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Modelling phytoplankton succession and nutrient transfer along the Scheldt estuary (Belgium, The Netherlands)

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ABSTRACT

The freshwater (RIVE) and the marine (MIRO) biogeochemical models were coupled to a 1D hydro-sedimentary model to describe contemporary phytoplankton succession and nutrient transfers in the macrotidal Scheldt estuary (BE/NL) affected by anthropogenic nutrient loads. The 1D-RIVE-MIRO model simulations are performed between Ghent and Vlissingen and the longitudinal estuarine profiles are validated by visual and statistical comparison with physico-chemical and phytoplankton observations available for the year 2006. Results show the occurrence of two distinct spatial phytoplankton blooms in the upper and lower estuary, suggesting that neither the freshwater nor the marine phytoplankton gets over the maximum turbidity zone (MTZ) at the saline transition. Sensitivity tests performed to understand how changing conditions (salinity, turbidity and nutrients) along the estuary are controlling this bimodal spatial phytoplankton distribution identify salinity and light availability as the key drivers while the grazing pressure and nutrient limitation play a negligible role. Additional tests with varying salinity-resistant (euryhaline) species in the freshwater assemblage conclude that the presence (or absence) of euryhalines determines the magnitude and the spreading of freshwater and marine phytoplankton blooms in the estuary. Annual nutrient budgets estimated from 1D-RIVE-MIRO simulations show that biological activities have a negligible impact on nutrient export but modify the speciation of nutrients exported to the coastal zone towards inorganic forms, thus directly available to phytoplankton. The implementation of nutrient reduction options (upgrading of waste water treatment plants, conversion to organic farming) on the Scheldt watershed influences the whole estuary and affects both the magnitude and the speciation of nutrients exported to the coastal zone with expected impact on coastal phytoplankton dynamic.

1. Introduction

Estuaries are shallow open systems strongly influenced by river inputs, mixing with the coastal ocean and exchanges across the sediment–water and atmosphere–water interfaces. These transitional zones between the freshwater and the marine systems are characterised by important salinity (SAL) gradients and receive large amounts of dissolved and particulate carbon (C), nitrogen (N), phosphorus (P) and silicon (Si) of natural and anthropogenic origin from rivers. This riverine material undergoes profound transformations in estuaries before being transferred to the adjacent coastal zone (Wollast, 1983). Under the dual influence of climate and anthropogenic changes (e.g. Paerl et al., 2006), estuaries are characterised by a large variability of physical and chemical properties that affect directly planktonic communities and indirectly the biogeochemical role of estuaries, in terms of e.g. transformation, retention or removal of nutrients.

At the interface between freshwater and marine ecosystems, estuaries are characterised by distinct phytoplankton assemblages along the salinity gradient (Attrill and Rundle, 2002; Muylaert et al., 2009; Quinlan and Philips, 2007). While freshwater phytoplankton is adapted to low salinity and marine species to high salinity, some species are resistant to small salinity fluctuations and grow at intermediate salinity (e.g. Muylaert et al., 2009; Roubeix et al., 2008). In addition to the impact of salinity, the mixing of fresh and marine waters creates unique hydrodynamic and hydro-sedimentary conditions (in particular water residence time and turbidity) that structure the estuarine ecosystem and impact the associated carbon and nutrient cycles (Lancelot and Muylaert, 2012). Understanding the effect of

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these physico-chemical conditions on phytoplankton organisms and describing the phytoplankton succession is a pre-requisite to assessing the ecological and biogeochemical function of estuaries.

The Scheldt estuary, located in the southwest Netherlands and northern Belgium (Fig. 1), is a shallow, well-mixed, and relatively turbid macrotidal estuary. It is one of the most nutrient-rich and polluted systems in the world (Wollast, 1988) where human activities on the watershed have deeply altered the quality of surface waters since the second half of the 20th century (Billen et al., 2005; Meire et al., 2005; Soetaert et al., 2006; Van Damme et al., 2005). Increased river nutrient and organic matter inputs have changed the estuarine biological activities and biogeochemical cycles (Billen et al., 2005; Soetaert et al., 2006) and have contributed to the eutrophication of the coastal waters of the Southern North Sea (e.g. Lancelot et al., 2007). Since the 1990's the implementation of wastewater treatment led to a marked improvement in the water quality in the estuary (Soetaert and Herman, 1995a; Soetaert et al., 2006). In particular, the largest wastewater treatment plant of the city of Brussels (1.4 M inhabitant equivalent IE) is operating since March 2007. Phytoplankton communities are spatially structured in the Scheldt estuary with marked shifts between freshwater, euryhaline and marine species (Lancelot and Muylaert, 2012; Muylaert et al., 2000). Despite important changes in nutrient concentration, primary production in the Scheldt estuary does not seem to have changed significantly with nutrient load modification (Gazeau et al., 2005; Kromkamp and Peene, 2005). Although the recent improvement of dissolved oxygen concentrations in the estuary had modified the importance and the composition of zooplankton organisms (e.g. Appeltans et al., 2003; Mialet et al., 2011) with an impact on the phytoplankton biomass (Kromkamp and Van Engeland, 2010).

Over the last two decades, several physical–biogeochemical models have been implemented in the Scheldt estuary for estimating the nutrient export to the coastal zone (Arndt et al., 2007; Hofmann et al., 2008; Regnier et al., 1997; Soetaert and Herman, 1995a,b; Vanderborght et al., 2002, 2007). The description of the biological processes in these estuarine models is generally simple (based on total primary production) and the estuary is often considered as a unidirectional land–ocean transition. However, global change also affects the functioning of the coastal ocean and subsequently impacts the lower estuary. The adjacent coastal sea has been explicitly considered in a few Scheldt estuary models (Arndt et al., 2007; Vanderborght et al., 2007) but these were constrained by observed concentrations at the upper boundary of the estuary. A step further then consists in implementing high resolution coupled physical–biogeochemical models of the whole river-estuary-ocean system for describing the effect of changing climate and human pressure on estuarine communities and related biogeochemical processes. Such models exist for the river drainage basin, the estuary and the adjacent coastal sea and have been partially coupled (e.g. Cugier et al., 2005) in an offline mode (e.g. Arndt et al., 2011; Lancelot et al., 2007). For instances, the marine biogeochemical MIRO model (Lancelot et al., 2005) was recently implemented in a fully transient two-dimensional, nested-grid hydrodynamic model of the Scheldt estuary and adjacent near-shore coastal zone continuum to quantify biogeochemical transformations and carbon and nutrients fluxes exported to the coastal zone (Arndt et al., 2011). This application allowed to estimate the importance of coastal intrusion in the estuary and to quantify the biogeochemical transformations and fluxes of C and nutrients in the lower estuary. However, the explicit description of the freshwater community was missing in this model as only freshwater diatoms were imposed at the upper estuarine boundary and an artificial threshold allowed the shift between freshwater and marine diatoms.

In this study, we coupled the river (RIVE) and the marine (MIRO) ecologically-based biogeochemical models to describe contemporary plankton succession and the associated nutrient transformation, retention and removal in the Scheldt estuary and to estimate the nutrient export to the coastal zone. For this application the resulting RIVE-MIRO model is coupled with a one-dimensional hydrodynamic model of the Scheldt estuary that includes a suspended sediment module. The offline coupling with the marine 3D-MIRO&CO model (Lacroix et al., 2007) of the Southern North Sea and the Seneque-Riverstrahler, a biogeochemical model of the Scheldt river system associated to a geographical information system (GIS) description of the watershed (Ruelland et al., 2007), provides respectively the marine, upper estuary and lateral tributary boundary conditions. To the best of our knowledge, this paper is the first attempt to use a river-estuary-coastal sea model that describes explicitly the fate of both freshwater and marine plankton species in the Scheldt estuary and their impact on the nutrient cycling and delivery to the sea. The ability of the model to reproduce biogeochemical trends in the Scheldt estuary is statistically appraised based on a comparison of model simulations with available observations in 2006. Sensitivity tests are further conducted to understand how changing conditions (salinity, turbidity and nutrients) along the estuary drive the spatial distribution of phytoplankton assemblages. Due to the high pressure of human activity on the Scheldt watershed, the coupled model is also

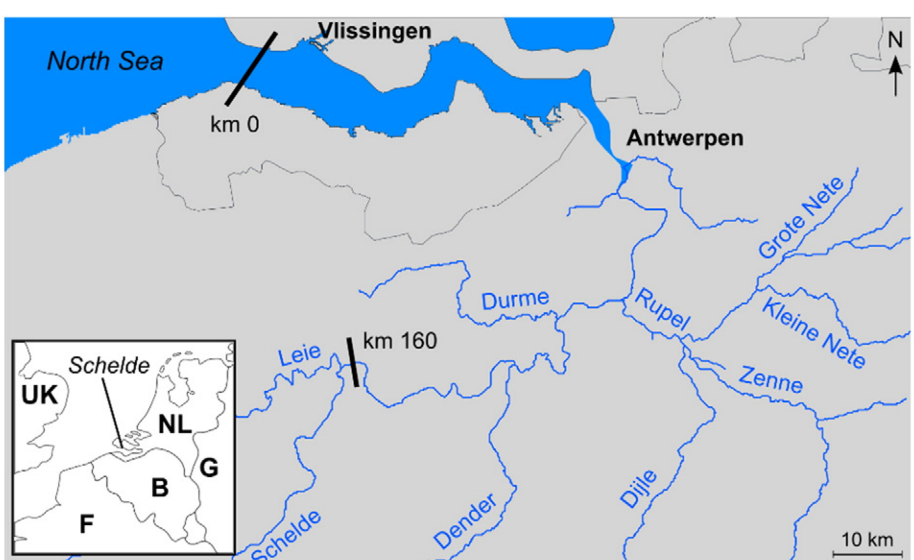

Fig. 1. River network of the 1D RIVE-MIRO model. km 0 and km 160 are giving the limit of the model domain.