Floeser, G.; Burchard, H.; Riethmueller, R.:

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In: Continental Shelf Research (2011) Elsevier

DOI: 10.1016/j.csr.2011.03.014

Observational evidence for estuarine circulation in the German Wadden Sea

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Abstract

Observational evidence is presented that corroborates the hypothesis of the general presence of estuarine circulation in the Wadden Sea as put forward in a previous study (Burchard et al., 2008). Current velocity data from moored ADCPs (in the Hörnum Deep south of Sylt Island, 2002-2009) and ship cruises (in several locations in the German Wadden Sea, 2000-2008) were analyzed. As a general result, the vertical current profiles above the benthic boundary layer are usually more homogeneous during flood than during ebb, with a pronounced dependence on the cross-shore horizontal density difference. This tidal asymmetry consequently must lead to a residual outflow of Wadden Sea waters in the upper part and a residual inflow of water in the lower part of the water column, thus giving a generic explanation for the obvious net import of suspended sediments from the German Bight into the Wadden Sea.

Keywords: estuarine circulation, velocity profiles, Wadden Sea

1. Introduction

Wadden Sea waters are on the average much higher (20-70 g m^{-3}) concentrated in suspended particulate matter (SPM) than those of the open North Sea (1-5 g m^{-3}), as is obvious from satellite scenes and from in-situ measurements (Puls et al., 1997; Gemein et al., 2006; Staneva et al., 2009). Due to the shear dispersion induced by turbulent tidal water movement, this gradient should disappear within a few days or, as indicated by its persistence, erase the intertidal flats within several months. The stability of the Wadden Sea on the time scale of several thousands of years hence requires the existence of a counteracting mechanism that balances the sediment outward transport generated by the density gradient. Sediment budget estimations (Pejrup [1988a], Pejrup [1988b], Eisma [1993], Puls et al. [1997], Townend and Whitehead [2003]) often yield an inward transport of fine sediments resulting in a sea bottom rise of 0.07 - 8 mm y^{-1} that may be altered by human influence such as the construction of dikes, land reclamation measures or closing of coastal lagoons.

It is, after several decades of research, still not clear which mechanism is dominantly responsible for that inward transport. Several mechanisms were proposed: Settling and scour lag (Postma 1954; van Straaten and Kuenen 1958; Postma 1961; Bartholdy 2000), asymmetrical ebb/flood velocity curves (Groen 1967; Dronkers 1986a,b), enhanced flocculation (Pejrup 1988a; Dyer 1994), or Stokes drift (Dyer 1988, 1994; Stanev et al. 2007).

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The various proposed mechanisms were discussed in Burchard et al. (2008) and found to be either applicable only in parts of the Wadden Sea or during part of the year.

Lumborg et al. (2003, 2005) has set up a numerical suspended sediment transport model for the Sylt-Rømø Bight (Figure 1) that comprises hydrodynamic forcing from 2-D currents and waves as well as biological processes that control the settling velocities, sedimentation and resuspensation / erodibility. For a one year simulation period, the model computes net inward transport of suspended matter that corresponds to sediment growth of 0.1 mm y^{-1} in reasonable agreement with results from dated sediment cores, whereby single storm events have the potential to nearly annihilate the steady inward transport of several months. Lumborg et al. (2003, 2005) did not put forward a prominent process that drives the inward transport of suspended matter. Settling and scour lag are mentioned as potential mechanisms, but due to the manifold of non-linear interactions between the physical and biological processes included in the model, an individual contribution was not – and perhaps can not be – separated. Furthermore, estuarine circulation was excluded from this model study due to the use of vertically integrated equations.

Burchard et al. (2008) have proposed estuarine circulation as an alternative, quite generic physical process based on the observation of a nearly persistent horizontal density gradient between Wadden Sea (less dense) and German Bight (denser) waters that is higher in winter and spring than in summer / autumn. This effect is known from tidal estuaries where significant Estuarine Turbidity Maxima develop in the area of the upstream end of the salt intrusion, but was largely ignored so far in the Wadden Sea because most areas in the tidal basins between the Danish and the Eastern Dutch Wadden Sea do not exhibit significant river runoff. The reason for this horizontal density gradient, mostly due to the salinity differences, is simply the relative shallowness of the area: in the temperate humid climate, the excess of precipitation over evaporation leads to a lower salinity in shallower waters. Another factor that contributes to the salinity gradient is the direct runoff from the mainland via floodgates.

The transport mechanism consisting of gravitational circulation (Postma and Kalle 1954, Festa and Hansen 1978) and tidal straining (Jay and Musiak 1994, Burchard and Baumert 1998, Burchard and Hetland 2010) was theoretically adapted to the Wadden Sea in Burchard et al. (2008) and numerically simulated in a one-dimensional vertical model with the observed horizontal temperature and salinity gradients as input as well as with a three-dimensional model with a salinity gradient forced by realistic net precipitation and river run-off. During ebb, the vertical current profiles transform the horizontal density gradient into a vertical stratification damping the effect of tidal stirring, whereas on the opposite its breakdown during flood is accelerated by tidal stirring. The most important result of the stratification is that vertical current profiles above the benthic boundary layer are more homogeneous during flood than during ebb and the residual currents point outwards of the Wadden Sea in the upper part of the water column and inwards in the lower part. Given that the suspended matter concentration profiles increase towards the bed, this effect would lead to a steady net inward transport of suspended materials over a realistic range of settling velocities.

Testing this model by direct observation of the suspended sediment transport is hardly possible for two reasons: First, the sediment budget of the Wadden Sea is nearly balanced even at the scale of several years. Ebb and flood transport masses would be nearly identical. Second, in order to detect a statistically significant net transport as a difference of two large numbers would require a substantial observational effort given the high temporal and spatial variability of suspended sediments that cannot be achieved with reasonable means over a longer observational period.

This study therefore concentrates on one specific hydrodynamic key feature predicted by the model: the above described ebb/flood asymmetry in the vertical shape of the current profiles, and its dependence on the horizontal density gradient. If this feature is indeed observed, it can be concluded with high probability that density induced estuarine circulation is indeed a mechanism that transports suspended sediments against the concentration gradient into the Wadden Sea. To assure that this mechanism prevails in time and space, time series over months to years at fixed positions and from surveys at different regions of the German Wadden Sea are analysed here.

2. Study Area

The observations were carried out at three locations of the German Wadden Sea, the coastal fringe of the German Bight in the North Sea (Figure 1): the Sylt-Rømø and Hörnum tidal basins in the North Frisian Wadden Sea and the tidal inlet Accumer Ee between the East Frisian Islands of Baltrum and Langeoog. The Sylt-Rømø basin is a semi-enclosed back barrier tidal inlet, bordered by the islands of Rømø (Denmark) and Sylt (Germany) in the west and the mainland in the east. The watersheds in the north and south are locked by artificial causeways, leaving the Lister Deep between Rømø and Sylt as the only connection with the German Bight. The bight comprises an area of approximately 400 km^2 and a low water volume of $0.6\cdot10^9$ m^3. The mean tidal prism amounts to the same value (Lumborg and Windelin, 2003) at an average tidal amplitude of 1.8 m. Two small rivers Brede Å and Vidå are the fresh water sources to the area. However, these rivers only contribute approximately 0.2 % of the tidal prism over one tidal cycle. The water column is thus well mixed and the estuary classifies as a well-mixed coastal plain estuary.

The Hörnum tidal basin, surrounded by the mainland and the islands of Sylt, Amrum and Föhr follows directly in the south. It covers an area of about 300 km^2 and is connected to the North Sea by the Hörnum Deep and to its southern basins by two shallow inlets. The low water volume is about $0.4\cdot10^9$ m^3, the mean tidal prism amounts to about $0.5\cdot10^9$ m^3 and the average tidal amplitude is about 2.3 m (BSH, 1998). Based on two surveys, Ross et al. (1998) estimated that over a tide, the basin gains water of a volume of some 10 % of the tidal prism through the shallow tidal inlets (between the island Föhr and the mainland, and between Amrum and Föhr) around high water, and exports this net excess volume through the Hörnum Deep. There are no significant freshwater sources discharging into the Hörnum Deep.

The third area is the Accumer Ee, the tidal inlet between the barrier islands of Langeoog and Baltrum in the East Frisian Wadden Sea. Here, the mean tidal amplitude is 2.8 m, the back-barrier catchment area amounts to 90 km^2, its low water volume is $0.08\cdot10^9$ m^3 and with a tidal prism of $0.19\cdot10^9$ m^3 it is smaller than the considered areas in the North Frisian Wadden Sea. Freshwater runoff coming from the mainland is discharged through the floodgates and amounts to only about 1.5 m^3 s^{-1}, discharged mostly during low water slack (NLWK, 2000).

Thus, in all three areas the average water depth at sea level is 2-2.5 m.

3. Materials and Methods

Two types of datasets were analysed. The first set comprised data from fixed stations at several locations in the Sylt-Rømø and Hörnum bight (s. Figure 1). An upward looking RDI broadband Acoustic Doppler Current Profiler (ADCP), operating at a frequency of 1200 kHz, was fixed in the bed sediments of the main tidal channels at average water depths of 20 m (Lister Deep), 17.5 m (Lister Ley), 18.5 m (Høyer Deep), 11 m (Rømø Deep), and 9.5 m (Hörnum Deep). The first four moorings in the Sylt- Rømø bight lasted for three to four weeks in 1996 and 1997, resp. The Hörnum Deep mooring started in 2002 and is still in operation. Here, the ADCPs are replaced by identical systems every two to three months to download the data and to exchange batteries. In this study all Hörnum Deep data until July 2009 were considered. In general, the ADCPs were operated in mode 5 with a ping repetition time of 1 min, an ensemble repetition time varying between 10 and 30 minutes and a vertical bin resolution of 0.25 m except for the Hörnum Deep mooring in 2006/07 where the vertical bin size was set to 0.5 m. The ADCPs' roll and pitch angle was in the range -10° to 10° and changed usually less than 5° during the instrument's operating time.

In addition, poles carrying a set of standard oceanographic sensors about 1 to 1.5 m above the bed were fixed into the sediment at the margin of the tidal channels approximately at 3 m low water depth. The systems are described in more detail in Lane et al. (2000) and Onken et al. (2007). The along channel distance between the locations of the ADCPs and the poles varied from 1 to 5 km. The pole sensors deliver data as 10 minute averages from a 2 Hz sampling. In this study only water temperature and specific conductivity were considered, and salinities and water densities were computed from these parameters using the UNESCO formulae (Fofonoff, 1983). The poles were – due to the danger of ice damaging the cables and sensors – taken out of the water in November and placed back in March every year.

The second set of data stems from several ship cruises that were performed between May 2000 and April 2008 along cross-sectional transects and anchored stations in the Lister Deep, the Hörnum Deep and the Accumer Ee (Figure 1) using the research vessel "FS Ludwig Prandtl". Vertical current profiles were continuously measured by means of an RDI 1200 kHz Zedhead ADCP running with a resolution of 0.25 m. The uppermost bin was, on average, about 2 m below sea surface, the lowest 0.25 m above the seabed. At selected locations, vertical profiles of water temperature and specific conductivity were measured using a CTD probe and from these data, salinity and water density was computed. Recording rate was 8 Hz for all experiments and the profiling velocity about 0.25 m s^{-1}. During fixed stations, vertical profiles were taken every 30 minutes; during cruises the probe was towed from shipboard at a speed of max. 5 knots, at a water depth of 1-2 m.

In order to quantify the shape of the vertical current profiles in a consistent way, the following procedure was applied. For the moored ADCP, data during 2.4 hours around the current maximum were averaged. The ship-borne data were averaged over 1 minute each. These averaged profiles were fitted according to the logarithmic law-of-the-wall profile:

$$u(z) \quad = \quad a \ln \frac{z}{b} . \tag{1}$$

Here, $u(z)$ is the current velocity profile, z the distance from the seabed, and a and b constants. For comparability, only the data from the lowest bin up to the low water level were considered. In our analysis, a and b are regarded only as pure integration constants, where the depth-averaged current velocity is independent of a, so b controls the shape of the vertical profiles: a lower b means more homogeneously distributed currents above the benthic boundary layer and vice versa (Figure 2). In 96 percent of the cases, the R^2 value of the fit was below 0.001 (in order to account for the varying number of data points, the R^2 value was divided by the number of data points). Only those 4 percent of the cases where R^2 was above 0.001 were excluded from the analysis. Generally, the logarithm of the ratio b_{ebb}/b_{flood} is evaluated.

In order to account for different water depths and current velocities in estuaries, Burchard (2009) has proposed to use the modified horizontal Richardson number as a measure for the intensity of horizontal density gradient forcing:

$$r_x = g \frac{\partial \rho}{\partial x} \frac{H^2}{\rho_0 U^2} , \tag{2}$$

where g is gravitational acceleration, $\partial\rho / \partial x$ the (tidally and vertically averaged) density gradient, H water depth, ρ_0 the reference density, and U the depth-averaged current velocity amplitude. Note that this is the definition of the horizontal Richardson number which is consistent with Simpson et al. (1990). Although this definition of r_x based on the current velocity amplitude is easier to handle from an observational point of view, from a theoretical point of view the definition of the horizontal Richardon number (now also denoted as the Simpson number) through the bottom velocity scale is preferred, see the discussion by Burchard et al. (2011). The horizontal density gradient $\partial\rho / \partial x$ was not observable directly. Instead, the density gradient was estimated from the difference between high and low waters, measured at the close-by observational poles or by the CTD profiler onboard the research vessel, divided by the tidal excursion estimated from the tidal velocity amplitude and the tidal period $T = 44714$ s:

$$\hat{r}_x = \pi\, g\, \Delta\rho \frac{H^2}{\rho_0 U^3 T}, \tag{3}$$

which we therefore denote as the difference horizontal Richardson number. This approach – the proportionality between the high water - low water difference and the horizontal gradient – was tested for the case of the Accumer Ee tidal inlet. In the years 2000 and 2002, several cross-shore profiles of water temperature and specific conductivity along the main tidal channel were recorded. In parallel, the pole station close to the tidal inlet recorded (ten minutes average) time series of these parameters. The mean density gradient was determined by a linear fit of the measurements against latitude as the coastline has a West-East direction. The result shows (Figure 3) that the measured mean density gradient on the one hand and the density difference between high and low waters, as recorded at the pole station on the other, are statistically significantly and positively correlated. This demonstrates that the high water – low water density difference, as measured at the pole station, can be used as a reliable proxy for the density differences between the Wadden Sea and the German Bight waters.

4. Results

First, the data of the Hörnum Deep mooring are shown, because they contain by far the largest amount of data. They are fitted to the log-profile given above. For a first comparison, all ebb and flood b values are plotted in Figure 4 versus time over the entire sampling period from 2002 to 2009. b varies by five orders of magnitude between 10^{-6} and 10^{-1} m. This high variability reflects its logarithmic property in the fit. It is also evident that, on the average, the ebb values are generally larger than the corresponding flood values. But at some occasions, also the opposite is observed. A comparable pattern was also found for the other moorings and ship data. To gain further insight into the considerable scatter and overlap of the data, the ebb/flood asymmetry of b was ordered by the horizontal density gradient (as expressed by the horizontal Richardson number), because this quantity should be one of the drivers of the hypothesized estuarine circulation.

In Figure 5, this b ratio is plotted versus the horizontal Richardson number. The data show a weak, but statistically highly significant ($p < 10^{-4}$) positive correlation. Noticeably, also events with negative horizontal Richardson numbers are present. In these cases the tidal asymmetry in b became less than one, which means that flood profiles are more curved than ebb profiles.

Although the relationship between b asymmetry and horizontal Richardson number is statistically significant, the scatter is quite large. The situation improves when the data pairs are averaged over larger temporal intervals. As shown in the inlet of Figure 5, the R^2 increases with an inverse exponential with increasing averaging intervals. For intervals above two weeks, it saturates at $R^2 = 0.95$ with a characteristic time constant of 8.7 days.

This large scatter and its reduction with increasing length of the sampling period can be explained by the effect of the relative tidal frequency, as quantified by the inverse Strouhal number,

$$S_i = \frac{H}{UT}, \tag{4}$$

which varies with the fortnightly spring-neap cycle. Burchard (2009) could show that the tidal dynamics varies with both, the horizontal Richardson number and the inverse Strouhal number. In Figure 6, the moored Hörnum data are shown together with those from the other observational points (mostly ship data). In these other cases, there is also a positive correlation between the tidal *b* asymmetry and the horizontal Richardson number. As these data are based on much smaller data sets, the correlations are statistically less significant ($p = 0.45, 0.15, 0.21$ for data from moored ADCPs in Sylt, ship data from East and North Frisia, resp.) At the same time, the slope differs from location to location, with by far the highest slope for the moored Hörnum data set. As indicated by the colour coding in Figure 6, the major reason for this large scatter is due to the variation in the inverse Strouhal number S_i between the observations. Small values of S_i dominate in the Hörnum data due to the shallower water depth at this pole station (9.5 m) and still relatively high maximum current velocities of more than 1 m/s (see Figure 2), whereas the other stations are significantly deeper.

For time scales above seven days, where the correlation between the tidal *b* asymmetry and the horizontal Richardson number becomes more predictive, the close connection between the two parameters became also evident in their temporal development. Two examples are introduced. After a high discharge event in April 2006 of the close-by Elbe river, the main fluvial water supplier of the German Bight, the discharged water body propagated north along the North Frisian coast and reached the tidal inlet of the Sylt-Rømø Bight around 20th April, as conjectured from a decrease of salinity at high waters observed at the Hörnum pole station (Figure 7). At that time, the generally positive cross-shore salinity – and thus density – gradient was reversed for more than two weeks (i.e. the coastal water became less saline than the Wadden Sea water), before it turned positive again. The *b* ratio follows this development very closely. The behaviour is very similar in the case of the Elbe flood in August 2002 (data not shown).

The second example refers to the seasonal dependence of both the *b* ratio and the horizontal Richardson number, both measured and calculated for the Hörnum Deep mooring (Figure 8). The monthly averages are from the period of 2002 to 2009 where both the moored ADCP and the pole were in operation. This covers the months from March to October. Again the tidal *b* asymmetry follows closely the density difference: both are highest in March and decrease steadily until September where they reach a minimum. In October a slight increase is observed in both cases.

5. Discussion

The purpose of this study was to find significant evidence for the presence of an estuarine type of residual water circulation between the Wadden Sea and the German Bight. This circulation should be driven by the prevailing but varying horizontal density gradient between the Wadden Sea (most of the time less dense) and German Bight (most of the time denser) waters, a feature that was observed at several long-term measuring stations in German Wadden Sea bights (Burchard et al., 2008). For these conditions, Burchard et al. (2008)

predicted an ebb/flood asymmetry in the vertical shape of the current profiles, i.e. ebb current profiles are more curved above the boundary layer than flood profiles. This asymmetry may be caused by both gravitational circulation and tidal straining. In our analysis we parameterised the curvature by fitting the measured profiles to a logarithmic function where *b* acted as a measure for the degree of curvature. In most cases, the ratio of b_{ebb}/b_{flood} was found to be positive. At the same time, sign and magnitude of this effect are significantly correlated to the variation of the horizontal density gradient, or more generally, the horizontal Richardson number, as shown in Figure 5. Although this was not part of the model study in Burchard at al (2008), this behaviour should be expected (Burchard and Hetland, 2010). Averaging the current profiles only over one day (i.e. about two tides), the correlation coefficient amounts to only 0.22, but is statistically highly significant. It increases to 0.95 when averaging the selected profiles over more than 14 days, reaching 70 % for averages over 7 days. This means that a predictive relationship between horizontal Richardson number and ebb/flood asymmetry of the profiles shows up only at time scales above about a week. Much of the variability at time scales shorter than 14 days may be explained by the influence of the changes in the relative tidal frequency (as quantified by the inverse Strouhal number) due to the spring-neap cycle. The two shown examples, where horizontal Richardson number and profile asymmetry seemed to be closely correlated in their temporal development, the Elbe 2006 discharge event (Figure 7) as well as the mean seasonal development (Figure 8), are above this time scale.

In order to ascertain that these findings are no artefacts caused by hydrodynamic peculiarities of the observational sites, it was investigated whether the relation between horizontal Richardson number and tidal current profile asymmetry was sensitive to the ebb and flood tidal maximal velocities or flood or ebb dominance. No significant effect was found in any case.

Furthermore, the data from all of the observational sites reveal the same tendency of a positive correlation between tidal current profile asymmetry and horizontal Richardson number, but the statistical significance is not in all cases better than $p < 0.05$. For the Hörnum Bight, no sensitivity to wind speed or wind direction was detected. This suggests that the observations are of quite general nature and that estuarine circulation is a common feature between the Wadden Sea and the German Bight, even for most soft bottom coastal areas with intertidal flats.

In September and October after longer periods where evaporation over tidal flats exceeds precipitation within the Wadden Sea basins (Onken and Riethmüller, 2010) or in cases of significant river runoff events that lower the salinity of the innermost German Bight, the horizontal density gradient and hence the horizontal Richardson number may be reversed such that the flood velocity profiles are more curved than the ebb profiles. This process which in autumn is enhanced by differential cooling of the Wadden Sea may lead to a transient reversal of estuarine circulation even for periods in the order of several weeks.

To the knowledge of the authors there is only one other published study that showed an explicit comparison of the curvature of vertical ebb and flood current profiles in the Wadden Sea or other tidal soft bottom costs in the world. Buijsman and Ridderinkhof (2007) fitted, out of a 5 year series of ADCP data taken onboard the Marsdiep ferry in the Western Dutch Wadden Sea, two sets of maximal ebb and flood current profiles taken during one day at neap and spring tide, respectively. In both cases, they found stronger curvature during flood than during ebb, in contrast to our general result. It is not possible to assess their finding against our results, because these are only two examples taken within seven days and no information about the cross-shore salinity or density gradients was given. Considering that a branch of the Rhine River with 440 $m^3 s^{-1}$ discharges into the Western Dutch Wadden Sea (Zimmerman 1976), the density difference between that part of the Wadden Sea and North Sea should be at least of the order as observed in the German sites where freshwater discharges are small or absent. Hence it is an open question whether their finding represents a general feature of the Marsdiep and can be explained by other tidal asymmetries, such as the net residual transport out of the Wadden Sea or the pronounced tidal asymmetries measured at Den Helder.

The permanent salinity and density gradient may be compared to the cases where Simpson et al. (1990) and Rippeth et al. (2001) have found conditions for periodic stratification (SIPS: strain-induced periodic stratification). For the Irish Sea study showing SIPS, the horizontal Richardson number has been estimated to $r_x = 2\cdot10^{-3}$ by Burchard (2009) whereas typical Wadden Sea values for permanently mixed stations are $r_x < 2\cdot10^{-4}$ (see Figures 5 and 6). For situations with weak wind forcing, this is in accordance with the threshold values given by Simpson et al. (1990), see also Verspecht et al. (2009).

Although the presence of estuarine circulation suggests a mechanism for a net transport of suspended material into the Wadden Sea, direct conclusions from the observational findings presented here have to be taken with caution, as they reflect point measurements. Because of either ebb or flood dominance in the observational points, no suspended matter residual transports over full tides could be calculated. This would only be possible if the measurements (currents and suspended matter) would be taken at high resolution and accuracy over full cross-sections for a long period. That is technically not feasible.

On the other hand, the proposed mechanism of estuarine circulation, as we stated in the introduction, counteracts the dispersion that is due to the large horizontal suspended matter concentration gradient. So, if the proposed mechanism works, it can not be observed since it is balanced and thus covered up by the dispersion process. Net suspended particulate matter transports into the Wadden Sea would thus result from small imbalances between landward transport by estuarine circulation and seaward transport by dispersion. Thus, direct estimates of net SPM transport cannot be derived from current velocity measurements.

Still, the findings provide some implications for the development of the sediment budgets within the Wadden Sea. The horizontal density gradient shows a pronounced seasonal dependence for high positive values in winter and spring down to slightly negative values in September. The water densities within the Wadden Sea basins are strongly controlled by the balance of precipitation and evaporation because of the relative shallowness of the waters. Onken and Riethmüller (2010) have shown for the inner part of the Hörnum Bight that evaporation exceeds precipitation for most of the time between March and November, most probably due to enhanced heating of the tidal flats during daylight emergence. This demonstrates the importance of evaporation over the tidal flats for the residual water circulation in the Wadden Sea. In September and October, this circulation may come to a halt or even reverse direction. In the framework of estuarine circulation that would mean reduced import into or even additional export of fine sediments during these two months. On a decadal time scale, regional climate model scenarios for the German Bight (Meinke and Gerstner, 2009) suggest an increase in winter precipitation by 32 % and winter temperatures by 3.2 °C, and a decrease of summer precipitation by 17 % with increasing summer temperatures (+2.8 °C). That means that the mean seasonal pattern for the horizontal Richardson number as well as the sign of the estuarine circulation may be altered in the future. If estuarine circulation will be proven to be a significant mechanism for the net suspended sediment transports, it needs to be considered for the long-term development of the fine-sediment budgets of the Wadden Sea under sea level rise and climate change conditions.

6. Conclusions and Outlook

Our findings give congruent and clear evidence that estuarine circulation prevails between the Wadden Sea and the (German part of the) German Bight. The data indicate a significant dependence of the ebb to flood ratio of *b* on the density gradient, in all investigated study sites.

In order to further test the generality of this estuarine circulation in the Wadden Sea, we try to gather more existing long-term data from other sites since the majority of our data comes from the Hörnum Deep, and only a minority from other parts of the Wadden Sea. A further step we wish to take is to confirm our hypothesis by detailed measurements of water column parameters such as vertical density stratification, suspended matter profiles and turbulent dissipation rates to explain the processes driving the estuarine circulation. Furthermore, three-dimensional numerical modelling will be applied to quantify the strength of estuarine circulation and the subsequent net fluxes of suspended particulate matter at various locations and under various meteorological conditions, to better understand the temporal and spatial variability of this process.

7. Acknowledgements

We are grateful to the crew of the research vessel “Ludwig Prandtl” who helped very much in performing the ship experiments, and to the technical staff responsible for installation and maintenance of the pole stations and the bottom-bound ADCP, namely Helmut Bornhöft, Horst Garbe, Michael Janik, Bernd Peters, Heiko Rinck, Steffen Schmidt, Albert Werner, and Karin Wirth. Special regards to the Administration of the National Park Wadden Sea Schleswig-Holstein who pay for the maintenance of the Hörnum Deep pole station.

Figure captions:

Figure 1: Satellite scene of the investigated areas in North and East Frisia (South-Eastern part of the North Sea, see inset). From North to South: (1) Sylt-Rømø-Bight, (2) Hörnum Deep and (3) Accumer Ee. The location of moored ADCPs (yellow circles) and of permanent measuring stations (red circles) is also marked. The instruments in the Sylt-Rømø-bight were deployed in 1996/97, those in the Hörnum Deep from 2002 onwards from March - November. The pole in the Langeoog area (Accumer Ee) was running from 2000-2007 during the months March-November. At the lower right, the mouth of the Elbe River is visible, east of the cup-shaped Jade Bay the Weser River mouth.

Figure 2: Vertical velocity profiles from measurements on 26th April, 2002 (filled circles) and 8th July 2009 (open circles) by the moored ADCP in the Hörnum Deep. Solid lines are the respective fits. Flood currents are positive, ebb currents negative. The b fit parameters are given for each profile. The water depth is not exactly equal because locations as well as bathymetry vary slightly over the years. The data have been selected considering the extreme differences between the b fit parameters.

Figure 3: Cross-shore density gradient from 9 cruises through the East Frisian tidal inlet Accumer Ee versus density difference between high and low water, measured at the pole station at the time of the cruises.

Figure 4: b for all 2-day-velocity profiles (ebb: filled circles and flood: open circles) measured by the moored ADCP in the Hörnum Deep. Note the logarithmic scale at the left y (b) axis. The gaps are due to technical difficulties or unavailability of instruments. For 96 % of all data, the least squares sum per data point (from the logarithmic fit to equation 1) is smaller than .0001 m. The rest of the data was disregarded.

Figure 5: Logarithm of the ratio of b_{ebb} and b_{flood} versus the horizontal Richardson number from equation (3) for all moored ADCP measurements in the Hörnum Deep. The p values for the ADCP data are $< 10^{-4}$. The inset shows the increase of the correlation coefficient with the averaging period with an exponential constant of 8.7 days.

Figure 6: Logarithm of the ratio of bebb and bflood versus the horizontal Richardson number from equation (3) for the data from the moored ADCP in the Hörnum Deep (as in Figure 5) and other data. These data refer to ship cruises and moored ADCP data in other positions: ship measurements in the Hörnum Deep (August 2003), the Sylt-Rømø-bight (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). Moored ADCP data from the Lister Deep (between Sylt and Rømø) are also included. The colours indicate the inverse Strouhal number, calculated from equation (4). The size of the fewer dots at higher Strouhal numbers has been enlarged for better visibility.

Figure 7: Horizontal Richardson number, as calculated from the Hörnum pole station values, and the logarithm of the b ratio at ebb and flood tide versus time during and after the April 2006 Elbe discharge event. The arrow indicates the maximum river discharge on April 10th, at the location Neu-Darchau, 200 km upstream from the river mouth.

Figure 8: Seasonal dependence of the b ratio (b_{ebb}/b_{flood}), derived from the bottom-bound ADCP data, and of the horizontal Richardson number from equation (3) as measured at the pole station in the Hörnum Deep.

References

Bartholdy, J., 2000. Processes controlling import of fine-grained sediments to tidal areas: A simulation model. Coastal and Estuarine Environments: Sedimentology, Geomorphology and Geoarchaeology, Pye, K. and Allen, J.R.L. (Eds.), Geological Society of London, 435 pp.

BSH, 1998. Der Wasseraustausch im Tidebecken Hörnum-Tief. Berichte des Bundesamtes für Seeschiffahrt und Hydrographie Nr. 16.

Buijsman, M.C., Ridderinkhof, H., 2007. Long-term ferry-ADCP observations of tidal currents in the Marsdiep inlet. J. Sea Res. 57, 237-256.

Burchard, H., 2009. Combined effects of wind, tide and horizontal density gradients on stratification in estuaries and coastal seas. J. Phys. Oceanogr. 39, 2117-2136.

Burchard, H., Baumert, H., 1998. The formation of estuarine turbidity maxima due to density effects in the salt wedge. A hydrodynamic process study. J. Phys. Oceanogr. 28, 309-321.

Burchard, H., Flöser, G., Staneva, J.V., Badewien, T.H., Riethmüller, R., 2008. Impact of density gradients on Net Sediment Transport into the Wadden Sea. J. Phys. Oceanogr. 38, 566-587.

Burchard, H., Hetland, R.D., 2010. Quantifying the contributions of tidal straining and gravitational circulation to residual circulation in periodically stratified tidal estuaries, J. Phys. Oceanogr. 40, 1243-1262.

Burchard, H., R.D. Hetland, E. Fischer, and H.M. Schuttelaars, 2011. Drivers of residual circulation in tidally energetic estuaries: Straight and irrotational estuaries with parabolic cross-section, J. Phys. Oceanogr., in print.

Dronkers, J., 1986a. Tidal asymmetry and estuarine morphology. Neth. J. Sea Res. 20, 117–131.

Dronkers, J., 1986b. Tide-induced residual transport of fine sediment. Physics of Shallow Estuaries and Bays, van de Kreeke, J. (Ed.), Springer, 228–244.

Dyer, K.R., 1988. Fine sediment particle transport in estuaries. Physical Processes in Estuaries, Dronkers, J., van Leussen, W. (Eds.), Springer, 295–320.

Dyer, K.R., 1994. Estuarine sediment transport and deposition. Sediment Transport and Depositional Processes. Pye, K. (Ed.), Blackwell, 193–218.

Eisma, D., 1993. Sedimentation in the Dutch-German Wadden Sea. Mitteilungen des Geologisch-Paläontologischen Instituts der Universität Hamburg 74, 253-274.

Festa, J.F., Hansen, D.V., 1978. Turbidity Maxima in Partially Mixed Estuaries: A Two-Dimensional Numerical Model. Est. Coast. Mar. Sci. 7, 347-359.

Fofonoff, P., Millard, R.C., 1983. Algorithms for computation of fundamental properties of seawater. UNESCO Technical Paper in Marine Science 44, 53.

Gemein, N., Stanev, E.V., Brink-Spalink, G., Wolff, J.O., Reuter, R., 2006. Patterns of suspended matter in the East Frisian Wadden Sea: Comparison of numerical simulations with MERIS observations. EARSel eProceedings 5(2), 180-198.

Groen, P., 1967. On the residual transport of suspended matter by an alternating tidal current. Neth. J. Sea Res., 3, 564–574.

Jay, D.A., Musiak, J.D., 1994. Particle trapping in estuarine tidal flows. J. Geophys. Res. 99, 445–20 461.

Lane, A., Riethmüller, R., Herbers, D., Rybaczok, P., Günther, H., Baumert, H., 2000. Observational data sets for model development. Coast. Engin. 41, 125-153.

Lumborg, U., Windelin, A., 2003. Hydrography and cohesive sediment modelling: Application to the Rømø Dyb tidal area. J. Mar. Syst. 38, 287–303.

Lumborg, U., Pejrup, M., 2005. Modelling of cohesive sediment transport in a tidal lagoon – an annual budget. Mar. Geol. 218, 1–16.

Meinke, I., Gerstner, E.-M., 2009. Digitaler Norddeutscher Klimaatlas informiert über möglichen künftigen Klimawandel. DMG Mitteilungen 3-2009, 17.

Niedersächsischer Landesbetrieb für Wasserwirtschaft und Küstenschutz (NLWK), 2000. Nährstoffeinträge in die Nordsee.

Onken, R., Callies, U., Vaessen, B., Riethmüller, R., 2007. Indirect determination of the heat budget of tidal flats. Cont. Shelf Res. 27, 1656-1676.

Onken, R., Riethmüller, R., 2010. Determination of the freshwater budget of tidal flats from measurements near a tidal inlet. Cont. Shelf Res. 30, 924-933.

Pejrup, M., 1988a. Suspended sediment transport across a tidal flat. Mar. Geol. 82, 187 – 198

Pejrup, M., 1988b. Flocculated suspended sediment in a micro-tidal environment. Sediment. Geol. 57, 249-256.

Postma, H., 1954. Hydrography of the Dutch Wadden Sea. Archs. Neerl. Zool. 10, 405-511.

Postma, H., 1961. Transport and accumulation of suspended particulate matter in the Dutch Wadden Sea. Neth. J. Sea Res. 1, 149–190.

Postma, H., Kalle, K., 1954. Die Entstehung von Trübungszonen im Unterlauf der Flüsse, speziell im Hinblick auf die Verhältnisse in der Unterelbe. Dtsch. Hydrogr. Z. 8, 137-144.

Puls, W., Heinrich, H., Mayer, B., 1997. Suspended Particulate Matter Budget for the German Bight. Mar. Poll. Bull. 34, 398-409.

Rippeth, T.P., Fisher, N.R., Simpson, J.H. The Cycle of Turbulent Dissipation in the Presence of Tidal Straining. J. Phys. Oceanogr. 31, 2458-2471

Ross, J., Mittelstaedt, E., Klein, H., Berger, R., Ricklefs, K., 1998. Der Wasseraustausch im Tidebecken Hörnum-Tief. Berichte des Bundesamtes für Seeschifffahrt und Hydrographie, Vol. 16. Hamburg and Rostock, Germany, 100pp.

Simpson, J.H., J. Brown, J. Matthews, and G. Allen, 1990. Tidal straining, density currents, and stirring in the control of estuarine stratification. Estuaries, 26, 1579–1590.

Stanev, E.V., Flemming, B.W., Bartholomä, A., Staneva, J.V., Wolff, J.-O., 2007. Vertical circulation in shallow tidal inlets and back-barrier basins. Cont. Shelf Res. 27, 798-831.

Staneva, J.E. Stanev, J.O. Wolff, T.H. Badewien, R. Reuter, B. Flemming, A. Bartolomä, K. Bolding, 2009. Hydrodynamics and sediment dynamics in the German Bight. A focus on observations and numerical modelling in the East Frisian Wadden Sea. Cont. Shelf Res. 29, 302-319.

Townend, I., Whitehead, P., 2003. A preliminary sediment budget for the Humber Estuary. Sci. Total Environ. 314-316, 755-767.

Van Straaten, L., Kuenen, P., 1958. Tidal action as a cause of clay accumulation. J. Sediment. Res., 28, 406–413.

Verspecht, F, H. Burchard, T.P. Rippeth, M.J. Howarth, A.J. Souza, and J.H. Simpson, 2009. Processes impacting on stratification in a region of freshwater influence: Application to Liverpool Bay, J. Geophys. Res.114, C11022, doi:10.1029/2009JC005475, 2009.

Zimmerman, J.T.F., 1976. Mixing and flushing of tidal embayments in the Western Dutch Wadden Sea. Neth. J. Sea Res. 10, 149-191.