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Observational evidence for estuarine circulation in the German Wadden Sea

Götz Flöser[a,*], Hans Burchard[b], Rolf Riethmüller[a]

[a] Institute for Coastal Research, Helmholtz Centre Geesthacht, Max-Planck-Straße 1, D-21502 Geesthacht, Germany
[b] Leibniz Institute for Baltic Sea Research Warnemünde, Seestraße 15, D-18119 Rostock, Germany

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ABSTRACT

Observational evidence is presented, which 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 analysed. 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.

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

Lumborg and Windelin (2003), Lumborg and Pejrup (2005) have set up a numerical suspended sediment transport model for the Sylt–Rømø Bight (Fig. 1) that comprises hydrodynamic forcing from 2D 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 and Windelin (2003) and Lumborg and Pejrup (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 cannot 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

* Corresponding author. Tel.: +49 4152 87 2345; fax: +49 4152 87 1525.
E-mail address: floeser@hzg.de (G. Flöser).

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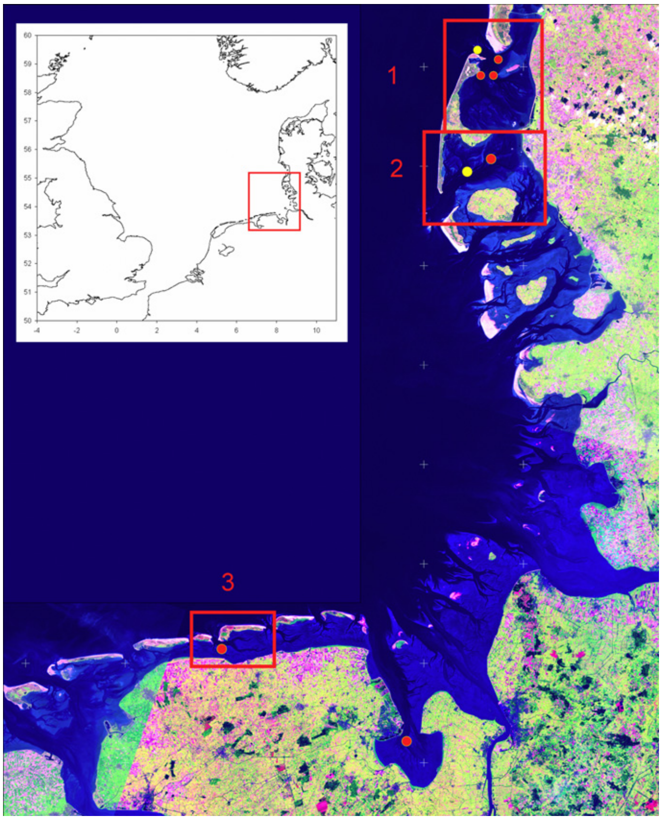

Fig. 1. Satellite scene of the investigated areas in North and East Frisia (South-Eastern part of the North Sea, see inset). From North to South: (1) Sylt–Rømø-Bight, (2) Hörnum Deep and (3) Accumer Ee. The location of moored ADCPs (yellow circles) and of permanent measuring stations (red circles) is also marked. The instruments in the Sylt–Rømø Bight were deployed in 1996/97, those in the Hörnum Deep from 2002 onwards from March to November. The pole in the Langeoog area (Accumer Ee) was running from 2000 to 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.

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 (Fig. 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 0.6×10^9 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 0.4×10^9 m^3, the mean tidal prism amounts to about 0.5×10^9 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 0.08×10^9 m^3 and with a tidal prism of 0.19×10^9 m^3 it is