SEASONAL STRATIFICATION AND BIOGEOCHEMICAL TURNOVER IN THE FRESHWATER REACH OF A PARTIALLY MIXED DREDGED ESTUARY

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Abstract

The Elbe estuary is a substantially engineered tidal water body that receives high loads of organic matter from the eutrophied Elbe river. The organic matter entering the estuary at the tidal weir is dominated by diatom populations that collapse in the deepened freshwater reach. Although the estuary's freshwater reach is considered to manifest vertically homogenous density distribution (i.e. to be well-mixed), several indicators like trapping of particulate organic matter, near-bottom oxygen depletion and ammonium accumulation suggest that the vertical exchange of organic particles and dissolved oxygen is weakened at least temporarily. To better understand the causal links between the hydrodynamics and the oxygen and nutrient cycling in the deepened freshwater reach of the Elbe estuary, we establish a three-dimensional coupled hydrodynamical-biogeochemical model. The model demonstrates good skill in simulating the variability of the physical and biogeochemical parameters in the focal area. Coupled simulations reveal that this region is a hotspot of the degradation of diatoms and organic matter transported from the shallow productive upper estuary and the tidal weir. In summer, the water column weakly stratifies when at the bathymetric jump warmer water from the shallow upper estuary spreads over the colder water of the deepened mid reaches. Enhanced thermal stratification also occurs also in the narrow port basins and channels. Model results show intensification of the particle trapping due to the thermal gradients. The stratification also reduces the oxygenation of the near-bottom region and sedimentary layer inducing oxygen depletion and accumulation of ammonium. The study highlights that the vertical resolution is important for the understanding and simulation of estuarine ecological processes,

because even weak stratification impacts the cycling of nutrients via modulation of the vertical mixing of oxygen, particularly in deepened navigation channels and port areas.

Keywords: Estuarine circulation, Stratification, Eutrophication, Oxygen depletion

1. Introduction

Estuaries around the globe, which are shaped by human intervention, suffer from similar environmental issues like sedimentation in dredged fairways, eutrophication and oxygen depletion. The primary scientific and management perception of these is two-dimensional or barotropic, neglecting processes in the water column that might affect both physics and biogeochemical turnover. Using an unstructured grid three-dimensional coupled physical-biogeochemical model of the Elbe estuary, an estuary shaped by human intervention for centuries, this study reveals a coupling between temperature-induced stratification in the dredged limnic reach and biogeochemical turnover. We show that the simplification made by depth-averaged modelling is not justified in heavily dredged estuaries as dynamical stratification can significantly affect water quality, e.g in terms of near-bottom oxygen concentrations. Our simulations further demonstrate that the dynamical stratification controls the region and quantity of trapping of biogenic particles emphasising the advantage of high-resolution three-dimensional models for simulating the accumulation of organic matter and nutrients (eutrophication) in the deepened estuarine freshwater reach. This outcome is a novelty in the field because traditionally estuarine particle transport has been explained by processes in the salinity front and the tidal current asymmetry. Here we show an additional factor, temperature-induced stratification, that is strongly connected to the history of human intervention (dreding, rectification) but that for the same reason can be used for the development of managing strategies (beyond the scope of this paper).

In this case study, we argue that the prevalent picture of the Elbe as a well-mixed estuary (Muylaert and Sabbe, 1996; Amann *et al.*, 2012) deserves to be revised. Hydrodynamic modelling studies have shown that buoyancy-driven density gradients induce periodic stratification in the brackish reaches (Burchardt *et al.*, 2004; Stanev *et al.*, 2019). We extent the focus of the 3D modelling into the freshwater-dominated reach using a coupled hydrodynamical-biogeochemical model. Earlier coupled modelling made use of Lagrangian (Schroeder, 1997) and idealised 2D models (Holzwarth and Wirtz, 2018) to simulate the dynamics of primary production and oxygen along the estuarine freshwater reach. While these works explained well the transition from autotrophy to heterotrophy in the port region, they did not elucidate why the zones of the oxygen minimum, biogenic particle sedimentation and ammonium accumulation linger close to the bathymetric jump (instead of being flushed downstream by river flow). In this study, we establish a coupled hydrodynamical-biogeochemical model validated for the freshwater and low-saline reaches of the Elbe estuary, aiming to i) identify spatiotemporal pattern of stratification in the deepened freshwater reach including the port region; ii) reveal the linkages between the dynamics of stratification, response of the local currents and the estuarine circulation; iii) examine the response of local oxygen and nutrient levels to the physics associated with stratification of the water column; iv) better understand the causality between hydrodynamics and biogeochemical dynamics in this highly engineered tidal freshwater regime to facilitate further research, development of management strategies and inter-system comparison.

In order to address the above aims, we analyse simulations of a coupled physical-biogeochemical model of Elbe estuary.

2. Modelling framework

The investigation of the above physical-biological interactions requires a modelling framework that is capable of the coupled dynamics and covers horizontal scales from the estuarine border with the coastal ocean to the upper tidal river in the horizontal direction. The model coupling needs to be at every time step ('online') to provide the immediate responses of biology to physics, which are highly dynamic in the estuarine environment. Additionally, a vertically resolved water column and dynamic coupling between the water column and sediments are required. The modelling framework that is used here builds on an unstructured mesh hydrodynamic core, the SCHISM (Zhang *et al.*, 2016), which is coupled online to an ecosystem module for the lower trophic levels, ECOSMO (Schrum *et al.*, 2006; Daewel and Schrum, 2013). ECOSMO has been developed to tackle the plankton, nutrient and oxygen dynamics in the North Sea and in the Baltic Sea and is herein applied to the estuarine environment with its strong nutrient loading, flooding and drying, high flow velocities and similar charateristics. The coupling of ECOSMO with SCHISM is of great advantage because it allows to simulate the coupled physical-biogeochemical dynamics on triangular mesh with a horizontal resolution of 500 m in the German Bight down to 30 m in the Hamburg port area (Figure 1). At the seaward open boundary the Elbe estuary model is forced by vertical and horizontal tides, temperature and salinity from a hydrodynamic model of the German Bight (Stanev *et al.*, 2019) downscaling the AMM7 reanalysis provided by CMEMS (O'Dea *et al.*, 2016). The biogeochemical forcing at the open ocean boundary has been compiled from ICES observations of nutrients, organic matter and oxygen in the región of the southern North Sea. The landward forcing is represented by freshwater fluxes and nutrient loads that have been derived from oficial discharge estimates and monitoring data of nutrients, chlorophyll and oxygen. Finally, the atmospheric forcing is provided by the German Weather service reanalysis based on the COSMO-EU model with 7 km horizontal resolution.

3. Results

The model has been integrated for two years, covering the period of 2012 and 2013. Validation of the model simulation against observed variability of sea level, horizontal currents, salinity, temperature as well as the key state variabiles of the coupled nitrogen and oxygen cycles are given in the complete paper currently under submission at Frontiers in Marine Science. In order to answer the research questions formulated in the Introduction, we focus in the following on the analyses of the model dynamics during May to September, 2012. During summer 2012 average Elbe discharge was approximately 400 m^3 s^1 which is well below the long-term average of 712 m^3 s^1. In recent years, summer discharges have been even lower and the low discharge of summer 2012 is far from an extreme. The competition between the stratification and mixing in the deepened freshwater reach is illustrated an along-channel profile of the gradient Richardson number, compiled from the simulated density and horizontal currents (Figure 2a). The area downstream of the bathymetric jump, that separates the shallow and the deepened freshwater reach, demonstrates enhanced stability of the flow. This region is of particular importance for the estuarine ecosystem because the bathymetric jump also separates the flood-dominated deepened reach from the ebb-dominated shallow reach. The current asymmetry (not shown) is associated with a mixing asymmetry (Figure 2b) favoring the upstream (downstream) transport of particulate matter from the deep (shallow) part toward the sloping region. The same region reveals enhanced vertical temperature anomalies illustrating the termal stratification in the port area (Figure 2c). The vertical anomalies of the longitudinal currents show a pattern similar to the well-known estuarine circulation suggesting enhanced particle trapping in the vicinity of the bathymetric jump (Figure 2c). Also the ecosystem dynamics respond clearly to the abrupt bathymetric change (Figure 4). Simulated chlorophyll and disolved oxygen decrease from surface to bottom (Figure 4a, c). Detritus, silicate and nitrate increase towards the channel bed (Figure 4b, e, f). Ammonium shows largely the same pattern but the vertical gradient is negative downwards around km 626 (Figure 4d). Some of the vertical variability may be explained by the inherent properties of the illustrated variables. Chlorophyll, for example, decreases towards the channel bed in the deepened reach because of the aphotic conditions in the deep water. Detritus is a sinking tracer and thus accumulates at the channel bottom. On the other hand, the vertical variability of ecological tracers may be enhanced by the physical stratification. In order to test this hypothesis, the water temperature has been set constant in the equation of state in a separate modelling experiment. In this modelling experiment the density variability is thus independent from the temperature variability. Here we are interested in the effect of this experiment in the area of the (slightly) stratified during summer freshwater reaches (Figure 3a). The comparison of the model experiment and the reference run for the period of May to September 2012 reveals enhanced mixing along the deepened freshwater reach (Figure 3b). Also, the vertical temperature anomaly and the estuarine circulation are weakened (Figure 3c). In consequence of the changed currents and vertical mixing, the particulate organic matter (detritus) decreases in the port area and increase in the estuarine mid reaches (Figure 3d). This modelling experiment shows that temperature-induced stratification partially controls the particle trapping in the port area. The stratification also impacts onto the oxygenation of the near-bottom region affecting the nitrication of ammonium to nitrate (not shown).

4. Conclusions

A nested modelling system for the prediction of the coupled physical-biogeochemical in the Elbe estuary is presented. By means of the sensitivity experiment in which the temperature was set constant in the density equation, it has been shown that density stratification is a mechanism that promotes the retention of the biogenic particles in the port area controlling the local oxygen budget and coupled nitrogen cycling. In comparison with the control run, the near-bottom oxygen concentration improved by 10% in several port basins, revealing the potential importance of density stratification for estuarine management in artificially deepened tidal rivers. The correlations between temperature and stratification, on the one hand, and stratification and oxygen depletion, on the other hand, emphasise the increased vulnerability of the human-shaped system to meteorological and climate forcing. Further model development shall consider the origin and specific characteristics of organic matter as well as specific interactions between organic and inorganic particles, such as flocculation. The current model is a useful new tool for regional studies and for exploring management options regarding channel construction and channel deepening. Such a tool is of particular relevance for further scenario studies that are planned for assessing the impacts of global warming, sea level rise and human intervention on the catchment scale. The model is able to quantify the impact of tailored management activities on a local scale. The mechanisms addressed herein are potentially crucial for solving future issues of ecological health and use conflicts in the area of the Elbe estuary and the Elbe River catchment.

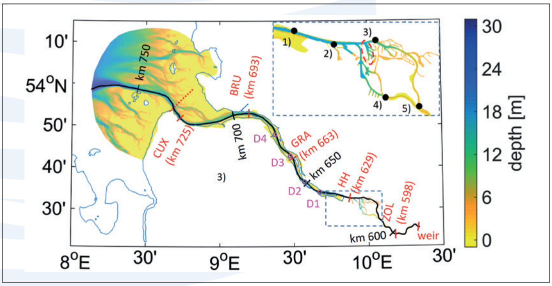

Fig. 1. Model domain with depth [m] given as a background. The black transect line indicates the Elbe navigational channel, with black labels identifying the official Elbe-km. Red labels and associated ticks mark the locations of observation stations for (but not only) water quality parameters, with respective official Elbe-km given as additional information. Purple circles mark the locations of permanent moorings where horizontal currents, salinity and temperature are measured, with purple labels D1-D4 identifying the individual stations. The inset in the upper right corner indicates the locations of gauges in the region of the port of Hamburg used for model validation in the FMAS paper.

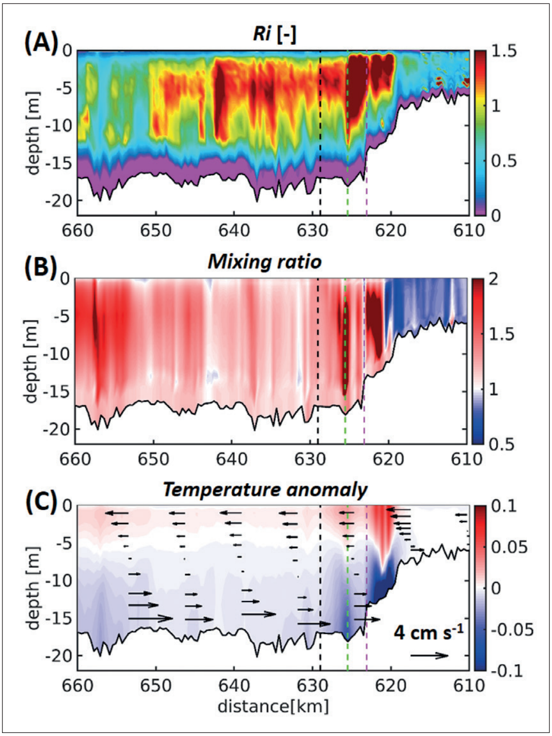

Fig. 2. Average summer physical conditions along the estuarine main stem: (a) gradient Richardson number (Ri), (b) ratio of average turbulent diffusivity during flood and ebb, (c) vertical temperature anomaly and vertical anomaly of the along-channel currents.

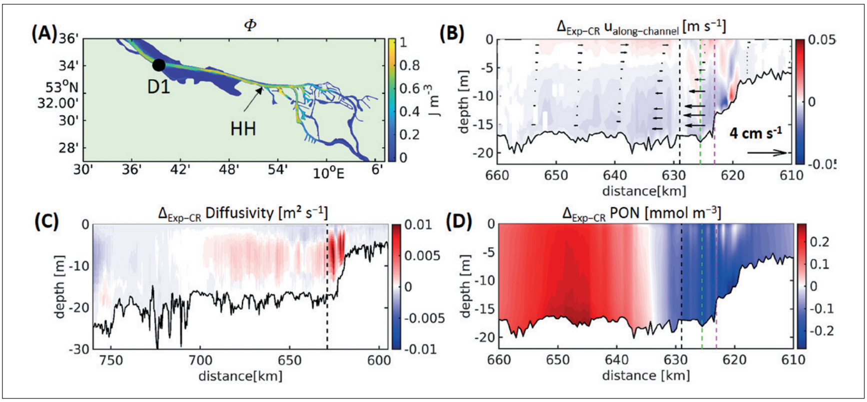

Fig. 3. Summer average (a) potential energy anomaly deepened freshwater reach and port area. (b) illustrates the average difference of turbulent diffusivity between the model experiment and the reference run. (b)shows the differences of the vertical temperature anomaly and longitudinal currents, (d) shows the differences of the concentration of detritus/particulate organic nitrogen (PON).

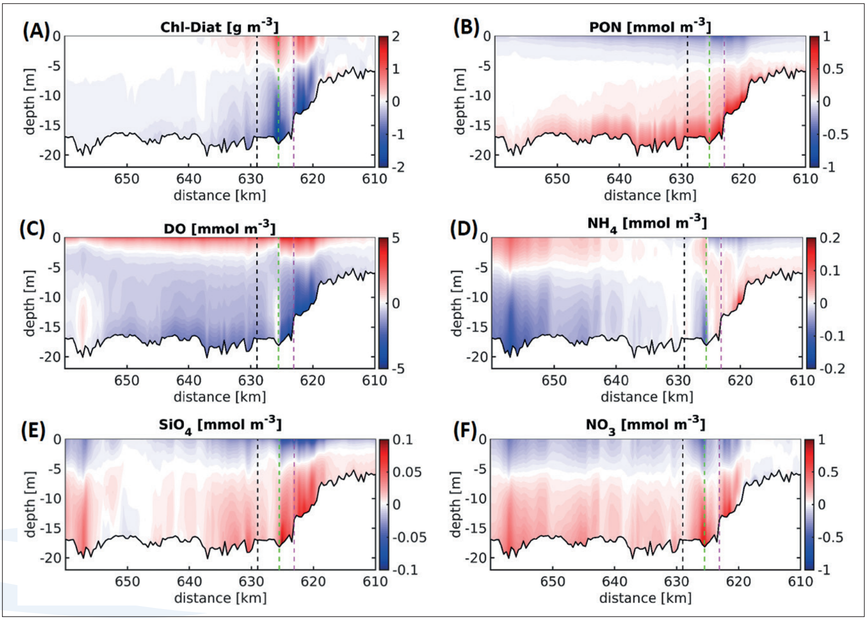

Fig. 4. Time-averaged vertical anomalies of (a) chlorophyll, (b) detritus, (c) dissolved oxygen, (d) ammonium, (e) silicate, and (f) nitrate concentrations are given for the main channel between km 610 and km 640 of the Elbe estuary. The time averages represent the simulation during the period of May to September 2012. The dashed black, green and purple lines mark the positions of station Seemannshöft ('HH', see Figure 1), the confluence of the northern and southern channel branches, and station Sankt Pauli (see inset in Figure 1), respectively.

Acknowledgements

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