition performed by Hansen (1965) and Dronkers and van de Kreeke (1986) for the salt flux:

17. An additional paragraph is added to this section, which explains why the M2 tidal frequency is dominant in the tidal velocity-concentration flux:

Response to reviewer comment No. 17:

Focussing further on the dominant term, e.g. the tidal velocity-concentration flux, $A_0(u_T c_T)_0$, we observe that interactions between u_T and c_T only contribute if both contain a significant amplitude and a small phase difference at the same tidal frequency, e.g.:

$$A_0(u_T c_T)_0 = A_0 \sum_{i=1}^N u_i c_i (\varphi_{c,i} - \varphi_{u,i})$$

where u_i and c_i are the amplitudes of the velocity and SPM concentration at the i -th tidal frequency and $\varphi_{u,i}$, $\varphi_{c,i}$ the phases. The largest contributions are from the M2 and S2 components, contributing 234 and 25 kg/s to the tidal velocity-concentration flux. At first glance, the M4 component seems to be important as well, because the SPM concentration has a significant contribution at this frequency. However, it actually causes an export of -3 kg/s, because the phase difference between the SPM concentration and the velocity is 97 degrees at this frequency. The tidally varying SPM concentration has a component on the M2 tidal frequency with an amplitude of 7.8 mg/l, which is comparable to the amplitude on the M4 tidal frequency, being 7.2 mg/l. The phase lag between the velocity and the SPM concentration on the M2 tidal frequency is only 22 degrees, or 47 minutes, which leads to a significant contribution in the flux. The fact that the SPM concentrations are higher during flood than during ebb introduces the M2 tidal frequency component in the harmonic analysis and of the SPM concentration and is the main cause for sediment transport from the North Sea to the Wadden Sea. Additional explanation on why the SPM flux is towards the Wadden Sea will be provided in the next section.

18. P 26 Line 33 The time series was low passed. What time series and for what period?

Response to reviewer comment No. 18:

The low-passed filtered time series and associated text are removed entirely from the manuscript for condensation.

19. P 26 Line 50-54. See my comments two lines above

Response to reviewer comment No. 19:

Additional analysis is provided in this section.

20. P 27 Line 39. In Fig 17 the black dots show that SPM increases with increasing current speed. That is as far as I get. Velocity -bin averaged values? Do you mean SPM averaged values for each velocity interval of 0.05 m/s? I am not sure what the yellow and red lines in the figure represent. In this part of the text reference is made to tidal asymmetry but tidal velocity asymmetry was never discussed. In the figure caption of Fig. 17 reference is made to eastward velocity in each transect. What then represents the - and + signs for the velocity on the horizontal axis? This part needs more explanation and expanded.

Response to reviewer comment No. 20:

Section 5.2 has been changed significantly: the figure is better explained, a reference is given to Buijsman and Ridderinkhof (2007), where tidal asymmetry in the Marsdiep is explained.

In the introduction line 11-12 on page 2 of the original ms is slightly changed to introduce the concept of tidal asymmetry already there:

“Tidal asymmetry is depended on the location in the Marsdiep: the southern two thirds of the Marsdiep inlet is flood dominant due to interaction of the M2 and the M4 overtide, whereas the northern part close to the island of Texel is ebb dominant.”

21. P 18 lines 49-54. You might refer to van de Kreeke and Hibma who, using a simple model involving advection of silt by the M2 tidal current and upward mixing and settling by the M4 current speed, explained the observed variations in silt concentration. The dominant variation in SPM is in the M4 band where the coherence between current speed and silt concentration is 0.92 and the silt concentration lags the current speed by 0.36 hours. It would be interesting to see if silt (SPM) concentrations in the Texel inlet follow the same pattern.

Response to reviewer comment No. 21:

It is unclear to us why a reference is made to p18 lines 49-54, as page 18 only contains a figure associated with the calibration and lines 49-54 are blank. We presume that this remark is made with respect to p 20: lines 49-54 where we discuss the lag of about one hour between the SPM concentration and the volume transport. However a comment on this piece of text is already given earlier by the reviewer (and changes have been made accordingly including a citation to Kreeke and Hibma, 2005). So, we are a bit confused by this comment.

Reviewer #3:

This paper presents the results from 3 years of measurements acquired with an ADCP mounted to the hull of a ferry making regular transits across a channel on the Dutch Wadden Sea coast. The ADCP backscatter is used to estimate suspended sediment concentration and, combined with the velocity data, to estimate the suspended sediment flux and net along-channel suspended sediment transport. The latter is compared to other estimates based, in part, on sediment deposition rates reported in the literature. An important feature of the work is the effort made, by using a second vessel at anchor midway along the ferry route, to acquire extensive suspended sediment samples for calibrating the ADCP backscatter. These calibrations include comparisons between ADCP backscatter and co-located measurements with an optical backscatter sensor (OBS). An interesting aspect of these comparisons is the clear separation between the backscatter response in high flow, turbulent conditions and low flow, less turbulent conditions.

My overall assessment of this paper is that it is an important piece of work and that should be published. The paper is important for several reasons:

- a. The long-term data set is very special, and I think unusual in respect of the use of a ferry-mounted ADCP to assess net sediment transport rate.
- b. The authors have been very careful and diligent in the steps taken to calibrate the response of the ADCP backscatter amplitude to the in situ suspended sediment concentration, over the course of the three-year period, and the results clearly indicate the importance of doing so.
- c. The above-mentioned difference between the backscatter response in more turbulent vs. less turbulent conditions, and the methodology and theory used to account for the difference will be of wide interest in the sediment transport community.
- d. The favorable comparison between the measured net transport rate and the sediment accumulation rate in the "Marsdiep area" is important, obviously for local reasons but because it tends to support the validity of the approaches in the paper, which can then have wider application.

Finally, before any critical commentary, I would like to add that the paper is on the whole very well written, and an enjoyable read. Also, I had not previously been aware of the Merckelbach (2006) and Merckelbach and Ridderinkhof (2006) papers, which I have now added these to my reading list.

Criticisms

These are quite few in number, considering the length of the paper and breadth of the material.

1. Definition of "the Marsdiep area". I get the impression from the MS that there is a net transport of material through the channel between Texel and den Helder and that the accumulation which is talked about in the paper is in the area to the northeast of the ferry crossing route. Not being so familiar with the area, I searched for Marsdiep, and according to Wikipedia it is the channel between den Helder and Texel. So, I'm a little confused, and so I think would other readers be who are not familiar with this region. Therefore, I would like to Figure 1 to be modified, perhaps with another inset, to clearly identify the area of net deposition being referred to in the MS.

Response to reviewer comment No. 1:

"the Marsdiep area" is changed by "the Marsdiep backbarrier basin in the Wadden Sea"

2. On p. 3, lines 12-19, the authors pointedly comment upon mechanisms proposed in the past that could lead to "(counterintuitive) net SPM transport from the North Sea to the Wadden Sea". I expected this point to be revisited in the paper, but it seems not to have been, unless I missed it. In any case, it is

not revisited in the conclusions, despite the conclusion there that "The main conclusion is that the long-term mean SPM flux is from the Wadden Sea to the North Sea". This conclusion indicates that there is no need for, nor grounds for, the counterintuitive upgradient transport from the North to the Wadden, at least not over this 3-yr observation period. Shouldn't this point be made, and made explicitly??

Response to reviewer comment No. 2:

Thanks for pointing this out, there was a typing error and has been changed into:

"and indeed from the North Sea to the Wadden Sea and thus from low to high concentration"

3. Line 6, p. 4, states that the ferry operates every 30 minutes, about 32 times per day. It did not strike me that this amounts to 16 h of operation, and until much later in the paper (p. 26) where it is stated that the ferry does not operate at night. Couldn't the MS be clear about this on p. 4?

Response to reviewer comment No. 3:

This line is changed into:

"The ferry crosses the 4.5 km wide Marsdiep inlet in approximately 15 minutes. Every 30 minutes a crossing takes place between 6:00 (7:00 on Sundays and holidays) and 22:00 local time. Emergency ambulance transportation introduces deviations from the planning and extra crossings and additional data when they occur during night."

4. p.7, line 27. I could not understand what was meant here. Is the meaning that "The original volume of the sample was used: i.e. the volume measured on board as part of the OBS dark chamber calibration procedure."? But the rest of this paragraph is still unclear. What was this "original volume" used for? The procedure here is first to reduce the volume to 120 ml. From what approximate initial volume? 1 litre? Does the 7 to 15% concentration needed by the Coulter LS correspond to the concentration in the 120 ml samples in which the sediment has become concentrated through settling?

Response to reviewer comment No. 4:

Indeed this was put rather unclear. We changed the description into the following:

"There is a linear relationship between the obscuration of the reduced sample and the SPM concentration (and therefore OBS value) of the in-situ sample. The obscuration of the reduced sample is in the optimal range between 7 and 13 %. In this range the concentration is low enough for the Coulter LS laser to penetrate the sample, while the sample contains enough particles within all size classes. Thus the total volume of the sample taken on board (thus before reduction) was roughly based on the OBS value measured in the dark chamber on board using this linear relationship and was somewhere between 200 and 1000 ml."

5. I could find no reference to Figure 4 in the text. The text from p. 9 bottom top. 10 middle jumps from Fig 3 to Fig 5. Fig 4 should be discussed just before Section 4.2, correct?

Response to reviewer comment No. 5:

Thanks for this remark. Figure 4 from the original version has been removed as it was not referenced. It was merely placed there to show that the calibration of the velocity resulted in smooth data for the residual flow without an odd jump from the first period to the second. But without a figure of the original data series, the information in this figure doesn't add a lot to the paper. Moreover, the low-passed filtered velocity is also shown later on in Figure 16a from the original version."

6. p.13, line 29. The statement "Only the data between 5.5 and 18 m depth were used as these are relatively undisturbed" is obscure. Please explain why the shallow and deep limits were chosen. The reasons are different, presumably.

Response to reviewer comment No. 6:

Changes made:

"The top of the water column is influenced by bubbles generated at the surface or beneath the hull and the bottom part of the water column may be subjected to side-lobe interference. Therefore, only the data between 5.5 and 18 m depth were used as these are relatively undisturbed. Note that, the exact numbers themselves are fairly arbitrary."

7. Figure 8. Nice! But, I would rather see two subplots, one for the classical regime, and one for the turbulent, because in this version one set of points obscures the other.

Response to reviewer comment No. 7:

Thanks for the suggestion. The figure has been changed and the caption accordingly.

8. Figure 15. The role of wind is discussed here, which is interesting. Can you perhaps also comment on the possible role of waves? i.e. is wave-induced sediment suspension likely to play any role here, possibly in relation to the wind?

Response to reviewer comment No. 8:

The role of wind is discussed here in relation to the water volume transport and not the sediment transport. This is done because of the observed difference between the residual water transport in the first and second period. As the ADCP was replaced between the two periods, we doubted the quality of the velocity data as measured on board of the ferry for a long period of time, until we made Figure 15 and found the fairly obvious relationship between the windspeed in the direction along the coast and the residual transport, which has not been observed before.

The word "water" has been added to "transport" to clarify as well as the sentence:

"This has not been observed in previous studies using ferry-based observation in the Marsdiep inlet for the period 1998-2002 in Buijsman and Ridderinkhof (2007a,b)." to indicate that this is a new result. Indeed it would be very interesting to look at the influence of wave-induced suspension, but that is outside of the scope of this paper.

9. Section 4.4. I found this section rather hard to read. I apologize to the authors for not having had the time to work through the 2006 papers, which would no doubt help. Regardless, I think clarification is needed.

i) Line 22, It is not obvious from Eq. 2b alone that an integration constant is needed. Cite M2006 or MR2006 here, agree?

Response to reviewer comment No. 9i:

If you wish to derive an expression for the SPM concentration, c , in equation 2b, you have to perform an integration over the vertical, z , which can be done after rearranging the terms in the equation. This requires constant of integration.

For clarification, the first sentence is changed into:

"To derive an SPM concentration profile, $c(z)$, from acoustic backscatter intensity, a constant of integration is needed to solve (2b), if the entire water column is in the turbulent regime. In the latter equation the acoustic cross-section, σ , is derived from (1)."

The second sentence is slightly expanded:

"In the calibration of the ADCP beneath the Navicula for SPM concentration, in-situ observations of the optically derived SPM concentration at a depth of $z=7$ m were used as a boundary condition, if necessary."

At the end of the paragraph, the following sentence is added for clarification:

"Therefore, we have derived a boundary condition empirically."

ii) Line 29. Again, it is not obvious from Eq 2b that a power law relation between dissipation and SPM should exist, whereas I agree that Figure 9 does suggest such a relationship. The reference to Eq 2b can/should be deleted from this sentence, agree?

Response to reviewer comment No. 9ii:

We have removed the reference to eq 2b in this sentence. Moreover, we have further clarified the paragraph by changing the sentences slightly:

"Below a certain critical dissipation rate, ϵ_{crit} in the classical regime, the SPM concentration can simply be derived from (2a). From figure 9a it appears that the SPM concentration may be related to the turbulent dissipation rate through a power law above a certain critical dissipation rate, ϵ_{crit} ."

iii) You speak of the 5th depth level and 8th depth level here, but it is not obvious whether you are counting up or down. Lines 47+ on p15 speak of "depth level". Is there a difference between "depth" and "depth level"? Line 53 on p 15 refers to $z = 9$ m, z being the height above bottom according to p8, as the 8th "depth level". Are you using "depth level" to refer to the vertical position of 8th ADCP range cell? Please revise the text to clarify.

Response to reviewer comment No. 9iii:

We fully agree with this comment. References to depth level are replaced with references to depths (in m).

iv) Bottom line here is that I came away after reading the text several times not being sure whether the boundary condition being discussed here was at the top or bottom of the ADCP profile.

Response to reviewer comment No. 9iv:

We think using true depths instead of depth levels has solved this issue as well.

Besides this, the explanation on how exactly the least square method has been applied is removed from the ms (lines 42-46). Even though the application of the least squares method needs a bit of creativity with the set of equations proposed in (6), all readers of this ms should be able come up with a similar approach, leading to the same results. Removing this text (as it is relatively unimportant) enhances the readability in our view.

10. Other (mainly typos)

a. I am accustomed to see units in roman, not italic. Is italic the convention for JSR?

b. p1, line 44: world heritage -> world heritage site

c. p2, line 9: have an amplitudes -> have amplitudes

d. p2, line 11. "on the order of" usually refers to order of magnitude, so "about 1.8 m/s" would be better

e. p.7, line 52: scatters -> scatterers

f. p.8, line 20: "linear of classical".do you mean "linear or classical"?

g. p. 9, line 25: is was -> it was

h. p.9, line 53: in theoretical -> in the theoretical

i. p10, line 44: constants -> constant

j. p. 15, line 53: units needed for epsilon

k. p17, line 8: "the worst and the best". is the order correct? Looking at the figure, I'd have thought that Panel b might be the better fit.

l. p17, line 21: remarkable -> remarkably

m. p17, line 46: bubble -> bubbles

n. p24, line 54: in first -> in the first

o. p30, line 33: adv, obs and lisst should be capitalized in the Fugate and Friedrichs title.

p. p. 31, line 16: "east frisian wadden sea" should be capitalized. There may be other instances of missing capitalizations in the references. Please check.

Response to reviewer comment No. 10:

Thanks for reading the manuscript carefully and indicating the typos. They have been changed all as suggested above. With respect to remark k: In the caption, the dates associated with the panels were accidentally swapped. The caption is corrected and the text in the ms was oke!