Mixing and Flushing of the East Frisian Wadden Sea

Emil Stanev[1], Jörg-Olaf Wolff[1], Hans Burchard[2], Karsten Bolding[3]

1: Institute for Chemistry and Biology of the Sea (ICBM), University of Oldenburg, Germany,
2: Institute of Oceanography, University of Hamburg, Germany, 3:CEC-Joint Research Centre, Ispra, Italy,

Abstract: The tidal embayments along the North German Coast undergo dramatic changes of water properties during the tidal cycle. Provided that the outflowing water during the ebb is completely substituted by the "new" open ocean water during the flood, the residence time would be the ratio between the mean inter tidal volume and the tidal prism. In the individual basins of the North Frisian Wadden Sea these two volumes are approximately equal, giving for the flushing times values ~ 1. However, numerous earlier estimates in similar coastal systems give numbers, which are 10-20 times larger. Obviously, the reduced flushing capabilities are associated with the fact that the water entering the inter tidal basins during the flood is essentially the same water, which has left the basins during the ebb. The poster attempts to objectively estimate the flushing times due to advection and diffusion using numerical simulations with a model, which is well calibrated to the local conditions in the East Frisian Wadden Sea.

1 The flushing of inter tidal basins

The flushing of inter tidal basins with water from the adjacent North Sea affects a wide spectrum of processes: physical, chemical, biological, geo-morphological. For some constituents of sea water the tidal basins might act as a trap (sediments), for others as a source (a variety of chemical elements originate from land sources and some are locally produced in the Wadden Sea).

The flushing time T is defined as the time required to replace the existing fresh water in the estuary at a rate of the river discharge (R). This is also known as the residence time $T = V_f/R$, where V_f is the amount of river water accumulated in the estuary. The prism method to calculate the flushing of estuaries (inlets) suggests that $T = T_t(V + P)/P$, where T_t is the tidal period, $V + P$ and P are the water volume at high tide and the tidal prism, correspondingly. In most of the East Frisian inter tidal basins (Figure 1) $V \sim P$ (see also Figure 3), thus the length of the tidal period is the shortest time for flushing the basin.

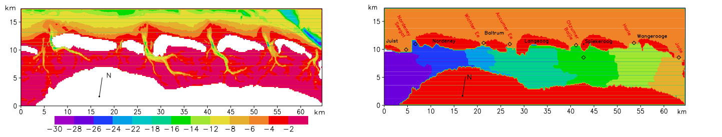

Fig. 1: Topography of the inter tidal basins (left) and individual basins (right). The identification of the basins is based on topography only.

At present, the flushing times of individual inter tidal basins in the East Frisian Wadden Sea are not well known, but there exist a number of estimates for the Dutch Wadden Sea. According to Postma (1954), the flushing time of fresh water discharged near Den Oever is 13 tidal periods. Van Bennekom et al. (1974) found flushing times of $\sim$ 14 and 26 tidal periods for, respectively, the western and eastern parts of the Dutch Wadden Sea (for more details see Zimmerman, 1976).

The German Wadden Sea is much better mixed than the West Frisian Wadden Sea and water mass analysis based on salinity data alone cannot give accurate estimates. Transient tracer estimates (with much stronger signals than for salinity) give times, which are substantially longer than one tidal period (Brumsack and Reuter, personal communication). An alternative approach to estimate the flushing times, which we present here, uses results of detailed numerical simulations.

2 The numerical model

The General Estuarine Transport Model (GETM, Burchard, 1998; Bolding and Burchard, 2000) is used to simulate the circulation in the East Frisian Wadden Sea (Figure 1). The model grid has a horizontal resolution of 200 m and terrain following coordinates in the vertical. The subgrid parameterizations are based on the $k-\epsilon$ turbulent closure scheme. The lateral boundaries of the model change with time representing the continuous processes of flooding and drying.

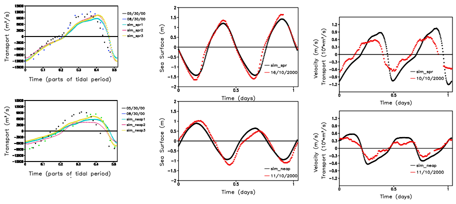

Fig. 2: Validation of the numerical model against observations. Left column: transport in the Accumer Ee during spring (upper plot) and neap (lower plot) tide. Middle column: Sea surface elevation at the northern boundary of the model area (forcing data) and the measured response in location with coordinates (27x12km, see Figure 1) during spring and ebb tide. Right column: Simulated transports in Accumer Ee and observed current velocities (the same location as above).

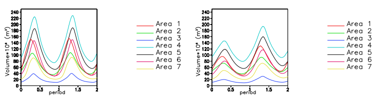

Fig. 3: Evolution of inter tidal volumes of the areas shown in the right panel of Figure 1 during spring (left) and neap (right) tide. This figure demonstrates that the lower bound of $T \sim T_t$ (note that $V \sim P$). The numbers compare quite well with the ones estimated by Ferk (1995).

3 The advective flushing

Horizontal dispersion in the natural system is enhanced by : (1) shear dispersion (Okubo, 1968), and (2) Lagrangian chaos (Aref, 1984). While, in the first mechanism, the prerequisite of dispersion is the diffusion, in the second mechanism particle trajectories might become random functions of time either by spatial randomness of the Eulerian field, or by the deterministic chaos in the Eulerian-Lagrange transformation. This means that the superposition of different Eulerian modes in the velocity field, organized at different length and time scales may give rise to Lagrangian trajectories that are chaotic functions in time.

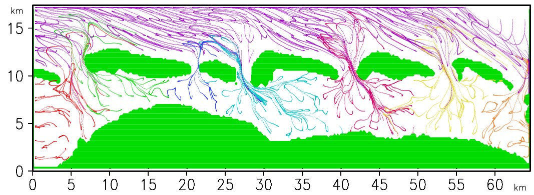

Fig. 4: Lagrangian trajectories

4 Discussion

Figure 5 shows that, after one spring tidal cycle, a large number of particles left the inter tidal areas (the comparison between upper right with lower patterns gives an idea about the temporal variability). The exponential decay of the number of Lagrangian particles in the Wadden Sea allows to estimate the flushing time T_a, which is due to advection only. For the basins of Wangerooge, Spiekeroog, Langeoog and Baltrum T_a is 4.8, 3.7, 4.8 and 1.5 times T_d, correspondingly. The deviation of the particle positions from their initial location is a measure of diffusion due to periodical oscillations of the velocity field.

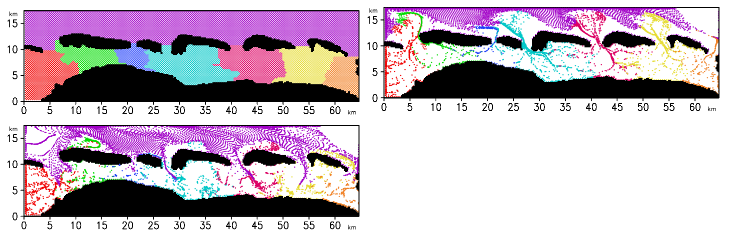

Fig. 5: Positions of Lagrangian particles. Upper left - initial time, upper right - after half a tidal period, lower left after one tidal period. For clarity of representation the ocean particles are plotted in the first figure only.

The length scale r of a patch of Lagrangian tracers during one tidal period is ~ 5 km (see the above figure). Taking for the mixing coefficient $K_h \sim 10 - 10^2 m^2 s^{-1}$, gives for the diffusion time $T_{diff} = r^2/K_h \sim$ 5-50 tidal periods. The the flushing time due to diffusion can be calculated as $T_d = T_t(V + P)/dP$, where d is the fraction of particles from the patch lost for the intertidal basin. If we take $T_{diff} = 5T_t$ (fast diffusion) and assume that $V \sim P$ (see Figure 3) and $T_{diff} = T_d$, then $d = 2/5$, that is about half of particles are lost in one tidal cycle due to diffusion. Obviously, the flushing time scale is subject to further reduction due to nonperiodicity in the forcing and in particular to extreme storm events.

This model will be used in the near future as a tool to provide input to an ecological model where the exchanges with the open ocean and between model compartments are crucial for the behavior of the ecosystem.

Acknowledgments: We are indebted to S. Dick for providing data from the numerical model of the German Hydrographic Office (BSH), which after interpolation onto our model grid are used as model forcing. Validation data were kindly provided by G. Floeser, GKSS.

References

[1] Aref, H., Stirring by chaotic advection. *J. Fluid Mech.* **143**: 1984.

[2] Bennekom, A. J. van, W. W. C. Gieskes, and S. B. Tijssen, Eutrofication of Dutch coastal waters. *Proc. Roy. Soc.* **B 189**, 359-374, 1974.

[3] Bolding, K. and H. Burchard, GOTM and GETM: Coupling of a water column turbulence model and an estuarine transport model, in preparation, 2000.

[4] Burchard, H., Presentation of a new numerical model for turbulent flow in estuaries and Wadden seas. Babovic, V. and L. C. Larsen (eds.): Hydroinformatics '98, Proceedings of the Third International Conference on Hydroinformatics, Copenhagen, Denmark, 24-26 August 1998, Balkema, Rotterdam, 41-48, 1998.

[5] Okubo, A., Some remarks on the importance of the "shear effect" on horizontal diffusion. *J. Oceanogr. Soc. Japan.* **24**: 60-69, 1960.

[6] Ferk, U. Folgen eines beschleunigten Meeresspiegelanstiegs für die Wattgebiete der niedersächsischen Nordsee Küste. *Die Küste* **B 57**, 135-156, 1995.

[7] Postma, H., Hydrography of the Dutch Wadden Sea. *Tijdschr. K. ned. aardijksk.* **67**: 4-33, 1954.

[8] Zimmerman, J. T. F. Mixing and flushing of tidal embayments in the western Dutch Wadden Sea. Part I: Distribution of salinity and calculation of mixing time scales. *Ned. J. Sea Res.* **10**, 149-191, 1976.