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Residence times in shallow waters help explain regional differences in Wadden Sea eutrophication

Fabian Schwichtenberg[a], Ulrich Callies[a], Justus E.E. van Beusekom[a]

[a]Helmholtz-Zentrum Geesthacht, Institute of Coastal Research, Max-Planck-Str. 1, 21502 Geesthacht, Germany

Corresponding author: Fabian Schwichtenberg, e-mail: fabian.schwichtenberg@hzg.de

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Abstract

Regional variations in eutrophication levels of tidal basins in the Wadden Sea can be caused by external factors like organic matter import and internal factors like morphology and hydrodynamics of the receiving tidal basin. For instance, benthic nutrients from remineralized organic matter may be more concentrated in shallow basins or diluted in basins with high exchange rates. In addition, the location of a monitoring station may determine which basin-specific water masses are actually observed. In the present paper a hydrodynamic intertidal imprint (IMP) is estimated for ten stations in various tidal basins of the Wadden Sea. The fraction of time water masses spent in intertidal areas prior to observation is calculated by linking the Lagrangian transport module PELETS to already existing hourly reconstructions of currents between 1959 and 2003. Irrespective of water depth, additional calculations of mean residence times (MRT) in the Wadden Sea indicate whether in case of low IMP values water masses originate from coastal areas or tidal channels. Results show distinct regional differences, with highest values in the eastern part of the Dutch sector of the southern Wadden Sea (IMP = 77 %, MRT = 99 %) and lowest values in the German/Danish sector of the northern Wadden Sea (IMP = 1.1 %, MRT = 21 %). The IMP correlates positively with observed nutrient levels ($R^2 = 0.83$). Evidently, this residence time-based intertidal signal is pivotal in explaining regional variations in eutrophication levels revealed by long-term comparative data from different monitoring stations.

1 Introduction

The Wadden Sea is a narrow and shallow intertidal coastal sea stretching along the Dutch, German and Danish North Sea sectors. It is subject to strong human influences involving fisheries, contaminants and nutrients (de Jonge et al. 1993; Lotze et al. 2005; van Beusekom et al. 2010). Of these, eutrophication plays a prominent role. Between the 1950s and the 1980s, nutrient discharges into the North Sea increased dramatically (van Bennekom and Wetsteijn 1990), leading notably to enhanced nutrient and production levels in the Wadden Sea (de Jonge and Postma 1974; Cadée and Hegeman 2002), associated with an increase in opportunistic macroalgae and loss of seagrass (Kastler and Michaelis 1997; Dolch et al. 2013). Since the 1990s a reduction of riverine nutrient loads into the North Sea is apparent (Radach and Pätsch 2007), accompanied by decreases in chlorophyll levels and primary production (e.g. Cadée and Hegeman 2002; van Beusekom et al. 2009a, b).

External and internal processes drive Wadden Sea biogeochemistry. Among the external factors, freshwater discharge impacts nutrient levels either directly if discharged into the Wadden Sea like lake IJssel (e.g. Leote et al. 2016) or indirectly if carried towards the Wadden Sea with the residual currents (e.g. Los et al., 2014). A further major external source impacting the Wadden Sea biogeochemistry is the import of organic matter fuelling the high productivity of this region (Postma 1984; van Beusekom and de Jonge 2002). Import of organic matter is driven by estuarine circulation and enhanced by flocculation of inorganic particles, organic matter and phytoplankton debris sinking in a coastward-directed bottom current (van Beusekom et al. 2012, Hofmeister et al., this volume). Within the Wadden Sea dissolved nutrients can be used by local benthic and pelagic primary producers each contributing about equal amounts (e.g. Asmus et al., 1998). Remineralisation of organic matter -both imported and locally produced- occurs in approximately equal shares in the water column and in the benthos (van Beusekom et al., 1999) and may replenish the nutrient pool thereby boosting the local primary production. If organic matter is transferred to the sediment (or locally produced by benthic primary production) it may be subject to microbial degradation. Nutrient release from pore water-surface water exchange may be fast due to bioturbation, bioirrigation and advective exchange in permeable sediments or may involve longer time scales when exchange of deep pore water is involved (e.g. Moore et al., 2011; Beck and Brumsack, 2012).

Although benthic organic matter turnover is highest in summer (e.g. Asmus et al., 1998), nutrient concentrations are low (van Beusekom et al., 2009b; Beck and Brumsack, 2012) suggesting that local primary producers take up most of the released nutrients. This situation changes in autumn when light limitation induces a strong increase in nutrient concentrations. Van Beusekom and de Jonge (2002) therefore suggested, that autumn ammonium (NH_4) and nitrite (NO_2) values indicate the level of organic matter turnover and correlated NH_4 levels with riverine total nitrogen loads.

In addition to autumn levels of NH_4 and NO_2, summer levels of dissolved organic phosphorus (DOP) and summer chlorophyll levels have been suggested to indicate the degree of eutrophication in the Wadden Sea (van Beusekom et al. 2001, 2009a; van Beusekom and de Jonge 2002, 2012). Based on these proxies, regional differences span lower eutrophication levels in the northern Wadden Sea sector of Denmark and Germany, and higher levels in the southern Wadden Sea sector of Germany and The Netherlands.

Several factors may contribute to the observed regional differences: the amount of imported organic matter, the surface area and depth of the receiving tidal basins and the exchange rates between the North Sea and the receiving tidal basin. Van Beusekom et al. (2012) evaluated the roles of organic matter import and tidal basin size and observed that eutrophication proxies are lower in tidal basins with a large distance between tidal inlet and the mainland (dilution of the imported organic matter over large surface). In this paper the combined effect of tidal basin depth and exchange rates between the Wadden Sea and the adjacent North Sea on the observed autumn NH_4 and NO_2 values at monitoring stations is evaluated. High values are expected if the water body at a certain monitoring location has experienced shallow depths for a long time. By contrast, lower values are to be expected in those areas earmarked by stronger exchange rates with the deeper North Sea, i.e. shorter residence time of water masses in the Wadden Sea.

In the present paper, regional differences in exchange between the North Sea and the Wadden Sea are analysed focusing on locations where NH_4 and NO_2 measurements are available. Using model-based reconstructions of currents on an hourly basis between 1959 and 2003, large ensembles of backward trajectories initialized in the Wadden Sea are calculated with the PELETS model system (Program for the Evaluation of Lagrangian Ensemble Transport Simulations, Callies et al. 2011). Based on these trajectories, a hydrodynamic intertidal imprint is quantified as the residence time of water masses less than 2 m deep.

Intertidal signals assessed for ten stations spanning tidal basins of the Dutch, German and Danish sectors (Fig. 1) could help understand observed regional ecological differences in the Wadden Sea. The overarching questions in this study are (1) to what extent are autumn concentrations of NH_4 plus NO_2 driven by the residence time of water masses in specific intertidal areas? (2) Do these signatures reveal regional patterns consistent with independent evidence of large-scale eutrophication levels in these tidal basins?

This study was part of a German scientific project carried out by an interdisciplinary research consortium addressing various European and German regulations to assess the state of the marine environment in the German Bight (for overviews, see Winter et al. 2014; Winter et al., Introduction article for this special issue).

2 Materials and methods

2.1 Nutrient data

The nutrient data were previously used to assess the eutrophication status of the Wadden Sea (van Beusekom et al. 2009a) as part of the Quality Status Report 2010 (see Wolff et al. 2010). The data are from official networks (Netherlands: Rijkswaterstaat, Germany: NLWKN and LLUR, Denmark: Danish Environmental Protection Agency), except for those collected by the Wadden Sea station of Sylt (see, for instance, van Beusekom et al. 2009b). Monthly means for each station have been calculated at first. The annual autumn proxy is the mean of monthly means of NH_4 and NO_2 in the months September through November. Annual values from 2000–2006 were then averaged (see van Beusekom et al. 2009a). It should be noted that for the Graadyb station (cf. Fig. 1), only NH_4 data were available and NO_2 concentrations were estimated as 15% of the NH_4 signal based on the NH_4/NO_2 ratio near Sylt.

2.2 Lagrangian particle tracking

Simulations comprising 1,000 trajectories tracked backwards in time were initialized within circles of 500 m radius of the locations of the monitoring stations in ten tidal basins (cf. Fig. 1). Starting simulations every 28 h in autumn (September–November) for the years 1959–2003 results in 3,510 simulations per tidal basin. Stations 1, 2, 4, 7 and 10 are located in tidal inlets, whereas stations 3, 5, 6, 8 and 9 are in the interior of the tidal basins. Small panels in Fig. 1 combine two example simulations starting at stations 8 and 9, with their corresponding backward integration after 75 h.

The particle trajectories are based on marine currents from the data base coastDat (www.coastdat.de; Weisse et al. 2009). The two-dimensional finite element model TELEMAC-2D (Hervouet and van Haren 1996) was used and it was stored on an hourly basis. Spatial resolution of the unstructured triangular grid reaches a few hundred meters in the intertidal zone and flooding and drying are taken into account. Weisse and Plüß (2006) give a detailed description of reconstructions over several decades in coastDat.

Particle movements were calculated using the Lagrangian transport module PELETS-2D (Callies et al. 2011). This offline toolbox allows for a specified number of particles to be released at random locations within user-defined source regions. Particle trajectories include effects of random movements due to subscale turbulence effects. The very detailed results can then be aggregated to obtain time series of the fractions of released particles that cross user-defined receptor regions of arbitrary shape. Here, the entire Wadden Sea was divided into 34 tidal basins (Fig. 1) designated as receptor regions in this model setup.

2.3 Intertidal imprint and residence time

The long-term environmental data represent different marine autumn conditions that occurred in the years 1959 - 2003. Therefore, these simulations can be expected to adequately reflect the average intertidal imprint on water masses observed at any specific location. There are two key features for each trajectory on an hourly basis during its integration backwards in time:

1. The intertidal imprint (IMP) characterizing a given monitoring station is the mean fraction of travel time spent in regions with water depths below 2 m. Averaging is performed over all particles initialized from this location at different times. IMP obviously is a function of maximum integration time; 1, 3 and 6 days are considered here.
2. The mean residence time (MRT) refers to either a specific tidal basin (i.e. that of the monitoring station) or the overall intertidal coastal region.

3 Results

Figure 2 relates the IMP values (integration time of 1 day) of all ten stations to the sums of observed mean autumn concentrations of NH_4 and NO_2. A positive correlation implies an effect of hydrodynamic conditions on the observed concentrations. The highest correlation is found at 24 h integration time ($R^2 = 0.83$, $P = 0.0003$) decreasing with longer integration times (e.g. $R^2 = 0.76$ at 3 days and 0.61 at 6 days). Stations above the regression line indicate higher than average autumn release of NH_4 and NO_2 at a given IMP value and tend to be from the southern Wadden Sea, whereas especially stations from the northern Wadden Sea (Sylt, Amrum) are below the line indicating lower than average release of NH_4 and NO_2.

The IMP is not necessarily from within a single tidal basin because of transport across watersheds (Duran-Matute et al. 2014). To circumvent this problem, MRT values are shown in the bottom panel of Fig. 3, differentiating between the basin in which particles were released (blue bars) and all the other basins (red bars). A low MRT (like at the Norderaue station, no. 7) indicates that a water body is likely to have spent much time outside the Wadden Sea. By contrast, a high or intermediate MRT accompanied by a low IMP (e.g. stations Marsdiep (1), Vlie (2) or Graadyb (10), cf. upper panel in Fig. 3) indicates that particles have spent much time in tidal channels within the Wadden Sea. From the top panel of Fig. 3, it can also be concluded that the MRT and IMP values at most stations in the southern Wadden Sea sector are notably more affected by exchanges of water bodies between different tidal basins than this is the case in the northern Wadden Sea sector. These differences are most pronounced for integration times of 3 or even 6 days.

In Fig. 3, the stations Sylt List (8) and Lister Dyb (9) show a similar extreme situation. Both stations are located within the same enclosed tidal basin with only one tidal inlet between the islands of Sylt and Rømø. They have no exchange with other tidal basins and even only minor exchange with the open North Sea.

At low IMPs the short-time contribution of specific basin is low indicating that processes in coastal waters or in the deeper tidal channels mainly determine the observed concentrations.

4 Discussion and conclusions

Eutrophication is one of the major factors shaping the ecological status of the Wadden Sea (van Beusekom et al. 2001) and has been a political issue during the past decades (de Jong 2007). A network of long-term monitoring stations documents spatio-temporal trends in nutrient concentrations and phytoplankton biomass, these being among the key parameters serving to assess the eutrophication status of the Wadden Sea (see Introduction section). These data reveal clear spatial patterns in eutrophication status with lower values in the northern Wadden Sea sector, higher values in the eastern Dutch sector of the southern Wadden Sea, and intermediary values elsewhere (van Beusekom et al., 2009a, van Beusekom et al, 2012, van Beusekom and de Jonge, 2012). Understanding these regional differences is important as a basis for setting internationally comparable environmental goals, including those of EU legislation (e.g. the Marine Strategy Framework Directive, MSFD or the Water Framework Directive).

Van Beusekom et al. (2012) highlighted differences in import from the North Sea and the size of the receiving tidal basin to explain regional differences. They noted, however, that other factors like the mean depth might play a role as well. The present study supports the hypothesis that nutrient concentrations increase with the time a water body spent in shallow regions, suggesting that shallow intertidal areas are major sources of nutrients due to remineralisation of imported organic matter. Already van Straaten and Kuenen (1958) argued that accumulation of particles originating from the North Sea is more likely in shallow than in deeper water. In addition, filter feeders, permeable sediments and benthic diatom biofilms support the retention of particles (van Beusekom et al. 2012) in intertidal and shallow subtidal areas. Subsequent remineralisation of associated organic matter releases nutrients. Moore et al. (2011) described two pathways: a fast release by advective processes in the upper layer of sandy sediments (during inundation of tidal flats) or a slower release of deeper pore waters at low tide. Which of these processes dominates is hard to distinguish based on monitoring data. Silicic acid (Si) may be an indicator of deep porewater exchange (Moore et al., 2011). This has not been evaluated in detail in the present study, but high-resolution data from the Spiekeroog tidal basin (Grundwald et al. 2010) indicate an excess Si export of 128 10^6 mol a^{-1}, and nitrite plus nitrate of 29 10^6 mol a^{-1} to the North Sea. Unfortunately, NH_4 was not measured and the DIN export may be higher. Nevertheless, excess Si export is feasible and Si/N ratios are possibly higher than the ratio of about 1:1 in diatoms (Brzezinski, 1985). Export of excess Si from deep pore water in the northern Wadden Sea is less probable: Autumn dissolved inorganic nitrogen (DIN) and Si increase in the List tidal basin are approximately 1:1 (van Beusekom et al., 2009b), i.e. at a ratio expected in biogenic particles. The correlation between autumn NH_4 and riverine nitrogen loads in the Western Dutch Wadden Sea (van Beusekom and de Jonge, 2002) suggest a rapid response of the released pore water to changes in organic matter input.

Although the intertidal signal can be high, most monitoring stations are in the vicinity of the tidal inlets and show low IMP values indicating exposure mainly to North Sea and deep Wadden Sea channel conditions and suggesting that the observations cannot indicate the eutrophication status of the inner reaches of a tidal basin. However, it should be born in mind, that intensity of biogeochemical process in the inner tidal basins and the coastal areas outside of the Wadden Sea are linked through a loop of organic matter transport to the Wadden Sea, remineralisation within the Wadden Sea, export of nutrients towards the coastal zone, primary production in the coastal zone and re-import of organic matter. This loop is also reflected by correlations between autumn NH_4 plus NO_2 levels and summer chlorophyll levels. Hofmeister et al. (this volume) successfully modelled this loop.

Although NH_4 plus NO_2 concentrations and the IMP are well correlated, a relatively high scatter of data remains (Fig. 2). This can be partly explained by regional differences in the amount of organic matter being turned over. Thus, relatively low concentrations in the List tidal basin (stations 8 and 9) of the northern Wadden Sea sector are consistent with earlier suggestions of a low eutrophication status for this area (van Beusekom et al. 2009a, 2012). This contrasts with observations of substantially higher concentrations for the Dutch sector of the southern Wadden Sea. This regional pattern awaits confirmation in future research based on more stations and also older data.

Water bodies may have spent several days in neighbouring tidal basins (cf. bottom panel in Fig. 3). Therefore, a high IMP value does not necessarily mean a strong influence of local sediments in the basin where observations were made. As the long-term history may have little relevance for short-lived NH_4 plus NO_2 concentrations, Fig. 2 referred to a 24 h integration time. Primary production, however, accumulates the benefits from favourable light conditions and nutrient supply over longer times. This allows for increasing loads of organic material transported across a chain of tidal basins. An example is the comparison of stations Vlie (2) and Zoutkamperlaag Zeegat (4). According to Fig. 2, similar IMP values are calculated at both stations based on a 24 h integration time. The mean concentration of NH_4 plus NO_2, however, is about 4 μmol L^{-1} higher at the Zoutkamperlaag Zeegat station. Taking into account the west to east direction of the mean circulation in this region (see, for example, Turrell 1992), exchanges with intertidal areas more to the east of the Dutch sector of the

Wadden Sea would lead to enhanced primary production and thus to a higher import of organic material and finally enhanced eutrophication in the vicinity of the more easterly Zoutkamperlaag Zeegat station. A similar effect may also exist in the German sector of the southern Wadden Sea, but cannot be proved based on only one station (Norderney, no. 6).

In contrast to the southern Wadden Sea, there is only limited exchange with other tidal basins at stations in the northern Wadden Sea. Especially the two stations in the List tidal basin (Sylt List, no. 8, and Lister Dyb, no. 9) have almost no contact with other basins (due to two dams connecting the islands of Rømø and Sylt with the mainland) and only minor exchange with the North Sea (within the maximum integration time taken into account). Both factors may contribute to a lower eutrophication status observed in this basin.

In conclusion, a model-based estimation of the average residence time of water masses in shallow intertidal areas shows that residence time can partly explain differences observed between long-term monitoring stations. Still, regional differences remain that are in line with a lower eutrophication of the central north Frisian Wadden Sea and a higher eutrophication level in the southern Wadden Sea. The intertidal imprint and mean residence time also indicate the exchange of matter (and biota) between tidal basins. This implies that monitoring stations may reflect the status of more than one tidal basin. Finally, these proxies may be used for an efficient positioning of additional monitoring and research stations in the Wadden Sea.

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Conflict of interest: The authors declare that there is no conflict of interest with third parties.

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Figures

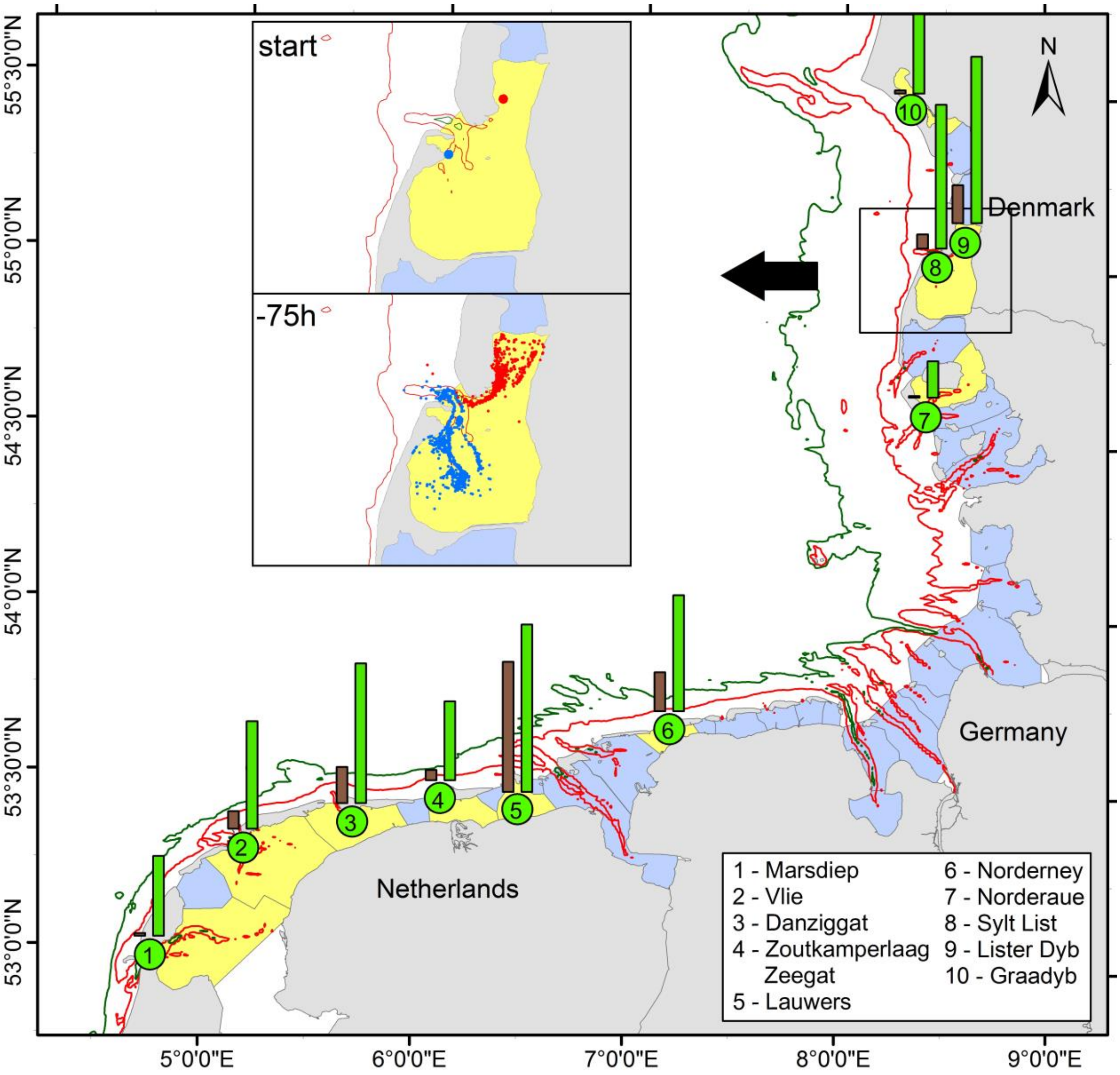

Fig. 1 Map of the Wadden Sea showing tidal basins and depth contours at 10 m (*red*) and 20 m (*green*). *Green circles* Monitoring stations 1–10, *brown bars* IMP at 1 day (see also Fig. 3 top), *green bars* MRT at 1 day (see also Fig. 3 bottom), *yellow areas* corresponding tidal basins. *Small panels* Two example simulations: start time on 9th April 2003 (00:00), and after a backward integration of 75 h

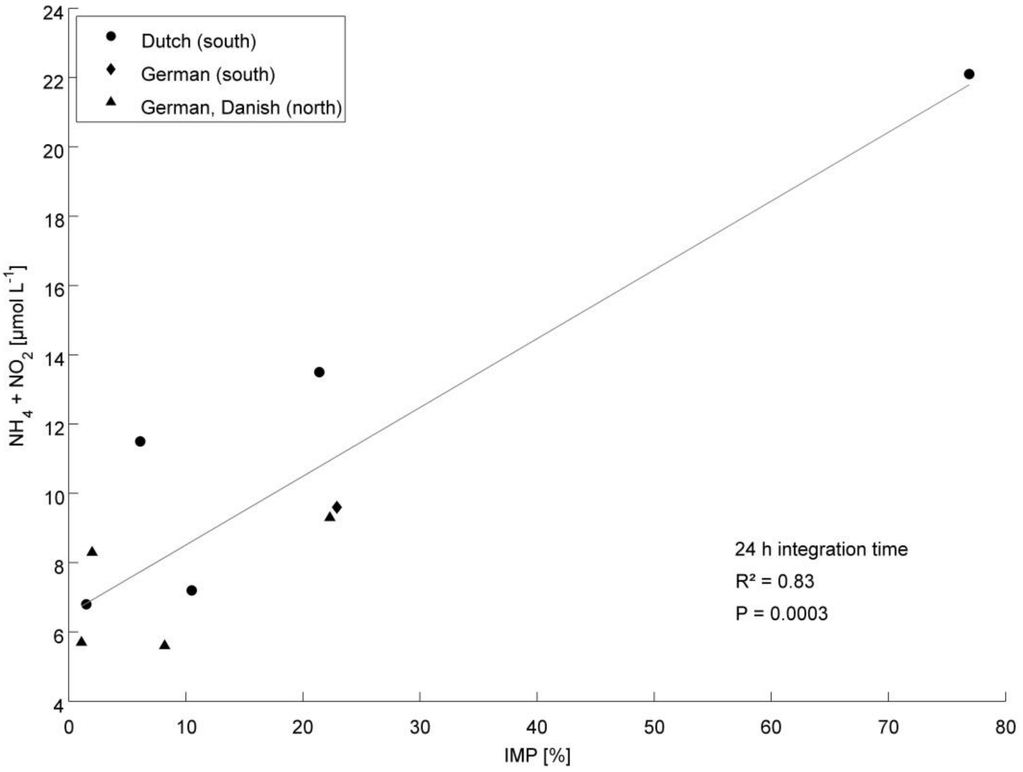

Fig. 2 Scatter plot of the sum of mean ammonium and nitrite concentrations versus IPM at stations 1–10 in autumn (September–November in the years 1959 - 2003), assigned to three sectors: the Dutch and German sectors of the southern Wadden Sea, and the German and Danish sector of the northern Wadden Sea

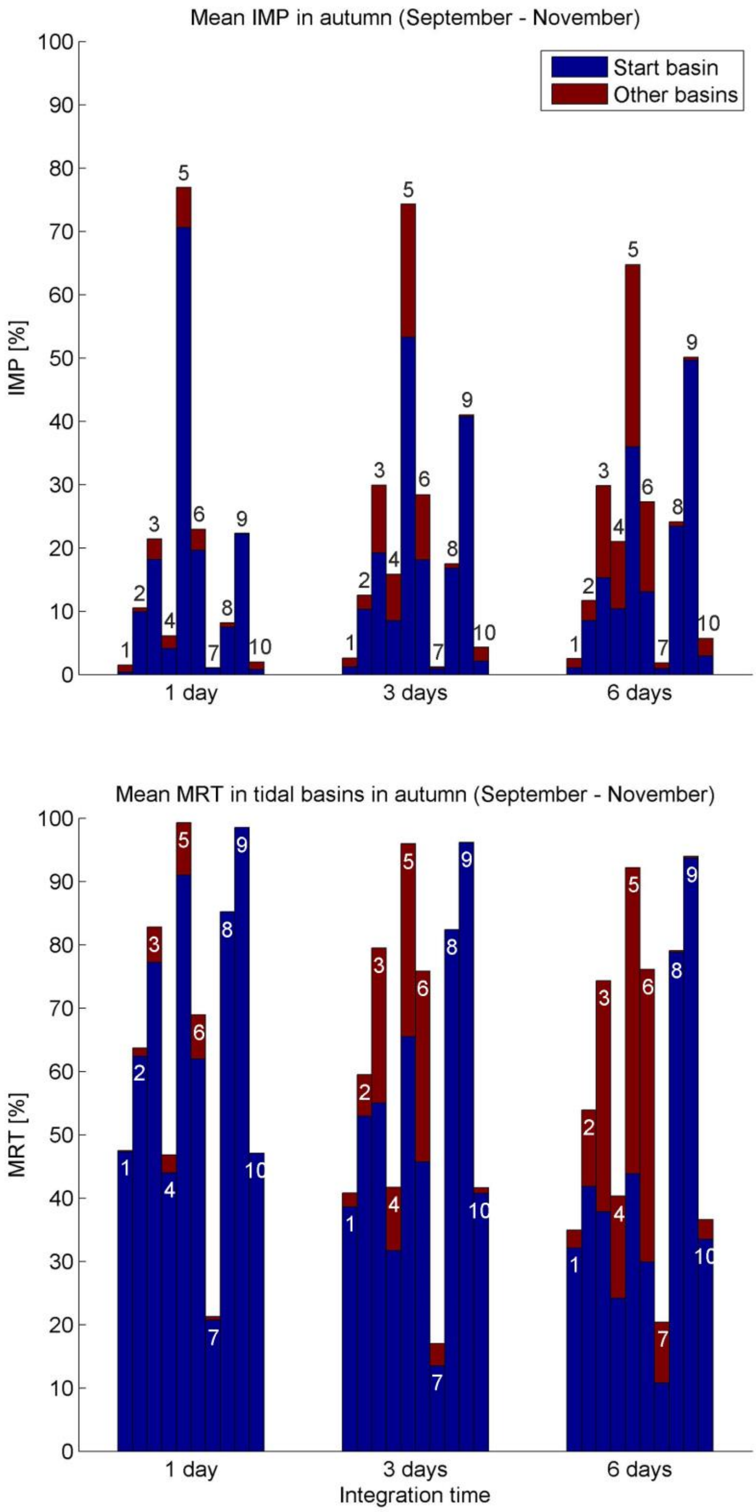

Fig. 3 Autumn IMP (*top*) and autumn MRT (*bottom*) in tidal basins 1–10 for 1, 3 and 6 day backward integration. *Blue* Contribution from basin itself, *red* contribution from any other basin. *Top panel* Labels 1–10 refer to locations marked in Fig. 1 by green circles; *bottom panel* corresponding basins (yellow in Fig. 1)