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Ferry observations on temperature, salinity and currents in the Marsdiep tidal inlet between the North Sea and Wadden Sea

H. Ridderinkhof, H. van Haren, F. Eijgenraam and T. Hillebrand

Netherlands Institute for Sea Research, P.O. Box 59, 1790 AB Texel, the Netherlands
e-mail: rid@nioz.nl

In a co-operation between NIOZ (Netherlands Institute for Sea Research) and the ferry company TESO (Texels Eigen Stoomboot Onderneming) continuous observations from the ferry 'Schulpengat' are carried out in the Marsdiep tidal inlet between the North Sea and Dutch Wadden Sea. The measurements include surface temperature, salinity and fluorescence as obtained from a through-flow system as well as vertical profiles of velocity and echo-intensity, obtained every 2 s with an Acoustic Doppler Current Profiler (ADP) mounted below the hull of the ferry. The continuing observations started early 1998.

The scientific aim of these observations is 1) to obtain more qualitative and quantitative insight in the temporal and spatial variability of oceanographic parameters in a tidal inlet and 2) to study the mechanisms for the transport and exchange of materials between the North Sea and the Wadden Sea. The latter topic has a long tradition at NIOZ, a.o. through studies performed by Postma (1954), Zimmerman (1976) and Ridderinkhof (1988) which were mainly based on a relatively small data set from the interior of the Wadden Sea. This project allows more detailed studies on transport processes in the tidal inlet itself, and the focus will be on the transport of suspended sediments.

Another aim of the project is to increase the interest of the general public for oceanographic research. Therefore, observations on salinity, temperature and the current distribution are presented directly on a screen in the passenger's lounge of the ferry.

This paper describes the site of the measurements, the instrumentation applied and some first results of the observations obtained in 1998.

1. LOCATION OF THE FERRY OBSERVATIONS

The ferry observations are performed in the Marsdiep tidal inlet, the southernmost tidal inlet of the Wadden Sea, a shallow tidal area to the north of the Netherlands and Germany that is enclosed by a chain of islands, see fig. 1. This shallow tidal area consists of more or less separated tidal basins; each composed of a system of tidal channels and tidal flats and drained by a tidal inlet. The Marsdiep inlet forms the connection between the largest basin of the Wadden Sea and the adjacent North Sea.

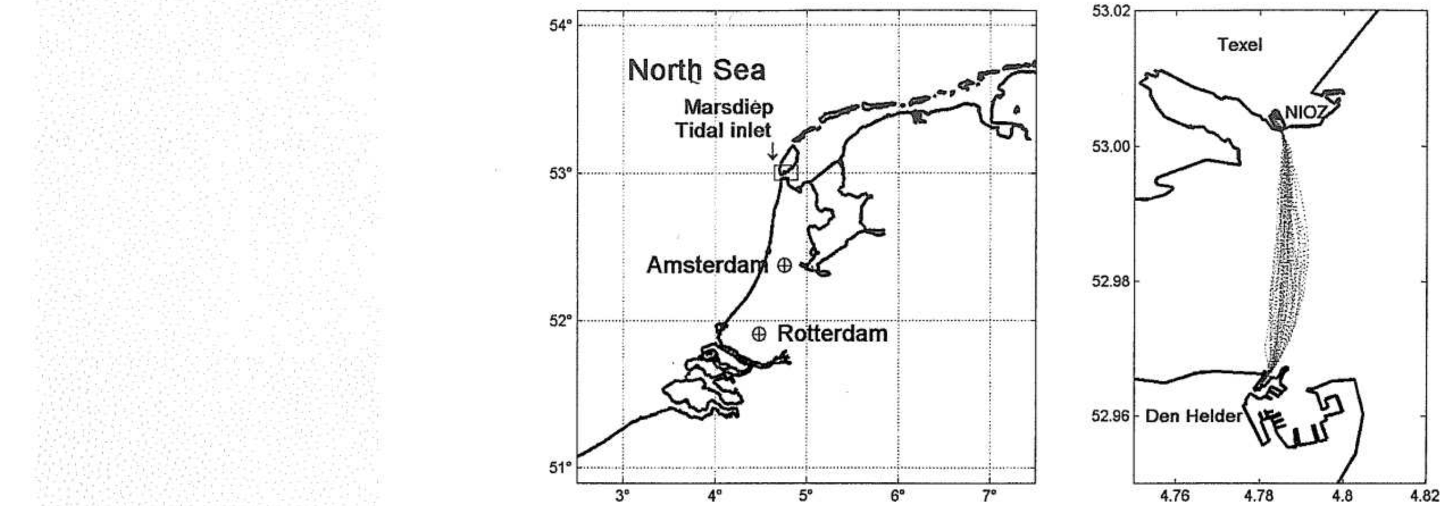

Figure 1. Map of the area where the ferry observations are carried out. The right side shows typical tracks of the ferry (small dots between Den Helder and Texel) during one day between 6.00 a.m. and 10.00 p.m.

The distance between the ferry harbours at both sides of the inlet, Den Helder on the mainland and the island Texel, is some 4.5 km. The water depth in the inlet varies between about 10 m just outside of the harbours and about 25 m in the deepest part.
The ferry crosses the inlet twice per hour, daily between 06.00 a.m. and 10.00 p.m. Each trip takes 12-15 minutes (the ferry speed is about 10-12 knots) so that more or less synoptic observations are obtained. Fig. 1 shows typical tracks of the ferry during one day. Navigational purposes cause some variation in the track of the ferry across the inlet. This variation depends strongly on the phase of the tide.

2. INSTRUMENTATION AND DATA PROCESSING

Through a separate water intake with an opening at 1.0 m below sea surface in the middle of the ferry, sea water is pumped continuously along sensors (Aquaflow system from Chelsea instruments) measuring salinity (accuracy .02 ppt), temperature (accuracy .02 degree C) and fluorescence (accuracy 5%). The system samples at a frequency of 1 Hz, so that during each trip about 800 observations are obtained, with an average distance of 5 m between successive observations. The capacity of the pump and the storage volume within the pipes is such that the average residence time of the water in the system before reaching the sensors is some 30 s, thereby causing a difference of 150-200 m between the location at which the intake takes place and the position of the recorded value.

A 1.5 MHz ADP (Nortek) is attached near the keel of the ferry in the middle of the vessel at 4.3 m below the sea surface. The instrument has been fastened to a plate below the ferry's hull leaving some 30 cm open space between the hull and the instrument. This device has been chosen to minimise the possibility of air bubbles, affecting the acoustic measurements, most presumably present in a thin layer below the hull of the ferry. The instrument is electrically shielded from the ferry and well protected against corrosion. An iron cage protects the instrument against damage from collisions with floating debris. The ADP records current speed and direction and intensity of the back-scattered signal in 0.5 m vertical bins between 5 m below the surface and the bottom every 2 sec. Each trip of the ferry across the inlet results in some 400 vertical profiles of each parameter.

The functioning of the observational system is fully automated using data from the GYRO and DGPS system onboard the ferry. Recording of data starts automatically when the ferry is outside the harbour jetties.

A dedicated computer onboard the ferry combines and stores the data from the ADP, the through-flow system and the DGPS and GYRO. Part of the data are presented directly on a screen in the passenger's room of the ferry. Data presented are: sea surface temperature, salinity, and current speed and direction as a function of the actual position of the ferry in the inlet. Each time when the ferry docks in the harbour of the island Texel, the collection of one hour of data is transmitted by telemetry to the computer system of the institute, located at about 300 m from the ferry harbour. Subsequently, part of these data, i.e. the cross-section averaged values of temperature, salinity and fluorescence are shown on Internet (http:\\www.nioz.nl).

3. FIRST RESULTS

3.1. Salinity and temperature observations

Fig. 2 shows typical observations on salinity and temperature during two subsequent trips of the ferry. Sharp gradients in sea surface conditions are observed, indicating the presence of different water masses. Here, a rather extreme situation with a salinity difference of 7 ppt and a temperature difference of 2.5 C between both sides of a sharp boundary in the centre of the inlet is shown.

Such sharp boundaries between different water masses, although less extreme, are commonly present. They are often visible also at the sea surface through clear differences in colour of the water masses at both sides. The boundary itself is often marked by a line of foam and/or of floating debris indicating a convergence in surface currents. This is typical for these so-called frontal zones where sharp density differences due to differences in salinity and temperature cause a frontal circulation with converging currents at the surface (Bowden, 1983). The presence and location of these frontal zones depends strongly on the phase of the tide. During ebb when the inlet drains the tidal basin these frontal zones are most pronounced. Then, the seawater in the inlet originates from different branches in the channel system of the tidal basin. Especially when the discharge of fresh water through sluices is large these different branches can have large differences in salinity, depending on their proximity to the sluices. Spatial differences in temperature appear to be strongly correlated to differences in salinity.

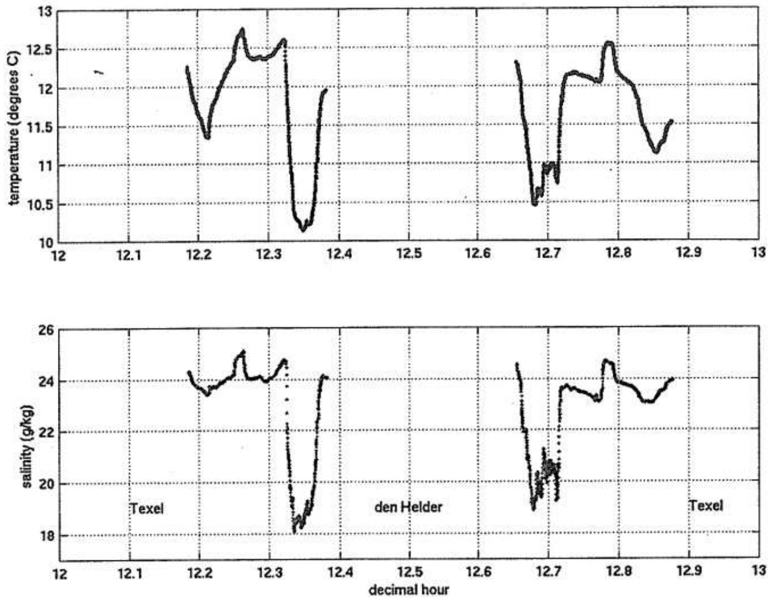

Figure 2. Salinity and temperature observations during two subsequent ferry trips on 5 October 1998 from Texel to Den Helder and vice versa.

Fig. 3 shows the result of averaging the salinity and temperature observations over each cross-section during two days, 5-6 October 1998. The temporal variability is directly related to the phase of the tide. Salinity increases during flood and decreases during ebb reflecting salinity differences between the Wadden Sea and the North Sea. Similarly differences in temperature between the relatively shallow Wadden Sea and the deep North Sea mainly cause the temporal variability in temperature in the inlet. In fall the cooling has a larger effect on the surface temperature of the shallow Wadden Sea than on the surface temperature of the deeper North Sea, resulting in a decrease in the temperature in the inlet during ebb.

Fig. 4 shows daily averages of salinity and temperature observations obtained in 1998. The temperature observations clearly show the seasonal variability in surface heating. On this time scale the temporal variations in salinity mainly reflect the temporal variability of the fresh water discharge to the Wadden Sea and, more indirectly, the fresh water discharge to the coastal zone by rivers south of the inlet.

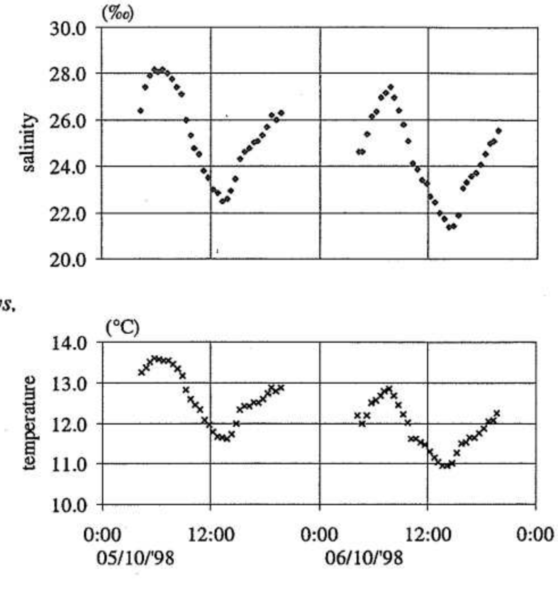

Figure 3. Salinity and temperature observations averaged for each cross-over during two subsequent days, 5-6 October 1998.

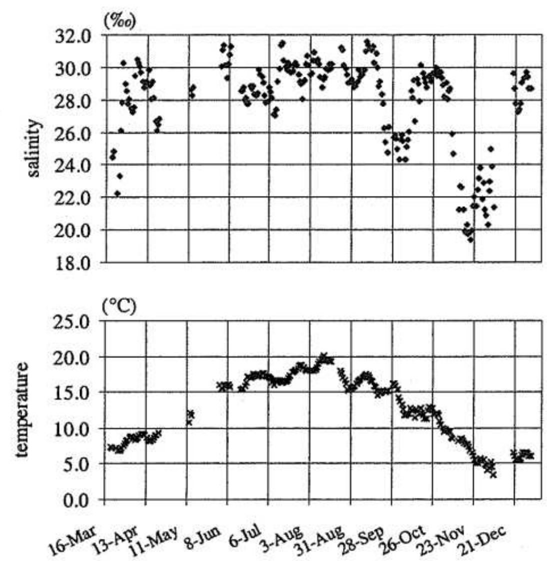

Figure 4. Daily averaged salinity and temperature in the Marsdiep tidal inlet in 1998.

3.2. ADP observations

The quality of the data from the first 4 bins immediately below the ADP appeared to be poor. Therefore these data are not used for presentation and/or further analysis.

Fig. 5 gives a typical example of the currents measured directly below the ferry (similar pictures are shown on board the ferry). In the central, deeper parts of the channel inertia causes the current to turn later than in the more shallow parts. During ebb the currents are strongest along the northern part of the inlet. Maximum tidal currents vary between 1.0 and 1.5 m/s, depending on the location in the inlet.

The more or less synoptic observations on the current speed in the tidal inlet allow the calculation of the water volume transport through the inlet during each ferry trip. This integrated measure is used also as a first check on the quality of the observations. It is determined by summing up the east-ward component of the transport rate in each bin over the entire cross-section, using the recorded position of the ferry to determine the north-ward displacement of the ferry between successive ADP observations (on average about 10 m). In this procedure it is assumed that the current speed between the surface and the first reliable observation (at a water depth of 6.3 m) is equal to the average value of the current from bins 6 - 10 (in order to smooth the applied vertical extrapolation).

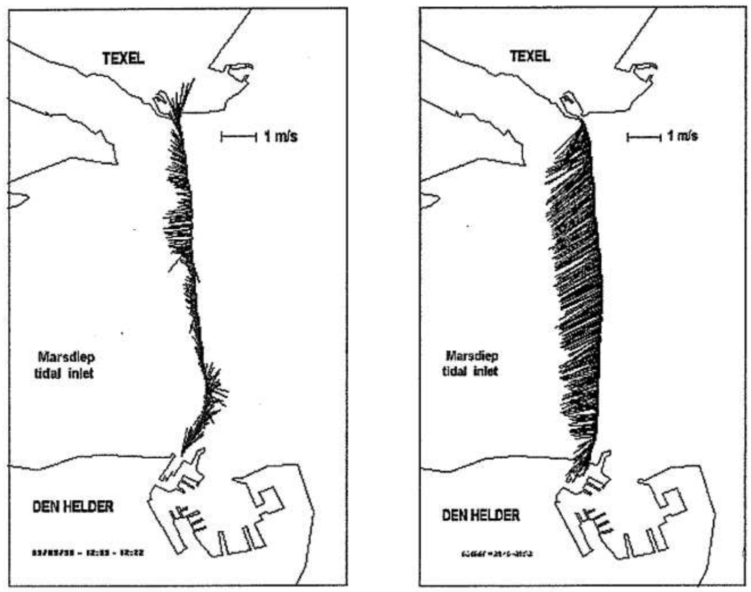

Figure 5. Current speed and direction at about 7.3 m below sea surface, as obtained by averaging the ADP signal from 6.3 to 8.3 m below sea surface (bin 6 to bin 10). On the left side a typical current pattern near the turn of the tide at low water slack is shown. The right side shows the current pattern during maximum ebb.

Other methods, e.g. using less vertical bins for the extrapolation, appeared to give similar results with respect to the calculated total volume transport but more noisy single vertical current profiles. Similarly, the cross-section averaged back-scattered echo-intensity is determined by averaging all reliable observations over each cross-section. Before averaging, the back scattered signal is first corrected for geometrical spreading and (salinity and temperature dependent) adsorption using standard formulations (Urick, 1975). This procedure results in 32 values per day for both integrated measures, with an interval of 30 minutes between successive values. Subsequently an harmonic analysis on this data set is performed, using 10 tidal components.

Fig. 6 shows typical results for two days in spring 1998, solid lines indicating the harmonic fit and dots the original data points. The harmonic analysis has been performed on a three months data series from spring 1998. The variance of the residual signal, obtained from the difference between the fitted curve and the original data points, is 29% of the variance in the original data series for the water volume transport and 59% of the variance in the original series for the back scattered signal. This indicates that, as expected, tidal harmonic components explain the water volume transport much better than the back scattered signal.

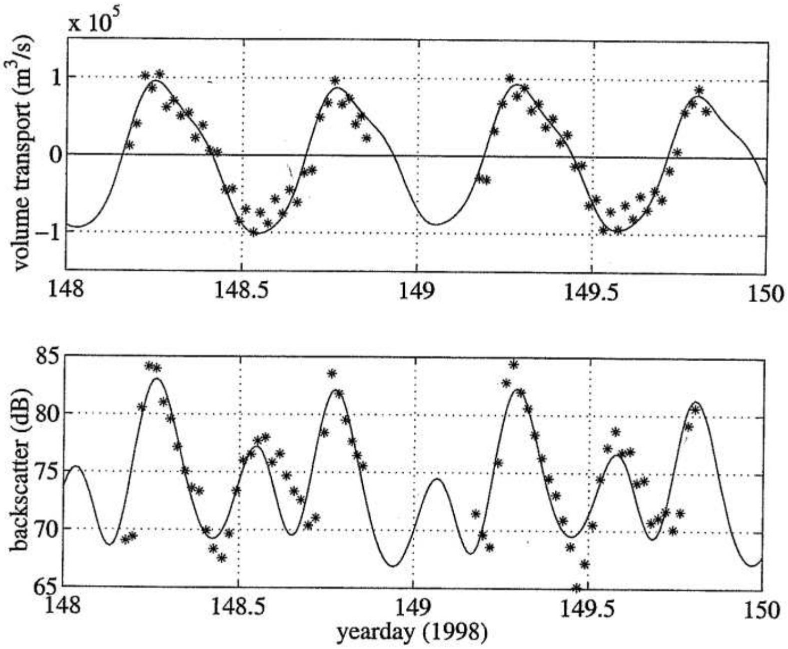

Fig. 6. Water volume transport through the Marsdiep tidal inlet (top) and cross-section averaged back scattered echo-intensity (bottom) during two subsequent days in spring 1998. Dots indicate the observations and the solid lines a harmonic fit through the observations.

The volume transport is dominantly tidally driven with the semi-diurnal M_2 and S_2 and their higher harmonics (M_4, MS_4) being the most important tidal constituents. The amplitude of the volume transport rate lies in the same range as previously found, based on 13-hours of observations from anchored vessels with conventional current meters in the early seventies, and from numerical model studies (Ridderinkhof, 1988). Moreover, the harmonic analysis also shows the presence of a net seaward flow through the inlet, with a magnitude of about 4% of the amplitude of the semi-diurnal tide. This confirms earlier (model) studies which suggested the presence of a southward tidally driven net flow between the largest tidal basins in the Dutch Wadden Sea, the Vlie basin and the Marsdiep basin (Ridderinkhof, 1988). Closer inspection of the series for the volume transport suggests that there is a systematic 'sawtooth-like' deviation between the harmonic fit and the original series. Most presumably the calibration of the ADP can be improved further. The fine tuning of the orientation of the instrument relative to the heading of the ferry will most likely further reduce the 'sawtooth-like' deviation. Moreover, the applied method does not (yet) take into account 1) the difference between the position of the DGPS antenna and the ADP on the ferry and 2) the difference between the ferry's orientation (obtained from the ferry's GYRO) and the direction of the ferry track through the inlet. The latter difference systematically changes in sign between subsequent trips (the ferry does not turn) and most presumably causes small systematic errors. Thus we expect to be able to reduce the 'noise' in the signal by further optimising the post-processing procedure. However, we assume that the effect of such a noise reduction will be small with respect to the results of the harmonic analyses.

The temporal variability in the cross-section averaged back scattered signal clearly suggests that this signal is a measure for the amount of suspended matter in the water column (see also Holdaway et al, 1999). The temporal variations agree qualitatively well with observed and known typical variations in the concentration of fine-grained suspended sediments (silt). For instance, the magnitude of the back-scattered signal is strongly related to the current speed, a typical time lag between variations in this signal and the current speed can be recognised and there is a strong spring-neap variability. In general the back scattered signal is significantly larger during flood than during ebb, suggesting a tidally driven net import of fine-grained sediments towards the Wadden Sea. However, quantification of the transport of fine-grained sediments needs further analysis including extensive calibration.

4. DISCUSSION AND CONCLUSIONS

The ferry that crosses the Marsdiep tidal inlet between Den Helder and Texel is an excellent platform to obtain long-term, cost-effective, observations on oceanographic parameters in a tidal inlet. Especially the high frequency of the ferry trips, each 30 minutes during daytime, ensures that a data set is obtained which allows detailed studies on (temporal variability in) the transport and exchange of materials between the Wadden Sea and adjacent North Sea.

First analysis of the data from the through flow system shows a strong spatial and temporal variability. The spatial variability in the tidal inlet is due to the presence of water masses with a different origin. Temporal variations on different time scales varying from intra-tidal to seasonal, can be recognised.

First analyses of the ADP data show that the results with respect to the integrated tidal water volume transport through the inlet is in agreement with previous observations and numerical model studies. The analyses suggests also that the noise in the ADP current data can be further reduced by optimising the calibration procedure. The temporal variability in the strength of the back scattered signal strongly suggests that it can be used as a measure for the concentration of fine-grained suspended sediments. However, more extensive calibration is needed, especially since the composition of the suspended material and its acoustic properties most presumably vary considerably with time. This is the main subject of study in present and ongoing additional studies using other techniques (e.g. optical sensors from moorings) to observe the concentration of suspended sediments at a specific location in the tidal inlet. Additionally we investigate the possibilities of a study on temporal variations in the bottom morphology (using the echo-intensity signal), e.g. on the migration of sand waves, which requires an extremely long continuous data-set.

The measurements will at least continue until the next dry-docking of the ferry, in the fall of 2000, and probably beyond that date.

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