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Model study on present and future eutrophication and nitrogen fixation in the Gulf of Finland, Baltic Sea

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ABSTRACT

The response of nutrient and chlorophyll fields to climate change by the end of the twenty-first century was evaluated in the Gulf of Finland (Baltic Sea) using comparison of a hindcast simulation for 1997–2006 and future climate forcing, assuming an A1B greenhouse gas emission scenario and business-as-usual riverine nutrient load for 2090–2099. The comparison of simulated oxygen, phosphate and nitrate levels from the hindcast model with the measurements indicated a good performance of the 3D ecosystem model, except for overestimated near-bottom layer nitrates. The mean chlorophyll level was slightly overestimated by the model, whereas the variability in the surface layer chlorophyll level was well reproduced. Future projection simulations indicate no considerable changes in the upper layer oxygen concentrations compared with the hindcast simulation and observations, but deeper near-bottom layers were projected to become anoxic, causing an increase in phosphate and a decrease in nitrate concentrations in these layers. The increase in surface layer phosphate and the decrease in nitrate concentrations lead to an increase in summer cyanobacteria blooms and an increase in nitrogen fixation, which therefore led to an increase in the annual mean chlorophyll content in the upper layer.

1. Introduction

According to the HELCOM eutrophication assessment, both the open and coastal waters of the Gulf of Finland are classified as being “affected by eutrophication” (HELCOM, 2009). Eutrophication signals include the winter nitrate and phosphate concentrations in the surface layer, chlorophyll *a* concentrations, depth distribution of submerged aquatic vegetation and status of benthic invertebrate communities, the latter being connected to near-bottom oxygen levels (HELCOM, 2009). The Baltic Sea Action Plan (BSAP) adopted in 2007 foresees the achievement of a good ecological status of the Baltic Sea by 2021 (HELCOM, 2007). The BSAP foresees the reduction of nitrogen input to the Baltic Sea of approximately 18% and reductions of phosphorus input of approximately 42%, which can be considered as an optimistic scenario. In addition to the BSAP scenario, Gustafsson et al. (2011) defined the following nutrient input scenarios: reference (REF), current legislation (CLEG) and business as usual (BAU). REF assumes the nutrient load remain constant at the level observed in recent years (average for 1995–2002). CLEG implies nutrient input reduction according to the EU directives on sewage treatment and the Nitrogen Emission Ceiling (NEC) directive on air emissions. The BAU scenario assumes rapid agriculture growth around the Baltic Sea, especially in transitional countries. Swinnen et al. (2009) have shown that gross agricultural output has increased in Central and Eastern European countries and the Former Soviet Union since the mid-1990s and is reaching the pre-reform output level. However, in the long term, changes in ecosystem status do not depend only on the levels of nutrient input, and climate effects must also be taken into account (Meier et al., 2011a; Savchuk and Wulff, 2009). The projections of climate change predict alterations in the physical conditions of the Baltic Sea in future decades (BACC Author Team, 2008). The physical status of the Baltic Sea depends on external forcing, comprised of direct interaction with the atmosphere through air-sea interface, freshwater runoff from the land and interaction with the ocean at the open boundary (Stigebrandt and Gustafsson, 2003). These changing physical conditions will inevitably impact the biogeochemistry of the sea. When the temperature remains above the temperature of maximum water density, deep convection weakens, and the amount of nutrients entering the euphotic zone decreases. In addition, an increase in precipitation increases the nutrient input from land and favours eutrophication in coastal areas (BACC Author Team, 2008). It has been suggested that an increase in precipitation and a decrease in the frequency of major Baltic inflows from the North Sea will result in a shift from marine to more brackish and freshwater species in the Baltic (Philippart et al., 2011).

Climate change in the Baltic Sea Basin has been studied using regional climate models (RCM). One of the first modelling studies investigating the impact of climate change on the future physical conditions of the Baltic Sea (2070–2100) using RCM was that of Meier (2006). More recent model simulations include the analysis of the impact of climate

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change on the Baltic Sea ecosystem. Accordingly, Meier et al. (2011b) investigated the impact of four climate projections and three nutrient load scenarios on the Baltic Sea ecosystem. One of their conclusions was that in the southwestern Baltic, the concentrations of phytoplankton biomass may increase, and cyanobacteria blooms will become more intense. Neumann (2010) used two regional data sets for greenhouse emission scenarios in a simulation of the Baltic Sea from 1960 to 2100 and observed no significant change in anoxic water area and no change in net nitrogen fixation in the future. Because the state-of-the-art coupled hydrodynamic-ecosystem models display different performances and statistics for different variables, the use of ensemble models has been proposed for climate change studies (Eilola et al., 2011).

Of equal importance is the application of sub-regional modelling case studies, which provide an insight into local processes and their effects, thus complementing large-scale model results. For this reason, the present paper focuses on the future ecosystem response to the changing climate in the area of the Gulf of Finland. The Gulf of Finland is an elongated (400-km long) and relatively narrow (50–135 km) basin in the eastern part of the Baltic Sea. The Gulf's maximum depth decreases from 80–100 m at the entrance to 20–30 m in the eastern part. The salinity distribution in the Gulf is controlled by a freshwater budget and water exchange with the open Baltic. The estuarine circulation of the Gulf results in a strong halocline that effectively prevents mixing between the surface and bottom waters, leading at times to low oxygen conditions in the near-bottom water. Southwesterly winds generate a temporary estuarine reversal that weakens stratification (Elken et al., 2003) and improves the near-bottom layer's oxygen conditions, in particular during the winter when the seasonal thermocline decays. Northeasterly winds support the estuarine circulation in the Gulf. The occurrence of low-oxygen conditions in the Gulf of Finland supports the high internal loading of phosphorus from the sediments, thus establishing conditions favourable for summer cyanobacteria blooms. The latter are a major environmental problem for the whole Baltic Sea and for the Gulf of Finland in particular (Vahtera et al., 2007). Nitrogen fixation is an important source of nitrogen in the Baltic Sea, reaching values up to 1000 kt year^{-1} (Rolff et al., 2007). Simulations by Neumann and Schernewski (2008) indicated that the highest nitrogen fixation rates (approximately 300 mmol m^{-2} year^{-1}) in the Baltic Sea occur in the western Gulf of Finland. They demonstrated that an intensified positive winter NAO index is a precondition for strong cyanobacteria blooms in the Baltic Proper, but in the Gulf of Finland, other processes, e.g., mixing or upwelling events, are of greater importance. Model simulation by Neumann and Schernewski (2005) also demonstrated that a 50% reduction in nitrogen and phosphorus loads causes an increase in nitrogen fixation due to the change in the nutrient ratio.

The objectives of the current paper were a) to assess on the basis of a hindcast simulation (1997–2006) the ability of a 3D-coupled physical-biogeochemical model to reproduce the natural variability in thermohaline and biogeochemical fields, and, b) based on a future projection simulation (2070–2099), to estimate the degree of change in chlorophyll, oxygen and nutrient conditions as well as nitrogen fixation rates in the Gulf of Finland in response to a projected climate change and the BAU nutrient load scenario by the end of the 21st century. Although the BSAP is being implemented, the BAU nutrient load scenario was chosen based on the observed increase of the gross agricultural output in the Eastern European countries (Swinnen et al., 2009).

2. Materials and methods

2.1. Coupled hydrodynamic and biogeochemical model

The hydrodynamic model applied is a 3D free-surface hydrodynamic model GETM (General Estuarine Transport Model, www.getm.eu), which has been described in detail by Burchard and Bolding (2002) and Burchard et al. (2004). GETM solves the primitive equations of water dynamics using Boussinesq and hydrostatic approximations with a mode splitting technique on an Arakawa C-grid. In the horizontal plane, spherical coordinates were used, whereas σ-coordinates were applied in the vertical plane. Subgrid vertical mixing was resolved using a turbulence closure scheme of the k-ε type via the General Ocean Turbulence Model (GOTM, www.gotm.net) coupled with GETM (Umlauf and Burchard, 2005). Subgrid lateral eddy viscosity was resolved in the present simulations using the Smagorinsky formulation (Smagorinsky, 1963).

Ecosystem processes were resolved by coupling the ERGOM ecological model (Ecological Regional Ocean Model) (Neumann, 2000; Neumann et al., 2002) with GETM. ERGOM uses nitrogen as a model currency. There are three nutrients (nitrate, ammonium and phosphate) taken up by phytoplankton.

The nitrate balance is calculated as:

$$dN/dt = -\text{uptake} + \text{nitrification–denitrification} + \text{external supply}. \quad (1)$$

Due to respiration and detritus mineralisation, ammonium is produced, which, in the presence of oxygen, may be converted to nitrate through the process of nitrification. This is parameterized as:

$$\text{nitrification} = nf * A \quad (2)$$

where nf is the nitrification rate and A is the ammonium concentration. The nitrification rate depends on oxygen and the temperature of the surrounding water:

$$nf = Ox/(0.01 + Ox) * 0.1 * \exp(0.11 * t) \quad (3)$$

where Ox is oxygen concentration and t is water temperature.

Under the anaerobic conditions ($Ox \leq 0$) and in the presence of nitrate, detritus is oxidised by reducing nitrate to dinitrogen gas that leaves the system (denitrification process):

$$\text{denitrification} = f(N) * (L_{DN} * D + L_{SA} * S/H_{bot}) \quad (4)$$

where $f(N) = 5.3 * N * N \,/\, (0.001 + N * N)$, L_{DN} is the detritus (D) recycling rate calculated as $0.003 * \exp(0.15 * t)$, L_{SA} is the sediment (S) recycling rate parameterized as $0.002 * \exp(0.175 * t)$ and H_{bot} is the thickness of the near-bottom layer.

The ammonium balance is calculated as:

$$dA/dt = -\text{uptake} + \text{excretion} + \text{detritus recycling–nitrification} + \text{sediment recycling} + \text{external supply}. \quad (5)$$

In the case of oxic near-bottom conditions, a fixed portion (60% in the current setup) of nitrogen recycled in the sediments is removed from the system through consecutive nitrification and denitrification. This process is parameterized as:

$$\text{sediment recycling} = (1-fdn) * (L_{SA} * S/H_{bot}) \quad (6)$$

where $fdn = 0.6$ under oxic conditions, and $fdn = 0$ under anoxic conditions.

Dissimilatory nitrate reduction to ammonium (DNRA) was not taken into account. A recent study suggested that DNRA plays only a minor role in the Gulf of Finland (Jäntti et al., 2011).

Oxygen is supplied to the system by photosynthesis and air–gas exchange at the sea surface and is consumed due to the mineralization of organic matter, excretion/respiration and nitrification. Accordingly, oxygen consumption processes are parameterized as:

$$\text{oxygen consumption} = f(Ox) * (L_{DN} * D + L_{SA} * S/H_{bot}) - 2.0 * fdn * L_{SA} * S/H_{bot} - 6.625 * \left(L_{PN} * P + L_{ZN} * Z^2\right) - 2.0 * nf * A \quad (7)$$

where $f(Ox) = 6.625 * (1.0 - N * N \,/\, (0.001 + N * N))$ if $Ox \leq 0$ and nitrate is present, otherwise $f(Ox) = 6.625$. L_{PN} is the excretion rate of