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EDITORIAL

The back-barrier tidal flats in the southern North Sea—a multidisciplinary approach to reveal the main driving forces shaping the system

Jürgen Rullkötter

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1 Introduction

Tidal flats are an important feature of many coastlines affected by tides in various climate zones of the world. They belong to the most productive natural ecosystems on earth and play an important role in global biogeochemical cycles. Tidal areas not only provide a habitat for many species of birds but are also the nursery for a wide variety of marine organisms. In addition, tidal flats may provide significant protection against marine erosion.

Throughout history, coastal regions have been major centres of human activity. Today, more than 50% of the world's population live in coastal areas, and it has been estimated that this number will increase to 75% by the year 2025. The demand for exploitation of this space will, therefore, increase. This applies to natural resources like oil and gas as well as marine organisms, marine biotechnology and the production of renewable energy in coastal wind and wave power installations. Exploitation of resources always carries by the risk of detrimental effects on the vulnerable coastal ecosystem. Knowledge of the ecological processes and the health status of the flats, which can be derived from this knowledge, is, therefore, of great importance to the costal population.

Responsible Editor: Jörg-Olaf Wolff

J. Rullkötter (✉)
Institute of Chemistry and Biology of the Marine Environment (ICBM), Carl von Ossietzky University of Oldenburg,
P.O. Box 2503, 26111 Oldenburg, Germany
e-mail: j.rullkoetter@icbm.de

2 The study area

The flat relief of the southern North Sea basin and the pronounced tides have created extensive tidal flats along its coast. The tidal range varies between about 1 and 4 m in the south-eastern part of the North Sea. The tidal flat system encompasses supralitoral salt marshes, dunes and beaches that extend above the mean high-tide level, intertidal flats that are exposed only at low tide and subtidal creeks and depressions that are permanently under water and run like rivers through the tidal landscape.

One of the largest continuous tidal flat zones of the world extends along the North Sea coast from Blåvands Huk in Jutland, Denmark, in the North down via Schleswig-Holstein and Lower Saxony in Germany to Den Helder in the Netherlands in the Southwest (Fig. 1). Particularly characteristic are the barrier islands, which were created a few thousand years ago by sand deposits off the coasts of the northern Netherlands, Lower Saxony and southwestern Denmark, whereas the islands off the coast of Schleswig-Holstein are mainly remnants of a former land mass that has been scoured by mediaeval storm surges (Streif 1990). During the most recent ice age about 18,000 years ago, the coastline was situated far out in the North Sea and only reached the modern shores after the continental ice masses melted some 9,000 years ago, forming today's coastal landscape in the course of the rising sea level (Behre 1993, 2003).

3 The research group on *BioGeoChemistry of Tidal Flats*

Extensive ecosystem research projects were carried out in the German Wadden Sea funded by the Federal Ministry of Science and Technology and the states of Schleswig-

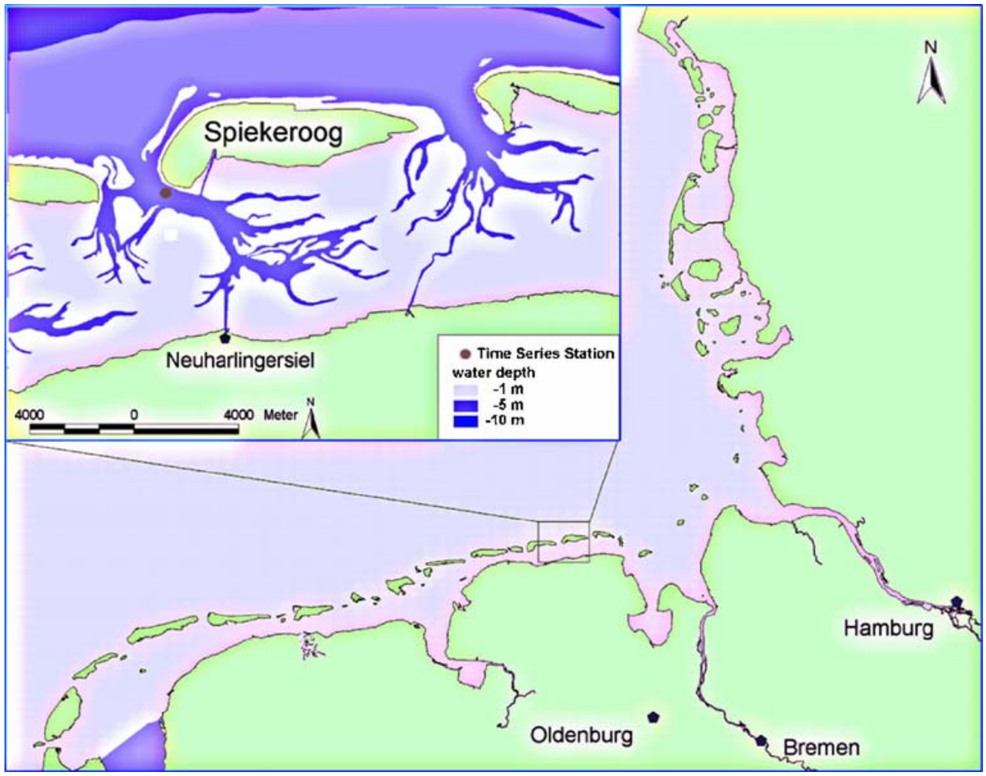

Fig. 1 Map of the extended tidal flat system in the southern North Sea along the coasts of Denmark, Germany and the Netherlands, also termed the Wadden Sea, and the study area in the back-barrier flats of the island of Spiekeroog. The position of the time-series station is marked with a red dot. Water depths given in blue colours refer to the Mean Sea Level (German reference surface, Normalnull NN) which is approximately 2 m above the lowest astronomical tide

Holstein and Lower Saxony in the mid to late 1990s (Dittmann 1999; Umweltbundesamt 2004). Despite the substantial efforts to understand the system as a whole, the participants in these studies retrospectively came to the conclusion that too little attention had been paid to two fundamental aspects, i.e. the tidal circulation system as the main morphological driving force and the microbial world at the base of the food web as the most important player maintaining the delicate balance of primary production and biomass recycling.

As a consequence, a few years later—profiting also from scientific and technical developments in physical sensor technology, analytical chemistry of trace components, molecular biological methods and mathematical modelling—a new interdisciplinary research project was designed that aimed at closing the gap of knowledge on the overall functioning of the physical, chemical and biological processes in tidal flats. Thanks to generous funding by the Deutsche Forschungsgemeinschaft (DFG, Bonn) and the State of Lower Saxony, the DFG Research Group on *BioGeoChemistry of Tidal Flats* commenced its work in spring of 2001 and—with two extensions after thorough reviewing by external experts—continued for eight years into 2009. This special issue of *Ocean Dynamics* forms an essential part of the final report of the project covering most of the important aspects of the overall work and its results, although a large number of manuscripts, many of them referred to in the articles of this special issue, have already been published earlier in a variety of international scientific journals. Indeed, data processing and evaluation will still carry on for years to come. Many of the final data sets have already been forwarded to the PANGAEA open access information system (http://www.pangaea.de), and many more will follow.

The project was co-ordinated by the Institute of Chemistry and Biology of the Marine Environment (ICBM) at the Carl von Ossietzky University of Oldenburg (Germany), cooperation partners in the northwest region of Germany including the Max Planck Institute for Marine Microbiology (Bremen), the Senckenberg Institute (Wilhelmshaven), the Terramare Research Centre (Wilhelmshaven; merged with ICBM in 2008) and the Institute of Physics of the University of Oldenburg. Some of the scientists involved continued their cooperation with contributions to the research group even after they adopted leading positions at other institutions, e.g., at the Institute of Baltic Sea Research Warnemünde (IOW), the GKSS Research Centre (Geesthacht) and the University of Cardiff (UK). Important milestones of the interdisciplinary effort were several coordinated field campaigns involving various boats and ships and even an airplane. In this way, both experimental and analytical research groups were brought together in the Wadden Sea at the same time, for several days or longer, to collect data under the same environmental conditions. As these datasets were particularly valuable for validation purposes in ecosystem modelling, it was the Mathematical Modelling Group of ICBM who organised and coordinated the field campaigns.

The research objectives in the initial grant proposal were phrased as follows: *the investigations of the Research Group aim at a fundamental understanding of important processes in a tidal flat system. For this purpose, biogeochemical transformations on water-column-suspended particles, at the sediment–water interface and in the sediments will be studied. Considering the hydrodynamic conditions, the influence of the different processes on the material budgets will be determined. A mathematical ecosystem model will be developed for the biogeochemical processes in the tidal flat sediments and at the sediment–water interface. On a higher level, a material budget will be established for a selected tidal flat area on the East Frisian North Sea coast (back-barrier tidal flat of Spiekeroog island). The results of the experimental study of sediment transport will be described mathematically with a hydrodynamical model. In addition, a tight coupling of methods for analysing non-linear dynamic systems with ecological problems will be used to reveal how spatial, temporal and/or spatio-temporal structures are formed due to non-linear interaction of reaction, diffusion and advection and if exceeding a critical threshold leads to the spontaneous formation of new structures or dynamics. With this fundamental methodological contribution to the field of integrative modelling, the research group would like to take a significant step forward to the development of a comprehensive mathematical model of tidal flat systems which beyond the initially selected study area should be applicable also to other tidal flat areas and similarly complex systems. The work of the research group is based on the results of past ecosystem research projects in the same coastal area, but in the analysis of the material budget and particularly in the integrative modelling, it will break new scientific ground due to the innovative methodological concepts applied.*

4 The time-series station

The dynamic processes that formed the tidal flats and continue to change them are exceedingly complex. A key unresolved question at the outset of the project was that of the sediment budget. Since the loss of natural mud flats and salt marshes to land reclamation along the mainland shore over the past 1,000 years, it was assumed that the modern tidal basins were still being deprived of fine-grained material because elevated energy levels prevented most of the imported mud to settle out permanently. This conceptual model, however, could not be readily confirmed by sporadic ship-borne measurement campaigns, because—as long time-series datasets and mathematical models later demonstrated—the main loss of fine-grained material from the tidal flats to the sea evidently takes place during stormy weather. Attempts notwithstanding, the operation of a small coastal research vessel in a tidal inlet at wind force eight and beyond was more than could be safely handled.

Similarly, the effects of severe winters, when ice floes freeze to the surface of the sediment at low tide and possibly carry this layer out into the open North Sea during flood tide, were also not yet fully understood. To overcome these limitations, the research group planned and installed a permanent, storm- and ice-proof time-series measuring station (Fig. 2) in the tidal inlet (Otzumer Balje) between the islands of Spiekeroog and Langeoog (Fig. 1) in August 2002. With this station, continuous measurements of the concentration and transport of suspended material in the water column even under harsh weather conditions became possible by means of a multi-spectral transmissometer (MST) and an upward-looking acoustic Doppler current profiler (ADCP). The MST was mounted to the station close to the sea surface, the ADCP about 1 m above the seabed on an 8-m long outrigger arm from the station in about 15 m of water depth. Long-term changes in the sediment budget will most likely affect the ecosystem because conditions for colonisation on the seabed will change as a function of the grain-size distribution of the surface sediment. To protect and manage the Wadden Sea ecosystem, as stipulated in the National Park regulations of the State of Lower Saxony, it is important to be able to differentiate between the delayed effects of dike construction and sea-level rise on the one hand and local human impact (agriculture, fishery, industry, tourism) on the other.

As a unique feature, the time-series station is equipped with several removable flow-through tubes, which not only allow the installation of sensors at different water levels but also to continue measurements when ice is floating on the water during severe winters. The tubes and the sensors inside the tubes require regular maintenance at time intervals not exceeding two weeks due to intense bio-fouling in the highly productive waters of the Wadden Sea (Fig. 3). In May 2003, the unlikely event occurred that a fishing vessel hit the 1.60 m diameter pole of the time-series station in the 900 m wide tidal inlet. Fortunately, only the external ladder of the station was seriously damaged (Fig. 4). Nevertheless, access to the top and inside parts of the station was impossible until the ladder had been repaired about 6 weeks later. Damage to the wooden hull of the fishing vessel was more serious, but fortunately, the fisherman—working at the stern at the time of the accident—did not get injured.

During the time of inaccessibility, bio-fouling in the flow-through tubes proceeded to the extent that the shut-off valves inside the pole could not be operated anymore. Thus, divers had to mount flanges onto the external openings of the tubes so that these could be removed for cleaning from the inside without flooding the pole. Even for professional divers, safe underwater operations were

Fig. 2 Time-series station in the tidal inlet (Otzumer Balje) between the islands of Spiekeroog in the east and Langeoog in the west (53° 45.02′ N, 7°40.27′ E)

limited to half-an-hour around each slack-water period due to the strong currents in the tidal inlet. Furthermore, because visibility is almost zero in the turbid water, all work had to be performed with almost no visual aids.

5 Pore water and sediment sampling

In the course of the investigations, the sand flats of the back-barrier basin were found to be highly active bio-reactors in which organic matter of decayed organisms is being remineralised by aerobic and anaerobic bacteria and archaea after the water pressure of the flooding tide has pumped the organic matter into the pore system of the sand body. During the ebbing tide, the mineralization products—i.e. nutrients, hydrogen sulphide and redox elements in their reduced form—leave the pore system and are transported into the open North Sea. The Janssand, a sand flat south of the main tidal channel opposite the south-western tip of Spiekeroog Island (Fig. 1), was selected as one of the main study sites.

In order to monitor and elucidate the biogeochemical transformation processes in the Janssand pore-water system, a new multilevel in situ-pore water sampler was

Fig. 3 Bio-fouling in the flow-through tubes of the time-series station and on a sensor recovered from one of the tubes

Fig. 4 Damaged external ladder of the time-series station after a commercial fisherman's boat had run into it in May 2003

developed that allows collection of pore water down to 5-m sediment depth (Fig. 5, top). After insertion into the sediment, the sampler stays on site, allowing repetitive sampling at identical locations and depth intervals. In the meantime the sampler has been successfully tested for more than 2 years and has produced depth profiles of several redox-sensitive elements at high resolution. Because of variations in advection and microbial activity in the course of a year, seasonal signals became apparent for some element species even at sediment depths of 3 m. Conventionally, sampling occurs at low tide when the Janssand falls dry for a few hours, but in order to study the processes "under hydrostatic pressure" at high tide, sampling was also performed from the top of a platform that was erected above the pore-water sampler locations (Fig. 5, bottom)—but, of course, only in good weather.

To investigate sedimentological, geochemical and microbiological processes and their imprint on the geological record, sediment samples were collected from mud, mixed mud/sand and sand flats. Initially, plastic tubes of 30 or 50 cm length were driven into the seabed and comfortably recovered by digging. Extension of the tube length to 1 m and applying the same technique not only became a physically exhausting exercise during retrieval (Fig. 6) but was also time consuming and, thus, afforded precise planning because "time and tide wait for no man". Vibro-coring with aluminium tubes and using a tripod for retrieval (Fig. 7) extended the investigative depth range down to about 6 m. Ultimately, a commercial flat-bottom drill ship (Fig. 8) was chartered to make the entire Holocene sediment section accessible together with the top of the Pleistocene. One of the holes penetrated a palaeo-tidal channel filled with marine sediments down to about 15 m depth, followed by a much older sandy section of yet undetermined age—possibly comprising reworked Pleistocene material—and ended in Pleistocene clay ("Lauenburg Clay") about 350,000 years old at a depth of around 20 m depth. At the second site, which was located on a structural high, the marine Holocene sequence was underlain by the typical basal peat (Streif 1990; Hoselmann and Streif 2004) at about 5 m depth. The deeper Pleistocene deposits comprised a section from the Eemian warm period (ca. 125,000 years ago) with lacustrine and marine mud and a peat layer which in turn overlies glacial sands of the penultimate (Saalian) ice age. The long cores from both locations are still being investigated by the research group.

Fig. 5 Multiple outlets of the newly developed pore water sampler (*top*) and sampling at high tide (*bottom*; in good weather conditions only)

Fig. 6 Short sediment cores were obtained by driving plastic tubes into the sediment and digging them out afterwards

6 The microbial world

An intensified interest in the role of microorganisms in the water column and in sediment began to crystallise about a decade ago when the modern array of microbiological and molecular biological methods for this type of investigation began to become available. Microorganisms, in addition to filter feeders such as mussels, are the "sewage treatment" system of the tidal flats. The former decompose the remains of dead plankton and other creatures and return the products to the food cycle. This is mostly done by the bacteria in the water column where they settle on aggregates of decayed biomass and mineral matter and in the upper sediment layers which are often only a few millimetres thick and still contain oxygen. The aerobic bacteria ensure that the anaerobic zone beneath does not extend to the surface, causing the tidal flat to deoxygenate and black spots to appear on the surface. The processes at the sediment–water interface were investigated with so-called landers that automatically monitor the microbial activity in the surface sediments and its influence on chemical gradients and fluxes (Fig. 9). On a small scale, the black spots do not pose a problem, but when a chain of natural phenomena caused large black areas to form in the wake of the hard winter of 1995/96, large numbers of mussels and worms died due to a lack of oxygen. However, the tidal flats were able to recover from this situation by the next summer thanks to their strong self-healing capacity (Delafontaine and Flemming 1997; Höpner and Oelschläger 1997).

The role of the bacteria that live in the anaerobic sediment zone below the surface was a complete mystery at the start of the project. Many were unknown organisms, and because they were impossible or at least difficult to grow in culture, their physiological characteristics could not be studied. In the course of the studies, the cultivation success rate increased by an order of magnitude from about 0.5% of microorganisms in the tidal flat sediments to about

Fig. 7 Vibro-coring tidal flat sediments down to 6 m depth with an aluminium tube and recovery using a tripod

5% or even 25% in the uppermost oxic sediment layer (Köpke et al. 2005). Although several other bacteria and archaea present could at least be addressed at a more general level by their molecular traces found in the sediments, 90% or more of these escaped detailed laboratory studies. As a consequence, it is still not evident whether the microorganisms, particularly in the deeper anoxic strata, extract their nourishment from hard-to-decompose organic matter left over by the surface bacteria, or whether the pore water in the sediments provides nutrients that can be utilised more easily. They may, perhaps, even be relatives of bacteria that live in similarly inhospitable conditions under more than a thousand metres of sediment in the oceans (Fry et al. 2008).

7 The tidal flats in mathematical models

Over the last 8 years, numerical models have been used to investigate the area-specific hydrodynamics and the suspended particulate matter (SPM) dynamics in the East Frisian Wadden Sea under the umbrella of the research group. Modelling in combination with high-resolution measurements at the Wadden Sea time-series station and new theoretical approaches have revealed various new and exciting insights into this complex system. The available suite of numerical models integrates worldwide experience with innovative concepts such as state-of-the-art parameterisations of physical processes and novel concepts of SPM transport. These models have been widely

Fig. 8 The deep subsurface of the tidal flats (≈20 m, Holocene plus top of Pleistocene) was accessible with the help of a commercial drill ship

Fig. 9 A flat-bottom ship (*bottom*) was chartered for microbiological work on the tidal flats over 1–2 weeks using landers (*top*) to automatically measure the microbial activity in the surface sediments at high and low tide

used for various research applications in the Wadden Sea and the German Bight at different horizontal resolutions. Sub-domains with higher resolution are nested within the areas of lower-resolution models, thus, allowing a better description of small-scale processes in the sub-domain, whilst keeping the amount of information needed from the larger-scale models at a manageable level.

The Wadden Sea area can be characterised as a well mixed estuary, although the extent of stratification associated with freshwater flux from the coast can locally substantially affect vertical overturning. To address this complex system, a model accounting for the most important processes, e.g. the vertical overturning, wind- and wave-induced turbulence, drying and flooding, has been developed.

The theoretical concepts reveal the effect of topography—caused by the bottom slope—on the drying and flooding of the tidal basins, while the exchange of water with the open sea varies with time. For most intertidal basins it takes about twice as long from low-water slacks to maximum flood current than from high-water slacks to maximum ebb current. There clearly is ebb dominance in the deep tidal channels of the Wadden Sea, whereas in their shallow extensions and on the tidal flats, transport during flood is larger than during ebb tide. In addition, distinct differences were found between the temporal variability of the transport

Fig. 10 Members of the DFG review group experience the typical working conditions in November 2006 when pore water sampling took place in heavy wind, rain and hail and at temperatures just above freezing

near the surface and that in deeper layers of the tidal inlets. The near-surface transport is dominated by the tidally induced drift, whereas transport in the deeper layer is asymmetrical due to the topographic properties of the intertidal basins.

Sediment dynamics in tide-dominated environments is strongly controlled by the joint actions of transport and turbulence. This process is complex because the concentration of SPM is not only controlled by changes in the individual levels of turbulence and advection but also by the correlation between the two. Such situations require up-to-date numerical models to reveal the important processes in space and time.

Modelling of the tidal flat ecosystem required several improvements on existing ecosystem models. Neither the simulation on a grid nor the traditional box model approach gave satisfying results. Consequently, a semi-Lagrangian model is suggested as the optimal solution because it combines the advantages of a Lagrangian tracer approach with those of an Eulerian box approach. The ecological tidal model EcoTiM simulates the cycling of carbon, nitrogen, phosphate and silicate and describes the tidal, diurnal and annual dynamics within the back-barrier system.

An important challenge in theoretical ecology is to find good representations of complex food webs. In a generalised modelling approach, it was shown that it may be possible to formulate a coarse-graining algorithm that conserves the local dynamics of the model exactly. Based on this observation, a mathematical algorithm was developed which identifies and groups several populations of complex food webs into a single variable without changing the local dynamics.

In the course of their studies, the modellers in the research group developed a set of models describing the physical processes, water column ecology and transformations in the sediment to investigate specific processes at different temporal and spatial resolutions.

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