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Observational evidence of estuarine circulation in the Wadden Sea - current velocity, salinity and turbulence

Bachelor thesis

- B.Sc., Physics of the Earth Systems -
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Kristin Burmeister
Matriculation number: 941761

First Examiner: Prof. Dr. Torsten Kanzow
Mentor: Dr. Götz Flöser

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Abstract

This Bachelor-Thesis is about estuarine circulation in the tidal Marsdiep inlet, Netherlands, and its influencing factors. The groundwork is given in the study Burchard et al. (2008) - presenting a one-dimensional model for the influence of tidal straining on estuarine circulation resulting in a net inward suspended matter transport - and a study of Flöser et al. (2011) - presenting observational evidence for Burchard's model in the German Wadden Sea.
Salinity and temperature data of a jetty station in Texel, water discharges of Lake Ijssel and the Rhine as well as current velocity data of a ferry mounted ADCP crossing the inlet every day (January 2009 to March 2012) were analysed. The results present high variations in cross-shore density gradients, tidal straining and tidal asymmetry in vertical current velocity profiles. The results are compared to the data of the German Wadden Sea and exhibits large differences due to the special water density conditionings in the Marsdiep inlet. Clear evidence for Burchard's model could not be found. In contrast, it is questionable whether the model is representative for this complex dynamical regime in the western Dutch Wadden Sea.

Zusammenfassung

Diese Bachelorarbeit befasst sich mit den Auswirkungen der Gezeiten auf ästuarine Zirkulationen und ihrem Existenznachweis im Marsdiep Seegat, Niederlande. Theoretische Grundlage bildet die Studie von Burchard et al. (2009), in der ein eindimensionales Model für ästuarine Zirkulation und den damit verbundenen Sedimenteintrag ins Wattenmeer entwickelt wurde. Grundlage zur Überprüfung dieses Models bildet die Arbeit von Flöser et al. (2011), in der das Model der ästuarinen Zirkulation in verschiedenen Teilen des deutschen Wattenmeeres bestätigt werden konnte.

Die Basis der hier verwendeten Analyse bilden Salzgehalt- und Temperaturdaten des Seegats, Abflussraten von Ijsselmeer und Rhein sowie vertikale Profile von Strömungsgeschwindigkeiten. Erstere wurden mit Hilfe einer im Seegat stationierten Messstation aufgezeichnet und Letztere mit Hilfe eines ADCP-Gerätes an Bord einer Fähre, welche täglich das Seegat überquert. Die Daten umfassen den Zeitraum von Januar 2009 bis März 2012.

Die Ergebnisse weisen hohe Variationen des horizontalen Dichtegradienten, der gezeitenabhängigen Schubspannung sowie der gezeitenabhängigen Asymmetrien der Geschwindigkeitsprofile auf. Sie werden mit den Daten des deutschen Wattenmeeres verglichen und zeigen entscheidende Unterschiede auf, welche auf die speziellen Dichteverhältnisse im Marsdiep Seegat zurückzuführen sein könnte. Es gibt keine eindeutigen Beweise, die das Model von Burchard et al. (2008) im Marsdiep Seegat bestätigen. Es stellt sich daher die Frage, ob das Model für dieses komplexe dynamische System repräsentativ sein kann.

Contents

1 Introduction

The Wadden Sea existed for several thousand years and oceanographic studies go back to the 1950th [Buijsmann, 2007]. The clearly visible accumulation of suspended particulate matter (Fig.1.1) in the Wadden Sea has been already examined by Postma (1961), but it is still not clear, which driving mechanism is the main contributor of the net inward transport of suspended matter in the Wadden Sea [Flöser et al., 2011]. Burchard et al. (2008) observed density differences between the German Bight (open North Sea - high density) and the Wadden Sea (low density) waters with typical tidal density amplitudes of 0.5-1.0 kg m^{-3} and developed a one dimensional model of estuarine circulation resulting from the observed density gradients as contributor to the high suspended matter concentration in the Wadden Sea. Flöser et al. (2011) confirmed this model of estuarine circulation in the German Wadden Sea by analysing current velocity time series.
In a study of Buijsman and Ridderinkhof (2007), indications of different flow conditions in the Western Dutch Wadden Sea to those in the German Wadden Sea are given. Therefore a closer analysis of current velocities is required to determine whether the model of Burchard et al. (2008) also applies to the Dutch Wadden Sea.

1.1 Estuarine Circulation in the Wadden Sea

Classical estuaries are commonly defined as "semienclosed and coastal bodies of water, with free communication to the ocean, and within which ocean water is diluted by freshwater derived from land" [Valle-Levinson, 2010] [1]. Horizontal (offshore-onshore) density gradients, resulting from freshwater input, tidal currents, bathymetry and energetic turbulence cause a complex, so-called estuarine circulation. In general, estuarine circulation describes a net near-bed inflow of denser offshore water and a net surface outflow of less dense onshore water [Valle-Levinson, 2010, MacCready and Geyer, 2010, Burchard et al., 2008]. The interaction of estuarine circulation with particulate suspended matter in the

[1] Reprinted from: Valle-Levison, A., editor (2010). *Contemporary Issues in Estuarine Physics.* New York: Cambridge University Press, p.1.

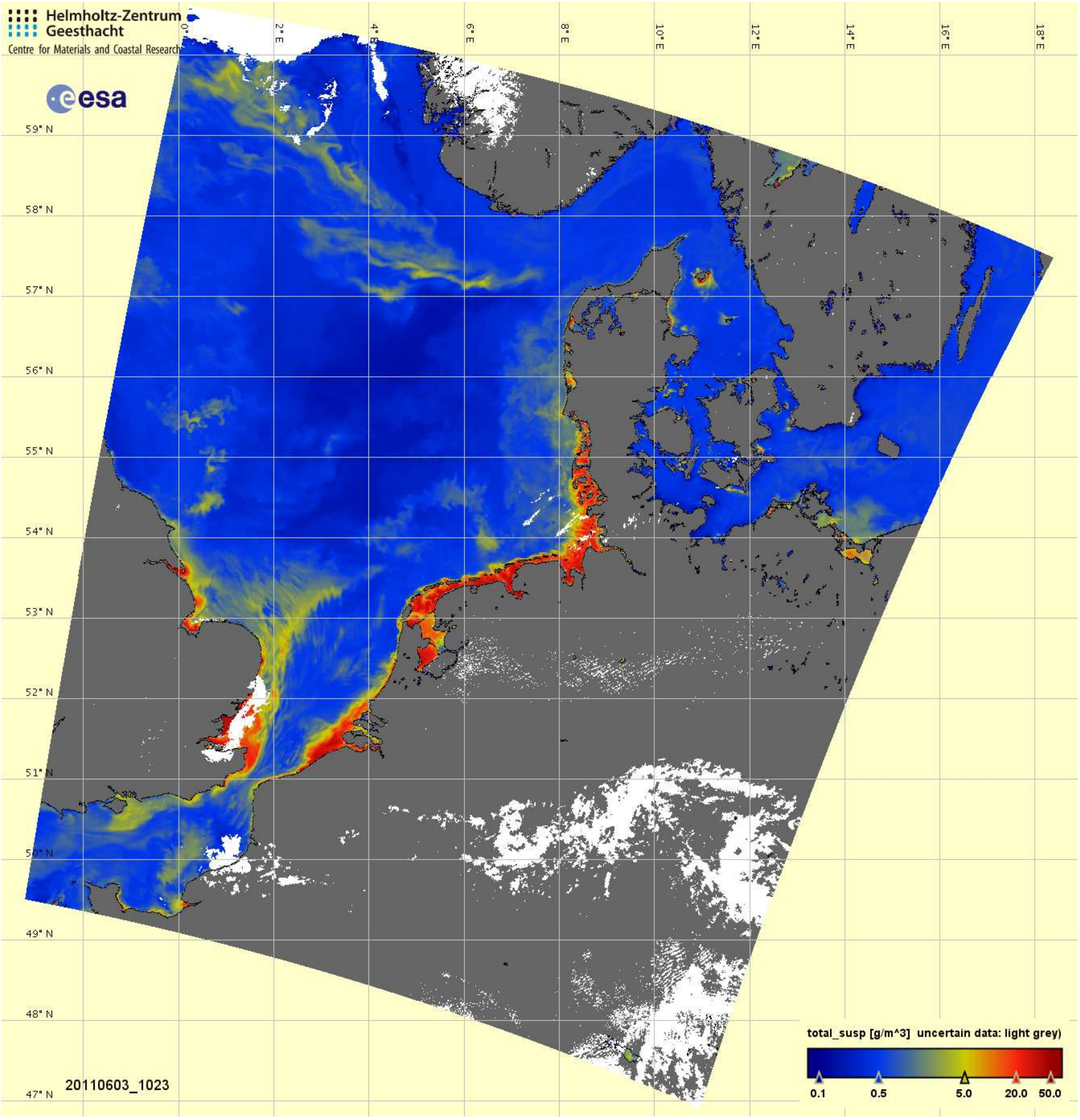

Figure 1.1: Medium Resolution Imaging Spectrometer (MERIS) measurements of total suspended matter in the North Sea taken by the European Space Agency (ESA) satellite *Envisat* on 3 June 2011. *Source: http://www.hzg.de/institute/coastal_research/structure/operational_systems/-KOF/satellite/index.html.de, 6 June 2012*

water column commonly leads to a landward sediment transport [Burchard and Hetland, 2010].

In tidal estuaries the circulation and consequently the net onshore suspended sediment transport may be augmented by tidal straining as described in Buchard et al. (2008): During ebb, less dense coastal waters are sheared above denser offshore waters. The water column becomes more stabilised, vertical mixing and downward momentum transport is suppressed. A stratification of the water column is possible and depends on the ratio of stratifying shear versus shear-generated turbulence. During flood, denser offshore water is sheared over less dense onshore water leading to gravitational circulation. Hence, vertical mixing and downward momentum transport in the water column occurs. A certain balance between tidal force and the horizontal pressure gradient implied a strain-induced stratification, i.e. the water column becomes stratified during ebb and well mixed during flood.

In the water column the turbulence increases during flood and decreases during ebb. This systematic change of turbulence implies a tidal asymmetry in eddy viscosity, i.e. eddy viscosity is substantially higher during flood than during ebb (1.2). Due to the fact, that the current velocity depends vertically on the reciprocal eddy viscosity, a tidal asymmetry in the vertical current velocity profiles follows. Thereby during flood the bulk of the velocity profile is more homogeneous than the ebb profiles, with higher speed above the benthic boundary layer and smaller speed at the surface. This forms an important basis for the measurement and verification of estuarine circulation.

Looking now on the transport of momentum towards the seabed, its tidal asymmetry creates a near-bed residual upstream [Burchard et al., 2008]. An additional onshore suspended matter transport results, due to the interaction between settling and vertical mixing, which in turn is implied by the increase of suspended particulate matter concentration towards the seabed. The limit of the salt intrusion implies the end of the upstream transport and forms a turbidity maxima in the estuary [Burchard et al., 2008].

In most areas of the tidal basins in the German Wadden Sea, estuarine circulation as an alternative for the observed sediment accumulation was ignored due to the lag of significant river runoff [Flöser et al., 2011] and the misconception, that no significant density gradient triggering estuarine circulation exists. In fact, a nearly persistent density gradient does exist [Burchard et al., 2008]. The reason for this is the shallowness of the Wadden Sea. Sea surface warming, mainland runoff and net precipitation lead to smaller vertically averaged densities for shallow waters than for deeper waters [Burchard et al., 2008]. Based on this persistent horizontal density gradient and the observed suspended particulate matter accumulation in the Wadden Sea, Burchard et al. (2008) hypothesised, that the above mentioned mechanism for the typical suspended matter accumulation in tidal estuaries also applies in the Wadden Sea. The authors simplified the dynamics of estuarine circulation and tidal straining in the Wadden Sea by an one-dimensional model.

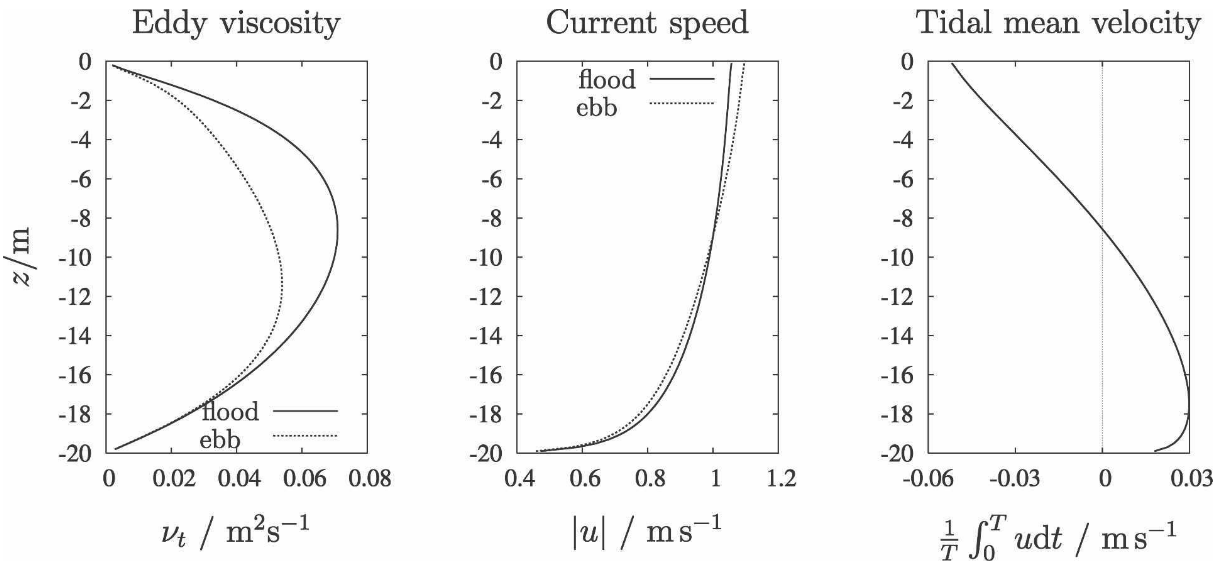

Figure 1.2: Results simulated with the one-dimensional model of Burchard et al. (2008). Profiles of eddy viscosity (right) and current velocity (middle) shortly after full flood and full ebb, tidal mean velocity (left). Positive values present onshore transports. [Reprinted from Impact of Density Gradients on Net Sediment Transport into the Wadden Sea, *Journal of Physical Oceanography*, 38:577, Burchard, H., Flöser, G., Staneva, J., Badewien, T., and Riethmüller, R. (2008), with permission from H. Burchard.]

In the model a constant depth H of the water column ($H = 20$ m) is considered. Earth rotation and sea level variations are neglected. A constant pressure gradient $\frac{\partial \rho}{\partial x}$ is superimposed by an external, with the Period T ($T = 44,714$ s in accordance with the M_2 constituent) oscillating pressure gradient aligned in the direction of $\frac{\partial \rho}{\partial x}$. The salinity is relaxed to 30 psu, with a salinity gradient of -1.4 $\cdot 10^{-4}$ psu with respect to the coast and a relaxation period equal to T. The model takes account of suspended matter transport with respect to gravitational circulation, strain-induced periodic stratification and tidal mixing asymmetry. The turbulence is presented by a two-equation k-ϵ model.

The results represent similar tidal asymmetries in vertical eddy viscosity and current velocity profiles as well as suspended particulate transport mechanisms as the above mentioned of tidal estuaries 1.2. Although the differences between flood and ebb are small, Burchard et al. (2008) points out, that they may trigger a long-term net onshore suspended matter flux due to the permanent, strong influence of the tides which overlay the horizontal density gradients.

Due to these subtle differences in suspended sediment transport between flood and ebb, a direct observation of this transport is hard to realise. But Flöser et al. (2011) verified the asymmetry in the vertical current velocity profiles in specific areas of the German Wadden Sea (Hörnum Deep, Sylt-Rømø-Bight, Accumer Ee). They observed higher curvature of the vertical velocity profiles during flood and therefore verified the numerical model predictions of Burchard et al. (2008). Hence, the net import of suspended sediment into

the German Wadden Sea can be explained by estuarine circulation.
Similarly, estuarine circulation should also occur in the Marsdiep inlet (Dutch Wadden Sea) which has been described as an estuary due to freshwater input about 400 m^3 s^{-1} by Lake Ijssel [Buijsman and Ridderinkhof, 2007]. However, the authors presented vertical current velocity profiles of the Marsdiep inlet during neap tide and spring tide showing higher curvature of the vertical current profile during ebb than during flood. On the basis of Burchards model, this would be linked to an outward transport of suspended matter in the Marsdiep Inlet, which is in contrast to the observed suspended matter accumulation in the tidal basins. As the results of Buijsman and Ridderinkhof (2007) are restricted to a duration of only seven days and no further information about longitudinal salinity or density gradients are given, the results may not be representative of the annual mean circulation.

1.2 Research motivation

This study will, based on data of long-term Acoustic Doppler Current Profiler (ADCP) and salinity measurements, investigate, whether the model of Burchard et al. (2008) also applies to the Marsdiep inlet in the Dutch Wadden Sea. Therefore an analysis of the vertical current velocity profiles during full flood and ebb flow is accomplished to investigate the common curvature of the profiles and whether the typical tidal asymmetry of estuarine circulation applies to the Marsdiep inlet. As a part of this, the prevailing density gradients are analysed, which form the triggering mechanism for estuarine circulation. Due to the peculiar condition in the Marsdiep inlet, also the freshwater discharge of the sluices in Lobith (Rhine) and in the Afsluitdijk near Den Oever and Konwerderzand (Lake Ijssel) and their influence on the density gradients are considered. Finally, the results of this study are compared to the results of estuarine circulation in the German Wadden Sea, given in the paper of Flöser et al. (2011).

1.3 Study area - Marsdiep inlet

The Marsdiep inlet is located at $52.98°N$ and $4.78°E$ [Buijsman and Ridderinkhof, 2007], bounded by the mainland city Den Helder, Netherlands, in the South and the Dutch island Texel in the North (Fig.1.3). It is therefore the westernmost inlet of the Wadden Sea and drains the Marsdiep tidal basin flanked by the Eierland basin to the Northwest

and the Vlie basin to the Northeast. The Marsdiep basin covers a horizontal area of about 680 km^2 and exhibits a length of about 50 km [Buijsman and Ridderinkhof, 2007].
The inlet is sheltered from surface waves by the subtidal sand shoal Noorderhaaks in the Northwest [Buijsman and Ridderinkhof, 2007]. At the basin side the inlet channel splits into the Northern Texelstroom and the Southern secondary Malzwin channel.

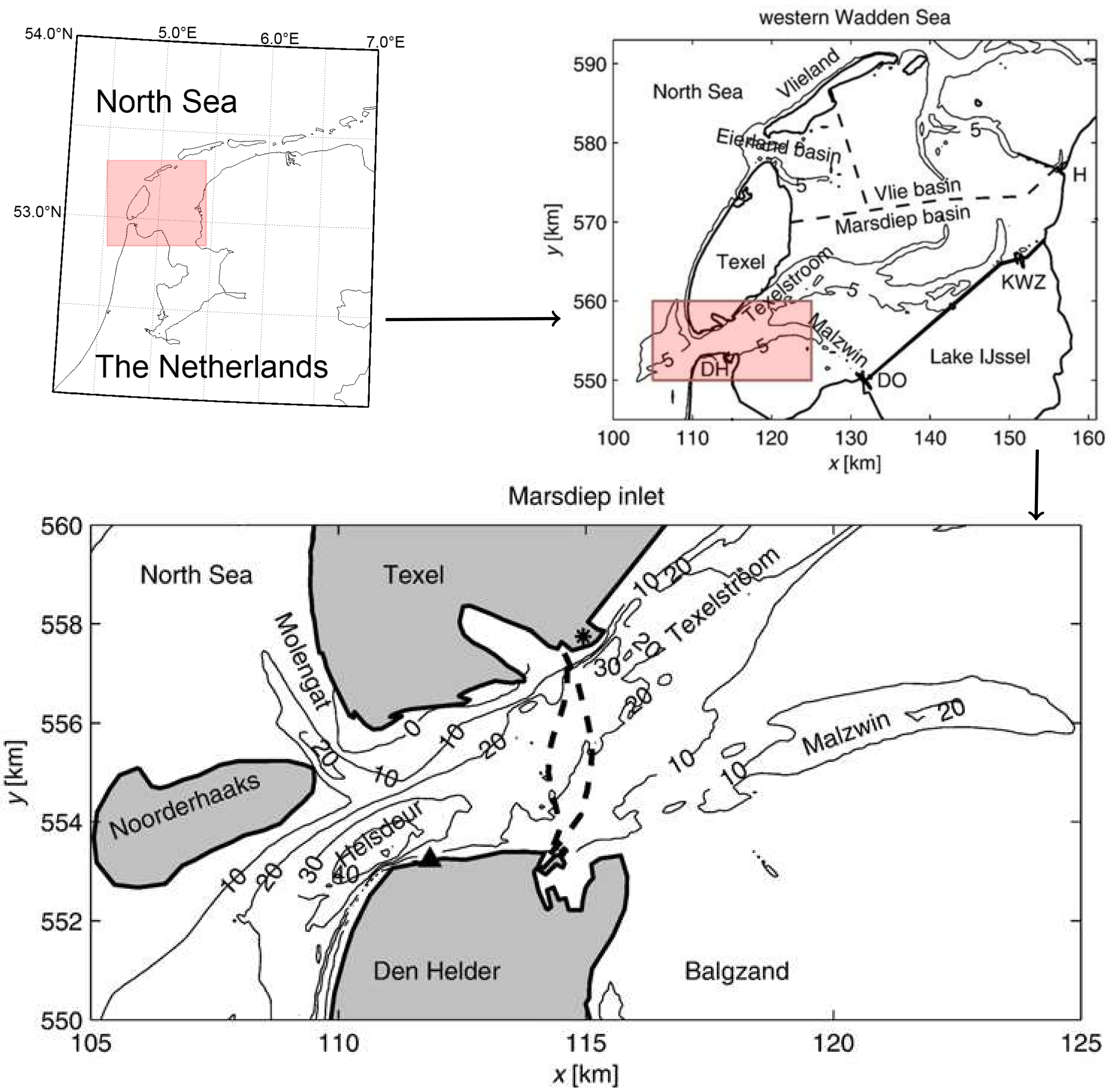

Figure 1.3: The western Dutch Wadden Sea and the Marsdiep inlet in the Netherlands. The bathymetry is plotted by the thin black lines. The thin dashed lines approximate the basins boarders. The thick dashed lines indicate the area of the ADCP measurements taken on board of a ferry. The star marks the location of the Royal Netherlands Institute for Sea Research next to the harbour of Texel. The thick black line indicates the Afsluitdijk. The abbreviations present the towns Den Helder (DH), Harlingen (H), Den Oever(DO), and Kornwederzand (KWZ). [Reprinted from Long-term ferry-ADCP observations of tidal currents in the Marsdiep inlet, *Journal of Sea Research*, 57:239, Buijsman, M.C. and Ridderinkhof, H. (2007), with permission from Elsevier.]

Buijsman and Ridderinkhof (2007) observed that the tides in the Marsdiep are primarily governed by the semi-diurnal astronomic M_2 tide, which is modulated by the astronomic S_2 constituent (27% of M_2 amplitude) and has an amplitude of about 1.4 m next to Den Helder. The tidal wave enters the Marsdiep inlet from the South near Den Helder and propagates northward to Texel and eastward in the Marsdiep basin. The tidal current profiles with velocities up to 2 m s^{-1} fit slightly better to power-law profiles (95-99% correlation) than to logarithmic profiles (91-98% correlation) [Buijsman and Ridderinkhof, 2007].

Water density in the Marsdiep inlet is mainly governed by freshwater discharge of Lake Ijssel from the East and saline North Sea water from the West, which is in turn influenced by northwards advected freshwater of the Rhine [Buijsman and Ridderinkhof, 2007]. The water columns of the tidal channel are well mixed [Zimmerman, 1976] with cross-shore density gradients developing their maxima in winter during maximum freshwater discharge, whereas in summer the gradients may even vanish [Postma, 1954].

2 Data and Methods

Four different types of datasets are available from January 2009 to March 2012. Current velocity, salinity and temperature data in the Marsdiep inlet are provided by the Royal Netherlands Institute for Sea Research (NIOZ), Texel. The data is collected by two ADCPs which are mounted on a ferry of Texel Eigen Stoomboot Ondemening[2] (TESO) operating between Den Helder and Texel and a jetty operated by NIOZ[3] in Texel. The freshwater discharge of Lake Ijssel and the Rhine is provided by Rijkswaterstaat[4], Ministry of Infrastructure and Environment, Netherlands. The time series of the tides in the Marsdiep inlet (station Texel) is calculated by the program WXTide32[5].
Furthermore, the data of the Hörnum Deep presented in Flöser et al. (2011) are used to compare the velocity profiles of the German Wadden Sea with those of the Dutch Wadden Sea.

2.1 Data

The TESO ferry crosses the Marsdiep inlet between Den Helder and Texel at a width of about 4 km (Fig.1.3) and a maximum depth of about 28 m [Buijsman and Ridderinkhof, 2007]. It operates twice an hour, up to 32 times a day, approximately 300 days a year. During a short period in January or February, no data are collected due to maintenance in the dock [Buijsman and Ridderinkhof, 2007].
Two down looking RDI 1.0 MHz ADCPs are mounted on the hull of the ferry in a water depth of 4.3 m, located horizontally in the center of the ship. The measured velocity profiles are stored in 50 bins (first bin in 1.52 m water depth below ADCP), with a resolution of 0.5 m water depth for each bin. Each ADCP has 4 beams with an angle of 20° to the vertical. Owing to the fact that the ferry traverses between the harbours without

[2] http://www.teso.nl/en/about-teso/vessels/doktor-wagemaker
[3] http://www.nioz.nl/nioz_nl/ccba2464ba7985d1eb1906b951b1c7f6.php
[4] http://www.rijkswaterstaat.nl/
[5] http://www.wxtide32.com/

reversing, one particular ADCP is always facing towards Den Helder and the other towards Texel. Two GPS devices are integrated in each ADCP respectively providing positioning data.
Due to unclear reasons, only the forward tracks of the ADCPs are reliable [Alebragtse, 2010]. Furthermore the Texel ADCP broke down in July 2012, for this reason from August 2010 only hourly data from the Den Helder ADCP have been available.
On-board measurements of salinity and temperature are also available, but exhibit large time gaps. Because of the good correlation (temperature over 99%, salinity about 84%) between the available ferry data and the salinity and temperature measurements of a jetty from NIOZ, the latter are used. The jetty is equipped with electronic sensors and measures continuously temperature and salinity in a distance of about 10 m from the Texel sea dyke [van Aken, 2008]. The salinity and temperature data have a resolution of 30 minutes in the period of January 2009 to March 2012.
The discharges given in $m^3\ s^{-1}$ of the sluices in the Afsluitdijk (2009 to 2011) and the Rhine river (2009 to March 2012) are daily averages.
The data of the Hörnum Deep were collected with a moored RDI 1200 kHz ADCP in the main tidal channel in a depth of 9.5 m from 2002 to 2009. The data for the density calculation were measured by sensors fixed to a pole next to the ADCP in a water depth of about 3 m.

2.2 Methods

The primary data processing follows the description given in Alebregtse and de Groot (2010). Due to differences in installation and sampling rates between the two ADCPs, the data are processed separately for each ADCP and are subsequently merged.
The ADCPs determine the bottom profile using the measured backscatter intensity and locating its maximum. Therefore the current velocity is corrected for the ship speed by using bottom track velocity. Due to air bubbles or strong sediment suspension gaps in the bottom profiles can occur. In this case the current velocity is corrected for the ship speed by using the GPS device data.
Because the Den Helder ADCP is mounted under an angle of $\theta = 11.3°$ the current velocities (u'_{east}, v'_{north}) are corrected with the following rotation matrix:

$$\begin{pmatrix} u_{east} \\ v_{north} \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} u'_{east} \\ v'_{north} \end{pmatrix}$$

For evaluating the current velocities during full ebb and flood flow, only data which were measured in a water depth below 15 m (between 52.9634°N and 53.0030°N) are selected,

because in shallower areas the full velocity is not developed. Furthermore data columns without reliable bottom depth data are neglected as something might have disturbed the acoustic signal of the ADCP and hence the velocity measurements may subject to large uncertainties. Due to sudden peaks in velocity data columns, all columns with velocities over 2 m s$^-1$ (maximum current velocity) are neglected, as these peaks of higher current velocities are not reasonable.
To get the times of the full tidal flow the maxima of the velocity for one day is calculated from the along-track and vertical average of the absolute velocity

$$v_{abs} = \sqrt{u_{east}^2 + v_{north}^2}$$

about the depth and section. As the ferry does not operate 24 hours a day, only one complete tidal cycle per day is found. Ebb and flood are determined using the current direction (negative currents correspond to westward currents and hence to ebb). Velocities during one hour around a maximum ($\pm\frac{1}{2}$ h) with equal distances to the sea bed are averaged. Thereby the data of the different ADCPs are combined.
The velocity profiles are fitted to the logarithm

$$u(z) = a \cdot ln(\frac{z}{b})$$

where $u(z)$ is the velocity profile, z the distance from the seabed and a and b logarithmic coefficients. This approach is based on the study of Flöser et al. (2011), where logarithmic profiles are used to quantify the curvature of vertical current velocity profiles. Hence for comparing the flowing condition in the Marsdiep inlet with the results of the model and the results for the German Wadden Sea, a similar processing is required.
Since the curvature of the velocity profiles above the benthic layer are of interest and large deviation from the logarithmic profiles occurs in the upper part of the water column (Fig. 2.1), the upper 10 bins (6.52 m below ADCP) of the velocity data are neglected.
The logarithmic coefficient b is a measure for the curvature of the logarithmic profile. According to the model of Burchard et al. (2008), the higher b, the smaller is the curvature of the profile. Hence, a higher b is linked to a more stratified water column whereas a lower b means a more homogeneous, vertical mixed water column. The logarithmic fits have an averaged mean square error of $mse = 0.0016$ m s^{-1} where 60% of the logarithmic fits are below the average mse and the maximum mse is 0.0255 m s^{-1} . The mse value of each profile is determined by the square root of the norm of the differences between the measured velocity values and the logarithmic values divided by the number of data points. Finally fits for 532 days in the period from January 2009 and March 2012 are available.
The tidal asymmetry of the velocity profiles during high tide and low tide will be pre-

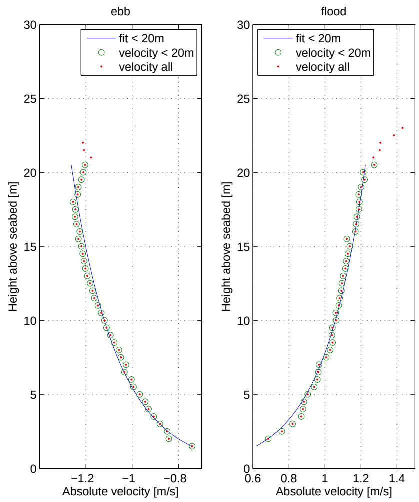

Figure 2.1: Vertical velocity profile during full ebb and flood current in the Marsdiep inlet on 8 Sept. 2011. Red dots represent the upper part of the velocity profiles which is neglected for the further data processing. A logarithmic function is fitted to the profiles (mse<0.001). The curvature coefficients are $b_{ebb} = 0.0360$ and $b_{flood} = 0.1065$.

sented by the logarithm of the ratio of the curvature coefficients b [6].
To connect the tidal asymmetry with estuarine circulation, information about the density gradients are required. The horizontal density gradient is proportional to the density difference of high water - low water [Flöser et al., 2011]. Due to the time gaps in the ADCP data, high tide and low tide for the density difference is calculated by the program WXTide32, a tide and current prediction program. With the calculated times the density is calculated by salinity and temperature data from the jetty. Note, that the on-board salinity and temperature measurements are not calibrated, nor the measurements of the jetty. However, these are the only available data of salinity and temperature for the Marsdiep inlet covering the duration of 3 years and because the difference of density during high water and low water is important for the analysis and not the absolute values, the uncorrected data can be used as guideline values.
As already mentioned in Chapter 1.1, tidal straining and its impact can differ from area to area, depending on the dynamic conditions, especially on the prevailing balance of stratification and mixing forces. It can be distinguished between permanently well-mixed, alternation between well-mixed and stratified or permanently stratified regimes [Becherer et al., 2011]. The non-dimensional parameter which quantifies this balance is the horizontal Richardson number also referred to the Simpson number

$$R_i = \pi g \frac{\partial \rho}{\partial x} \frac{H^2}{\rho_0 U^2}$$

[6] $(b = log(\frac{b_{ebb}}{b_{flood}}))$

where g is gravitational acceleration, $\frac{\partial \rho}{\partial x}$ the tidally and vertically averaged density gradient, H the water depth, ρ_0 the reference density and U the depth-averaged current velocity [Flöser et al., 2011]. Is $8.8 \cdot 10^{-2} < R_i < 8.4 \cdot 10^{-1}$ the regime is alternating, for smaller values of R_i the regime is well-mixed, for higher values of R_i the regime is stratified [Becherer et al., 2011]. One research approach of this study is the comparison of the circulation pattern in the Marsdiep with those in the German Wadden Sea. Because the tidal asymmetry can differ due to different dynamical influences on tidal straining in the study areas, these influences are considered by R_i. $\frac{\partial \rho}{\partial x}$ is approximated by the density difference of high water and low water divided by the tidal velocity amplitude and the tidal period. Hence R_i is modified to the difference horizontal Richardson number

$$R_x = \pi g \triangle \rho \frac{H^2}{\rho_0 U^3 T}$$

where $g = 9.81$ m s$^-2$ is gravitational acceleration, $\triangle \rho$ the high water-low water density difference, H the water depth, $\rho_0 = 1000$ kg m$^-3$ the reference density, $T = 44,714s$ the tidal period and U the depth-tidal-averaged current velocity amplitude [Flöser et al., 2011].

But R_x is not the only parameter influencing tidal straining. I also depends on the ratio of the vertical mixing time scale and the tidal period [Burchard, 2009]. This balance is given by the inverse Strouhal number

$$S_i = \frac{H}{UT}$$

where H is the water depth, $T = 44,714s$ the tidal period and U the depth-tidal-averaged current velocity amplitude [Flöser et al., 2011]. In conclusion, equal values of R_x may be linked to different tidal asymmetries of velocity due to different values for S_i.

3 Results

The driving force behind estuarine circulation and the associated additional sediment accumulation due to tidal straining in a coastal area is the horizontal density gradient. Furthermore, tidal straining is governed by the balance of stratification and mixing forces (quantified by the horizontal Richardson number R_x) and the balance of the vertical mixing time scale versus the tidal period (quantified by the inverse Strouhal number S_i) [Burchard, 2009]. To examine whether estuarine circulation applies to the Marsdiep inlet or not, the horizontal density gradient has to be determined first. If a permanent density gradient exists, a closer analysis of the dynamical regime and the velocity profile curvature will be taken. Therefore time series of temperature, salinity and density differences, freshwater discharge and curvature coefficients of the logarithmic fits are constructed. Furthermore the correlation between the tidal asymmetry of the velocity profile curvature ($b = log(\frac{b_{ebb}}{b_{flood}})$) and the horizontal Richardson number (R_x) is investigated. Here, also the data of the Hörnum Deep is presented.

3.1 Time series

The horizontal density gradient is approximated by the density difference $\triangle\rho$ between high water and low water. In the Marsdiep inlet $\triangle\rho$ has a mean value of (1.4457 ± 0.0257) kg m^{-3}, hence on average a distinct cross-shore density gradient does exist. Nevertheless, for particular days negative density differences also occur, meaning an offshore density gradient over a short period of days (Fig.3.1).

The water temperature (Fig.3.1) shows for the temperate humid climate typical annual variations from next to $0°C$ in winter and up to $20°C$ in summer. These annual variations (higher values in summer than in winter) can also be found in the salinity, although the variations are less distinctive. One exception is the year 2011, when salinity increases from February to May and decreases from June to September. While short-term variations (a few days) in temperature are low, salinity exhibits large short-term variations. The mean value of salinity during 2009 to 2012 is (27.7437 ± 0.0116) psu. The correlation between the salinity difference ($S_{hw} - S_{lw}$) and the density difference $\rho_{hw} - \rho_{lw}$ is over 96%, which indicates the high salinity influence on the density.

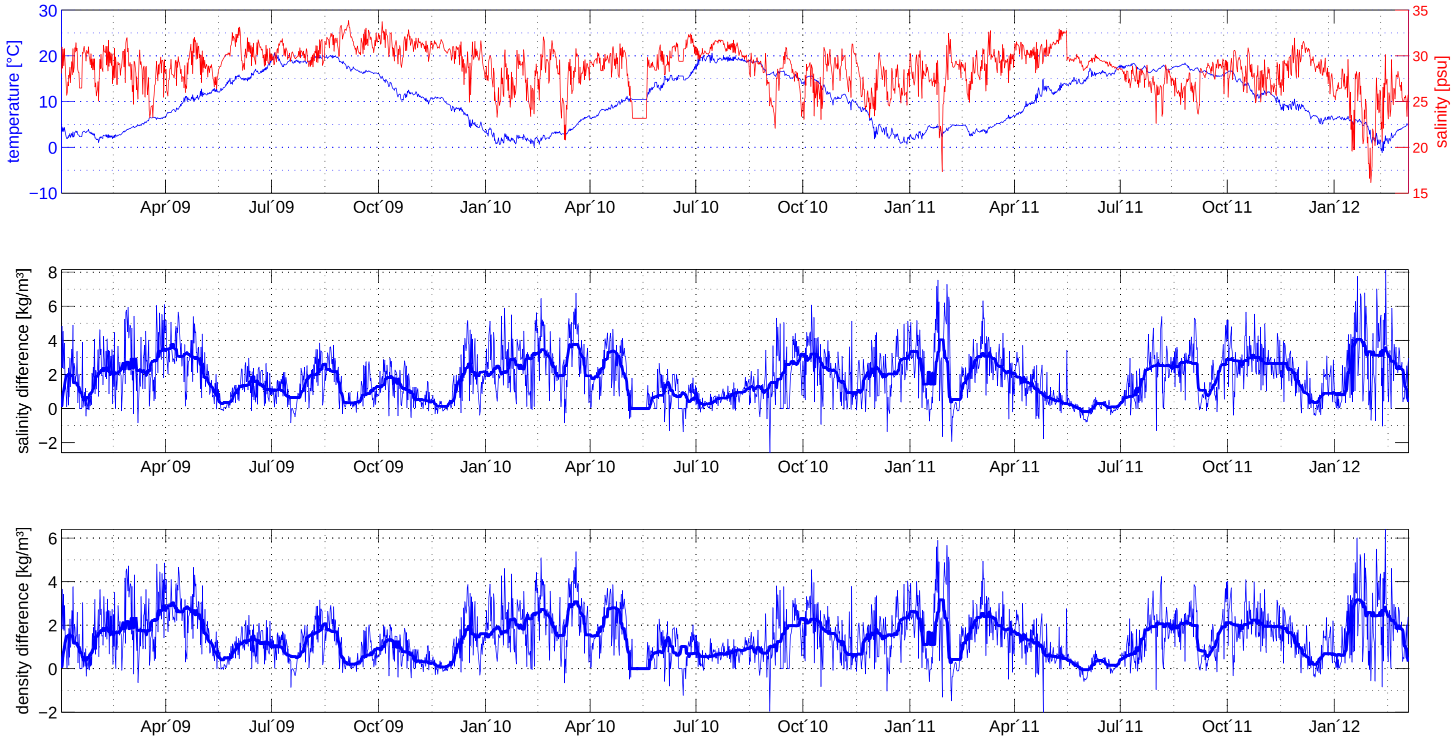

Figure 3.1: Time series of temperature and salinity (PSU) during high water (top), salinity difference $S_{hw} - S_{lw}$ (middle) and density difference $\rho_{hw} - \rho_{lw}$ (bottom) in the Marsdiep inlet for the period of January 2009 to January 2012 ($\frac{1}{2}$ day resolution). The thick, blue lines are the median filtered (window size: 31 days) time series of salinity and density difference, respectively.

According to salinity and consequently density variation, which are not governed by temperature, the water discharge of Lake Ijssel and the Rhine are considered (Fig.3.2). The Wadden Sea water in the Marsdiep basin is influenced by the freshwater discharge of Lake Ijssel (Fig.1.3). The higher the discharge is, the lower is the salinity and hence the density of the Wadden Sea water. The mean freshwater discharge of Lake Ijssel for the period 2009 to 2012 is (466 ± 10) m^3 s^{-1}.
The North Sea water next to the Marsdiep inlet is influenced by Rhine water, which is advected along the west coast of the Netherlands (about 150 km). So high discharge of Rhine water reduces salinity and hence density of the North Sea water. The freshwater discharge of the Rhine is measured in Lobith (3 years mean is (1968 ± 28) m^3 s^{-1}), next to the German border, about 150 km from the Rhine estuary away. The Rhine is also connected to Lake Ijssel, for this reason high water discharges of Lake Ijssel are often linked

to high water discharges of the Rhine (Fig.3.2). The maxima of the water discharges are commonly in winter (December, January) and the minima in summer (June, July) due to annual net precipitation, but the duration of higher water discharge clearly differs for the three years. The Lake Ijssel discharge has high short-term variation like salinity and density difference.

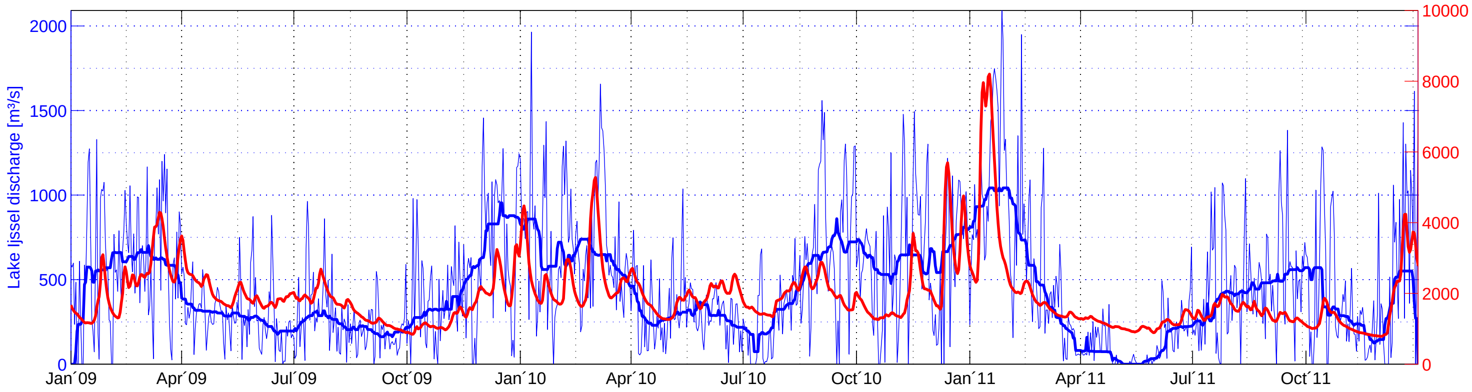

Figure 3.2: Time series of the sum of the daily averaged water discharges from the Lake Ijssel sluices in the Afsluitdijk as well as the sluice in Lobith from the Rhine river for the period of January 2009 to January 2012 (daily resolution). The thick, blue line is the median filtered (window size: 31 days) time series of the Lake Ijssel discharge.

In Figure 3.3 the logarithmic curvature coefficients for ebb (b_{ebb}) and flood (b_{flood}) are shown. For particular days Figure 3.3 clearly shows higher values for b_{flood} than for b_{ebb}. Furthermore b_{flood} forms the Minimum as well as the Maximum of all curvature coefficients. Their magnitudes vary between 10^{-4} and 10^{-1}. However, in average b_{ebb} [7] is higher than b_{flood} [8]. Over two thirds of the curvature coefficients showing a higher b value during ebb than during flood. About two thirds of the tidal cycles with higher b_{flood} than b_{ebb} appear all over the year in 2011, about one third all over the year in 2010.

3.2 Correlation of tidal current asymmetry and horizontal Richardson number

Following the study of Flöser et al. (2011), the tidal current asymmetry is quantified by the ratio $log(\frac{b_{ebb}}{b_{flood}})$ and plotted versus the horizontal Richardson number R_x considering density gradient and dynamical influences of different areas (Fig.3.4). The data of the

[7] $b_{ebb,mean} = 0.2068$
[8] $b_{flood,mean} = 0.1798$

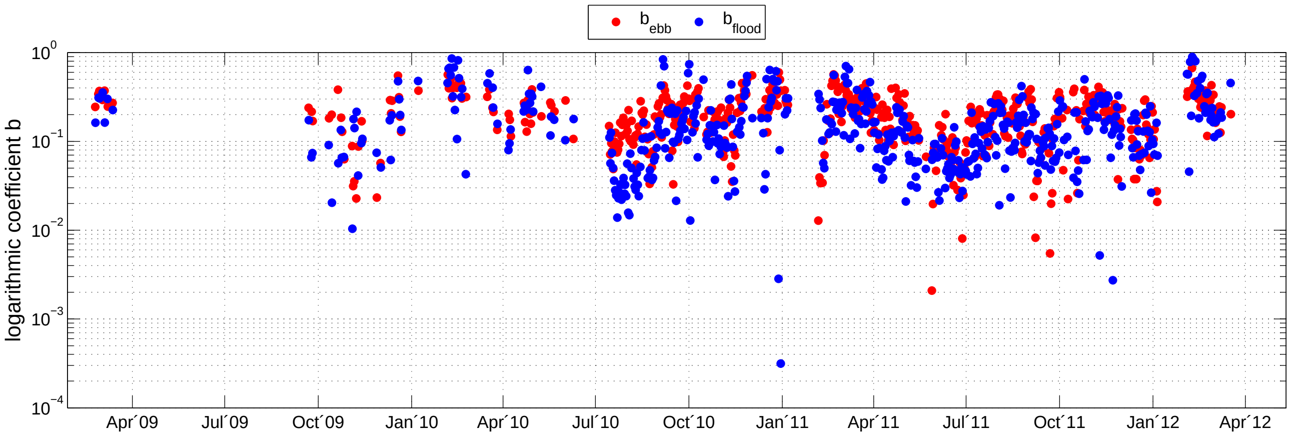

Figure 3.3: Curvature coefficient b of the logarithmic velocity profile fit $a \cdot ln(\frac{z}{b})$ for main ebb (b_{ebb}) and main flood (b_{flood}) flow during the period of January 2009 to March 2012 in the Marsdiep inlet. The vertical axis is logarithmic. The gaps are mainly due to interruption of data collection.

Hörnum Deep is also presented (red marks).
The model of Burchard et al. (2008) does not predict a correlation between the tidal asymmetry and R_x, but an effect on each other can be considered due to the influence of R_x on tidal straining and, in turn, the influence of tidal straining on the tidal asymmetry of the current velocity profiles [Burchard, 2009]. Hence a good correlation of the tidal asymmetry and R_x would explicitly support the model. Thereby the correlation (e.g. the regression gradient) can vary from area to area due to the inverse Strouhal number, which also influences tidal straining.

3.2.1 Marsdiep Inlet

The correlation between the tidal asymmetry and the horizontal Richardson number is weak, although for averaging periods up to 8 days it might be significant ($p < 0.02$[9]) (Fig.3.5). For averaging periods higher than 8 days, the correlation decreases, for an averaging period of 20 days it vanishes. The gradient of the linear regression is small compared to the Hörnum data. There is a high variation of R_x and S_i, both parameters which influence tidal straining and hence the tidal asymmetry. S_i varies between $4.6 \cdot 10^{-4}$ and $7.1 \cdot 10^{-4}$, R_x between 0.001 and $-7,3 \cdot 10^{-4}$.

[9] "p-values test the hypothesis of no correlation. Each p-value is the probability of getting a correlation as large as the observed value by random chance, when the true correlation is zero. If p is small, say less than 0.05, then the correlation R(i,j) is significant." [http://www.mathworks.de/help/techdoc/ref/corrcoef.html, 4 July 2012]

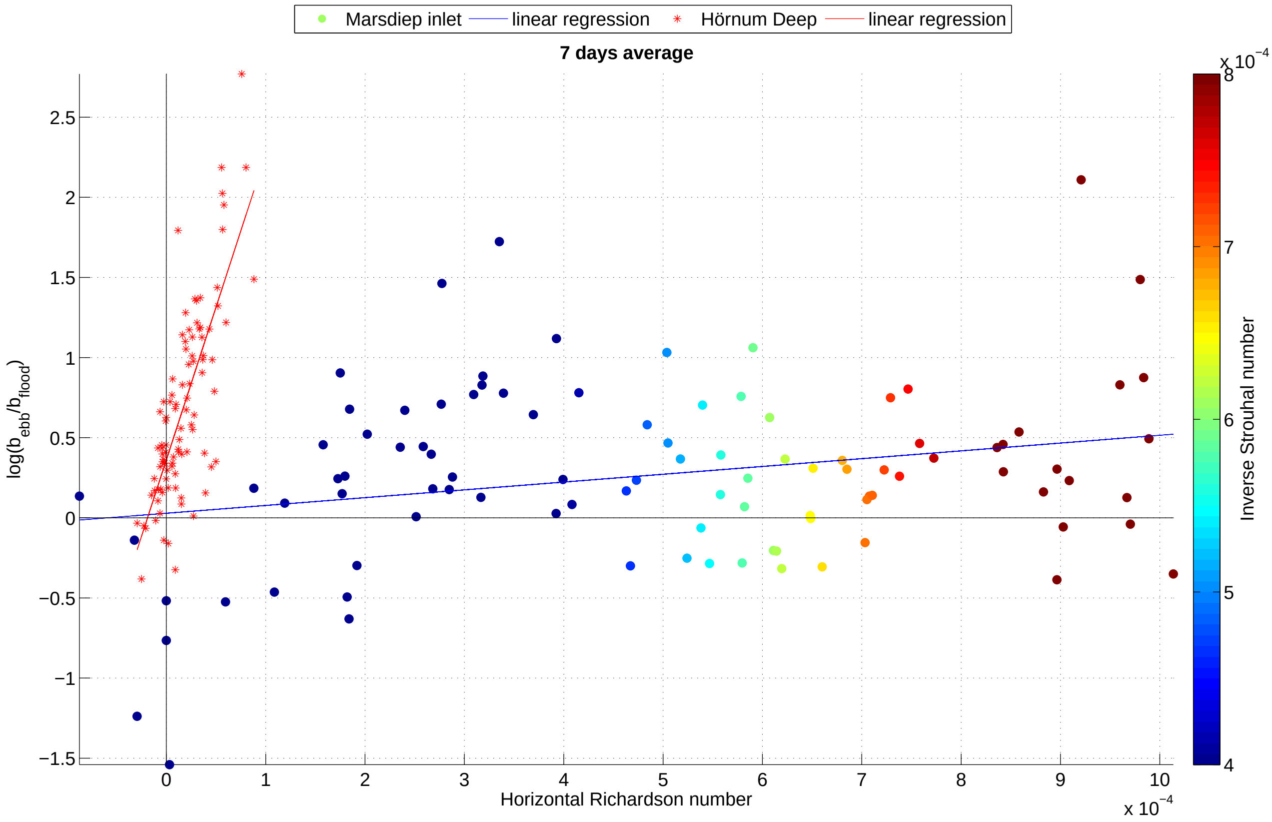

Figure 3.4: Seven days average of the logarithm of the ratio b_{ebb} and b_{flood} versus the horizontal Richardson number in the Marsdiep inlet (multicolour circles) and the Hörnum Deep (red stars). The correlation of the Hörnum data is about 70%, whereas the correlation of the Marsdiep data is below 30%. The color of the Marsdiep data is linked to the inverse Strouhal number S_i. Typical values of S_i for the Hörnum data are between $1.3 \cdot 10^{-4}$ and $3.05 \cdot 10^{-4}$.

3.2.2 Hörnum Deep

Flöser et al. (2011) computed curvature coefficients b with variations in magnitude of 10^{-6} to 10^{-1}. The positive correlation between $log(\frac{b_{ebb}}{b_{flood}})$ and the horizontal Richardson number is weak but highly significant ($p < 10^{-4}$) and increases with increasing averaging period. In the Hörnum Deep S_i varies between $1.3 \cdot 10^{-4}$ and $3.05 \cdot 10^{-4}$. Flöser et al. (2011) also obtained a positive correlation between $log(\frac{b_{ebb}}{b_{flood}})$ and R_x in other areas of the Wadden Sea (moored ADCP in Sylt, ship mounted ADCP in East and North Frisia), although the significance of the correlation and the slope of the correlation are smaller ($p_{Sylt} = 0.45$, $p_{EastFrisia} = 0.15$, $p_{NorthFrisia} = 0.21$). Thereby higher values of S_i were linked to smaller gradients. This fits with the observed higher values of S_i and the smaller regression gradient of the Marsdiep inlet data in comparison to the Hörnum Deep.

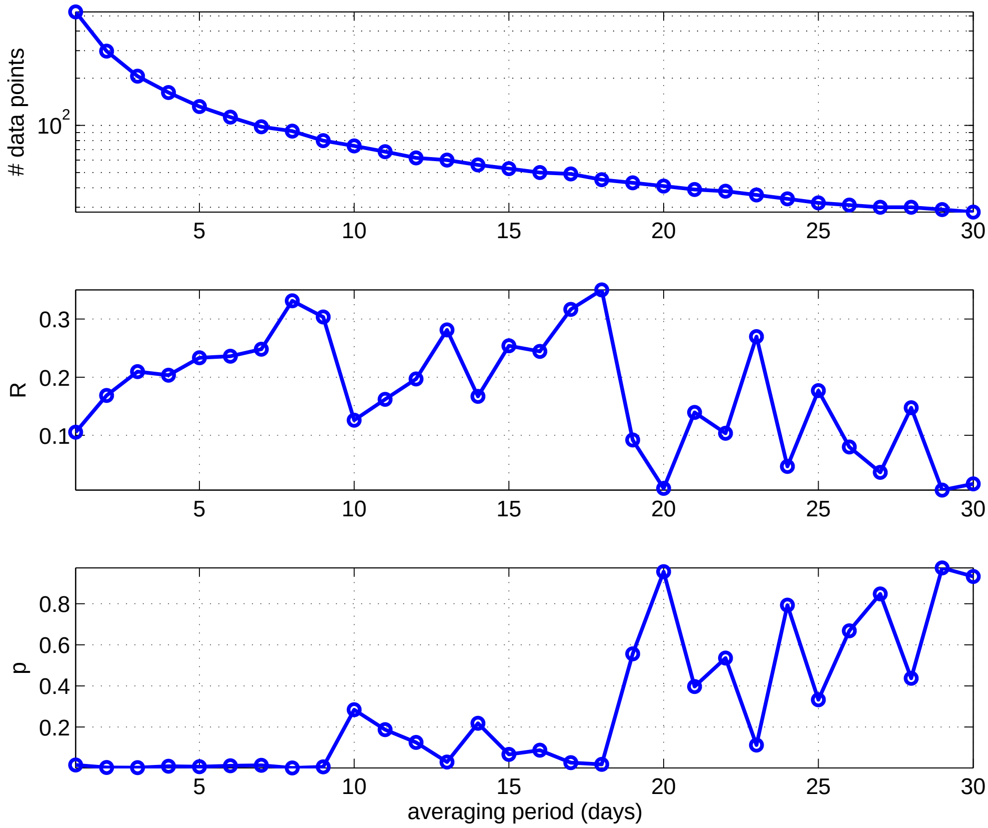

Figure 3.5: Number of prevailing data points (note logarithmic y axis), correlation coefficient R and the value for the significance p of the correlation between $log(\frac{b_{ebb}}{b_{flood}})$ and the horizontal Richardson number r_x versus the averaging period.

4 Discussion

The purpose of this study was to investigate whether estuarine circulation occurs in the Marsdiep inlet, Dutch Wadden Sea. The tidal asymmetry of the vertical current velocity profiles predicted in the one-dimensional model for estuarine circulation of Burchard et al. (2008) served as theoretical groundwork. As Flöser et al. (2011) successfully proofed the hypothesis of estuarine circulation for the German Wadden Sea on the basis of this hydrodynamical key feature of Burchards model, the methods in this study are guided by those used in the study of 2011.
The precondition for estuarine circulation is a persistent, cross-shore density gradient. The horizontal density gradient in the Marsdiep inlet is approximated as the difference of high water - low water density. The result is an averaged positive density difference, which fulfils the preconditioning of the model. The linked tidal asymmetry in the velocity profile of ebb and flood currents is characterized by higher curvature above the benthic boundary layer of the current profiles during flood than of those during ebb. In the Marsdiep inlet this fits to over two thirds of the observed velocity profiles.
The density gradient and the tidal asymmetry in the Marsdiep inlet may be partial in agreement with the model of estuarine circulation, which in turn predicts a net onshore sediment transport, but the special characters of the Marsdiep inlet, influenced by freshwater input from the coast and the seaside, does not allow definite conclusions.

4.1 Density difference and its influential factors in the Marsdiep inlet

The temperature mainly governs the annual cycle of salinity and consequently density in the Marsdiep inlet. Besides, salinity and density also seem to be influenced by freshwater input from the East (Lake Ijssel) and from the Southwest (Rhine), since higher variations in the differences arise during higher water discharge of Lake Ijssel and the Rhine. Striking is the difference between the annual cycles during the observation period from 2009 to 2012 in particular. These may be due to the annual differences of the freshwater discharges,

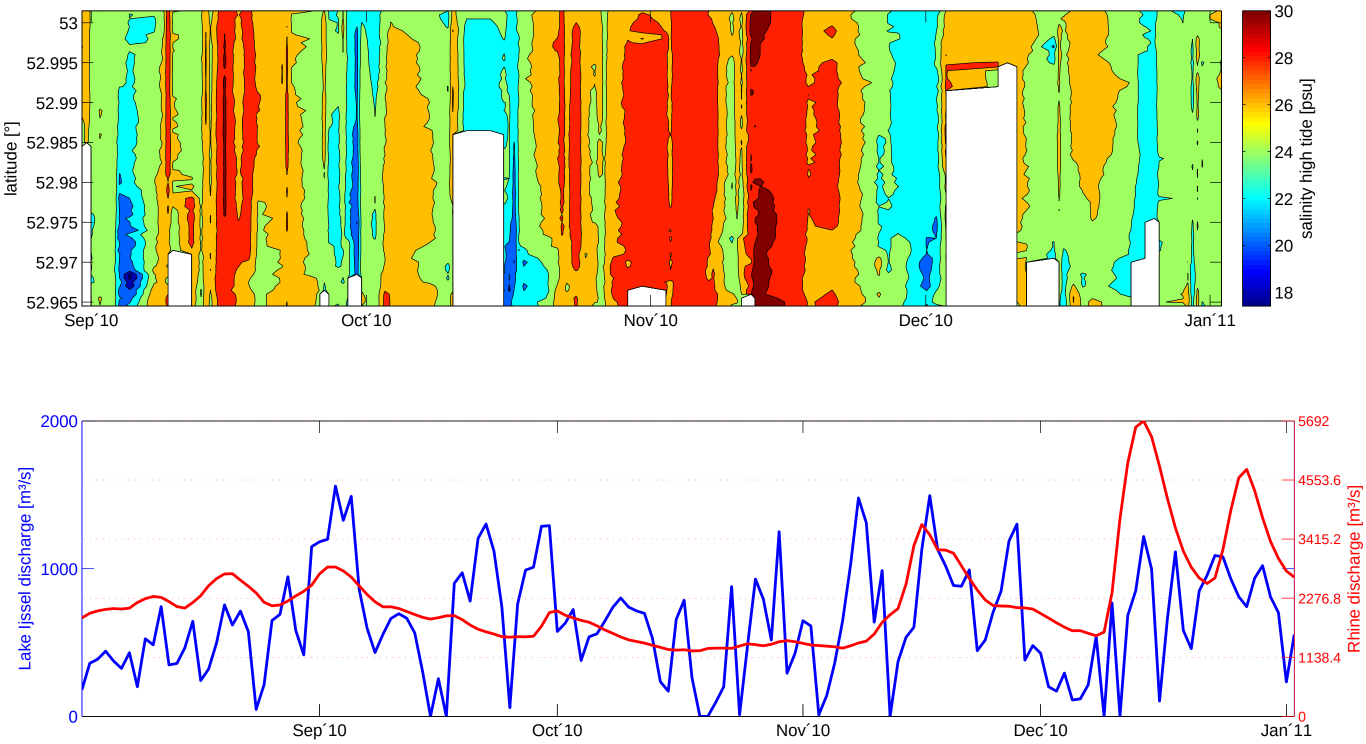

Figure 4.1: Salinity profiles of the ferry track versus time (September 2010 - January 2011) during high water (top) and time series (September 2010 - January 2011) of the freshwater discharge of Lake Ijssel and the Rhine (bottom). The harbour of Den Helder is located next the lowest latitude, the harbour of Texel next to the highest latitude. The Rhine water has to travel about 300 km from the discharge measurements in Lobith to the Marsdiep Inlet.

which in turn are linked to the weather conditions. Coincidently, during the winter 2009/2010 the NAO index (North Atlantic Oscillation)[10] reached one of its lowest minima during the last 150 years [Jung et al., 2011]. Hence these years form exceptions of extreme weather conditions. These may explain the annual differences during the observation period.

The density difference $\triangle\rho$ and the horizontal Richardson number R_x are based on not calibrated salinity and temperature measurements. In this study the calculated mean value of water salinity in the Marsdiep inlet over all three years is about 28 psu. According to several studies in the Marsdiep inlet, the water commonly exhibits a salinity about 30 psu [Postma, 1954, Buijsman and Ridderinkhof, 2007, Zimmerman, 1976], on account of this the absolute values of salinity (and consequently the calculated density differences)

[10] The NAO index is calculated by the difference of atmospheric pressure at sea level between the Azores high and the Icelandic low. It forms an important parameter to describe large-scale weather condition. [http://en.wikipedia.org/wiki/North_Atlantic_oscillation, 4 July 2012]

seem to differ from the actual values of water salinity (and density) and form a possible source of error. Following, $\triangle\rho$ and R_x must be regarded as guideline values.
Another critical point of the used salinity and temperature is the position of the jetty station. It is located next to the NOIZ on Texel (Fig.1.3). The on-board measurements of salinity and temperature exhibit large time gaps, therefore the data of the jetty are used. As already mentioned, the advected freshwater of the Rhine enters the Marsdiep inlet from the Southwest. It is possible, that this freshwater input is not noticed from the jetty station, because the water body does not reach the station in the North. In Figure 4.1 the salinity data of the on-board measurements for the period of September 2011 to January 2011 is plotted for each ferry track during high water. Bodies of fresher water occur in the North, not spreading to the northern parts of the track. These freshwater bodies may be linked to maximum discharges of the Rhine sluice in Lobith (water track about 300 km), which occur about two weeks earlier in Lobith than the freshwater bodies in the Marsdiep inlet. Hence, the apprehension that freshwater inputs of the Rhine may not be fully presented by the data of the jetty is justified. In fact, this may clearly have a negative effect on the correlation of the calculated tidal asymmetry and the horizontal density gradient, since the not always registered density difference has the same direction like the main tidal flow (south-west to north-east, see chapter 1.3). This has to be considered regarding the correlation of the tidal asymmetry and the horizontal Richardson number.
Figure 4.1 also indicates, that the approximation of the density gradient by $\triangle\rho$ is reliable, since the salinity for high water is presented and it seems to vary with the variation of the Rhine discharge containing a time lag of about two weeks, which in turn influences the density of the North Sea water entering the Marsdiep inlet.
Nevertheless, all these assumptions have to be taken with caution, since, as mentioned above, the data of salinity, temperature and density are only guideline values.

4.2 Velocity profiles, tidal asymmetry and the horizontal Richardson number

Buijsman and Ridderinkhof (2007) investigated the asymmetry of the vertical current velocity profile shape for spring and nip tide, using as well ADCP data of the TESO ferry. They observed higher curvature during ebb than during flood. Regarding the model of Burchard et al. (2008), this should be linked to a negative density gradient. But no informations on the prevailing density gradient were given by Buijsman and Ridderinkhof (2007). In this study, higher curvatures of current profiles during ebb than during flood have also been observed. In the time series of the profile curvature coefficients b (Fig.3.3), one third of the observations show higher curvature (i.e. smaller values of b) during ebb than during flood. Nonetheless, in the majority of the profiles, the typical asymmetry of tidal straining linked to estuarine circulation is observed.

The correlation between the tidal asymmetry of the ratio of b and the horizontal Richardson number R_x, is too weak for a predictive relation between the tidal asymmetry and R_x. For an averaging period of 20 the correlation is next to zero. Hence, there seems to be a physical force, which acts against tidal straining and its influence on the vertical velocity profiles. In the context of this study, this problem is not further analysed. The reason may be found in the density data. The jetty station does not always register water bodies of fresher Rhine water, because those do not propagated so far to the north. Hence, a reversing density gradient may occur without notice.

Near the density difference, also the absolute current velocity $U = (1.1 \pm 0.2)$ m s^{-1} contributes to variations of R_x. The variation of the current velocity without the influence of the density gradient is presented by the inverse Strouhal number S_i[11]. Regarding the high scatter in S_i and due to the fact that R_x is inversely proportional to U^3, the influence of U should not be neglected. In fact, regarding Figure 3.4 R_x seems to be more influenced by U than by $\triangle\rho$. But since U is alternating periodically, its variation should play a minor role by averaging over longer periods.

4.3 Marsdiep inlet versus Hörnum Deep

The Hörnum Basin covers an area of 300 km^2 and the averaged tidal amplitude is 2.3 m. The water volume entering the basin through two shallow tidal inlets at high tide is mainly exported through the Hörnum Deep. The area exhibits no distinct freshwater discharge [Flöser et al., 2011]. Due to the reason mentioned in chapter 1.1, a density gradient exists (0.5-1.0 kg m^{-3}). Because of smaller density gradients in the Hörnum Deep in comparison to the Marsdiep inlet, higher values of R_x have been expected, which is in fact the case (Fig.3.4). This effect is strengthened because of the higher water depth of the Marsdiep inlet (about 28 m in the Marsdiep inlet, 9.5 m in the Hörnum Deep), also effecting S_i in the same way. The water column in the Marsdiep inlet is three times the height of the water column in the Hörnum Deep, so bottom friction has a higher influence on the vertical current profiles there. Following, the curvature of the Hörnum Deep profiles are higher than those of the Marsdiep inlet (Fig. 3.4).

In the Hörnum Deep the relation between the tidal asymmetry of the vertical current

[11] According to small variation in the water depth and a constant tidal period T, variation in R_x are due to density and velocity, in S_i due to velocity (chapter 2.2)

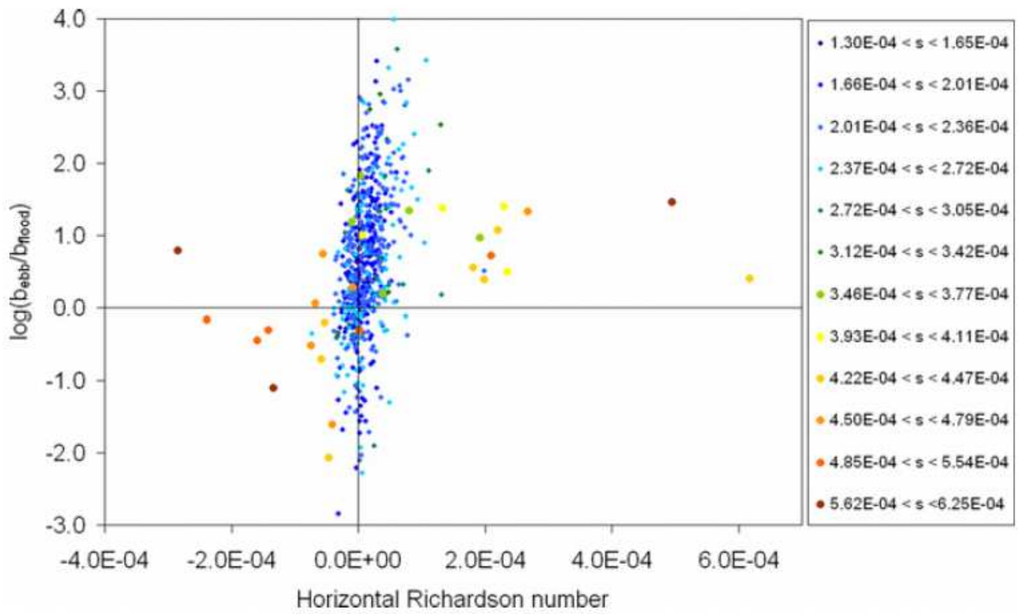

Figure 4.2: Tidal asymmetry versus the horizontal Richardson number for the German Wadden Sea data from the moored ADCP in the Hörnum Deep (2002-2008) and the Lister Deep, ship measurements in the Hörnum Deep (August 2003), the Sylt-RømøBight (May and September 2003, April 2008) and in the tidal inlet Accumer Ee between the islands Langeoog and Baltrum (May and August 2000, July 2001, November 2002, August 2004 and August 2007). [Reprinted from Observational evidence for estuarine circulation in the German Wadden Sea, *Continental Shelf Research*, 31:1637, Flöser, G., Burchard, H., and Riethmüller, R. (2011), with permission from Elsevier.]

profiles and the horizontal density gradient becomes predictive after an averaging period of seven days (correlation over 70%). In contrast, the data of the Marsdiep inlet never reaches a correlation >33% and with increasing averaging period, a decrease in correlation and significance is the case. Hence, in the Marsdiep inlet an external force seems to counteract the influence of tidal straining regarding to time scales over 10 days. As above mentioned this may be linked to the water discharge of the Rhine river regularly reducing the density of the North Sea water which enters the Marsdiep inlet during high tide (Fig.4.1). Due to the permanent reversing density gradient in the main tidal flow direction, a long-term balance of tidal straining versus density gradient and a linked suspended particulate matter net onshore transport may not result in the Marsdiep inlet.
Nevertheless, it should be noted that Flöser et al. (2011) also investigated velocity current profiles in other areas of the German Wadden Sea using sea bed moored and ship mounted ADCPs. The observation periods cover two to four weeks each, the water depth reaches from 11m to 20m. In these limited data sets smaller correlations, statistically less significant ($0.15 < p < 0.45$) were observed. This smaller correlation may be linked to the small observation durations. But the important point is that the regression gradients

between the tidal asymmetry and the horizontal Richardson number are smaller than those of the Hörnum Deep, too. Furthermore the smaller gradients also coincided with higher Strouhal numbers which is in agreement to the Marsdiep data (Fig. 4.2), hence it may be that there is a connection between higher S_i and lower tidal asymmetry.

5 Conclusion

This study presents how complex tidal estuaries may be. The Marsdiep inlet is characterised by short-term variations of freshwater input, which may regularly reverse the density gradient. These varying density gradients and periodical fluctuation of the current velocity have a major impact on the tidal straining. Hence, the tidal asymmetry of the vertical current profiles exhibits both, higher curvature during flood and lower curvature during ebb and vice versa. The correlation between the tidal asymmetry and the horizontal Richardson number is weak and not predictive. Maybe this is linked to the distinct short-term variation of the density gradient. Based on the observed results and according to the model of Burchard et al. (2008), tidal straining may not have an additional support of an inward suspended particulate matter transport in the Marsdiep inlet, hence the suspended matter transport would also permanently reverse. Due to the bad correlation of the tidal asymmetry and the horizontal Richardson number, it is questionable whether the one-dimensional model applies in the Marsdiep inlet at all.

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Declaration

I confirm that the bachelor thesis

OBSERVATIONAL EVIDENCE OF ESTUARINE CIRCULATION IN THE WADDEN SEA
- CURRENT VELOCITY, SALINITY AND TURBULENCE

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Kiel, 5 July 2012