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Offshore wind farms in the southwestern Baltic Sea: A model study of regional impacts on oxygen conditions

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ABSTRACT

Offshore wind farm piles are secondary hard substrate and hence an attractive colonization surface for many species. Especially in marine areas dominated by soft sediments, wind farms may lead to a significant increase in biomass by enlarging habitats from benthos layers into the pelagic column. A concomitant effect is the increase in oxygen consumption through respiration of living biomass and especially through degradation of dead biomass, mainly *Mytilus edulis*. This leads to impacts on the regional oxygen budget, and local anoxia in the direct vicinity of wind farm piles has been documented in scientific literature. The present study investigates the regional impact of multiple wind farms on oxygen concentration levels and on the appearance of hypoxia. A five-year data sampling with a steel cylinder and fouling plates delivered data for a 3D ecosystem model. The results show that wind farms do not lead to a significant decrease in oxygen on the mesoscale level. But additional anoxia may occur locally, which may lead to the release of hydrogen sulfide on microscale level and potential subsequent regional impacts.

1. Introduction

In light of the Renewable Energy Directive of the European Union (Directive, 2009/28/EC), many European member states have set themselves ambitious targets for achieving a larger share of renewable energy forms in their grids. This is also true for nations in the southwestern Baltic Sea Region, where energy production from offshore wind farms has become an important pillar in national energy strategies. Denmark, for instance, passed a new Energy Agreement in March 2012 with the target of 100% renewable energy by 2050 (ENS, 2012). As soon as 2020 half of the energy consumption is to be covered by wind farms. The German energy concept postulates a share of 50% of the national energy production to stem from offshore wind farms by 2050, with a capacity of 25 GW to be installed offshore as early as 2030 (BMU, 2011). Sweden's energy policy foresees a 50% share of renewable energies with 10 TWh offshore wind energy production by 2020 (Regeringskansliet, 2009). Despite current delays in the construction of previously approved wind farms, it is likely that the generation of renewable energy from offshore wind farms will increase significantly in the southwestern Baltic Sea, where single wind farms have already been built in Danish and German waters in recent years.

Local impacts of wind farms on benthic communities and water quality in the region have been researched in various studies (e.g. Birklund and Petersen, 2004; DHI Water and Environment, 2000a, 2000b; Petersen & Malm, 2006). Both issues are of high relevance in the southwestern Baltic Sea, where predominant soft-sediments (Emeljanov et al., 1993; Hermansen and Jensen, 2000) limit the spectrum of organisms and where oxygen supply is an issue due to limited water exchange and stratification (Lass and Matthäus, 2008). Wind farms, as well as other fixed offshore installations such as platforms, piles, and pillars, act as artificial reefs (Petersen & Malm, 2006; Maar et al., 2009; Wilhelmsson et al., 2006; Wilhelmsson and Malm, 2008). These provide substrates for organisms that would not be able to settle on the original soft sediment (Janßen et al., 2013; Svane and Petersen, 2001). Under the brackish conditions of the Baltic Sea, blue mussels (*Mytilus edulis*) are the predominant organism to settle on these artificial structures (Chojnacki, 2000; Malm and Isaeus, 2005; Qvarfordt et al., 2006; Zettler and Pollehne, 2006), and also in the North Sea this species seems to be relevant at least for inter- and subtidal levels (Joschko et al., 2008). Under adequate conditions blue mussels are able to achieve biomasses which exceed surrounding mussel beds by an order of magnitude (Frechette and Bourget, 1985; Frechette et al., 1989). Respiration, feces, and pseudofeces from mussels contribute to oxygen depletion (Chamberlain et al., 2001; Clausen and Riisgård, 1996). Under the hydrographical conditions of the Baltic Sea this may result in hypoxia or anoxia (Zettler and Pollehne, 2006).

Effects of artificial *Mytilus* spp. agglomerations, e.g. mussel aquaculture, on oxygen conditions, sedimentation, and benthic communities have been widely researched in different environments worldwide (Grant et al., 2005; Hatcher et al., 1994; Matisson and Lindén, 1983; Nizzoli et al., 2005). It is well documented that high density mussel agglomerations and their fecal deposits enrich both the aquatic and benthic environments, often causing lowered sediment redox potential,

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oxygen depletion, and a shift towards anaerobic benthic metabolism (Christensen et al., 2003). Similar processes may also be expected for mussel agglomerations on wind farms. However, most of these studies of the aquaculture sector have focused on shallow coastal waters, whereas most wind farms planned in the southwestern Baltic will be built offshore, where stronger currents may wipe both mussels and their fecal deposits away.

The Baltic Sea is a semi-enclosed sea. The inflow of water from the North Sea generates stratification in larger parts of the western Baltic Sea, with denser saline North Sea water penetrating below the less saline upper layer of water (Møller and Hansen, 1994). Vertical mixing is limited as the Baltic Sea has no significant tides of its own (Lass and Matthäus, 2008). Therefore stratification in the Baltic Sea is relatively stable in comparison to more open seas. Surface productivity in this region is high, partly caused by eutrophication (Wasmund and Siegel, 2008). Stratification does not prevent organic particles from sinking into deeper water layers while it does prevent dissolved oxygen from mixing downwards. This results in oxygen deficiency with negative impacts on benthic communities (Babenerd, 1991). Benthic biomass has already increased due to eutrophication over the past decades (Karlson et al., 2002). The secondary hard substrate created by wind farms or other fixed installations may intensify this development (Maar et al., 2009). This can result in an unbalanced oxygen supply and in consumption rates which may cause hypoxia or anoxia.

Studies by Zettler and Pollehne (2006, 2008) have shown a strong increase in biomass on and around wind farm piles in the first years after construction under the special salinity conditions of the southwestern Baltic Sea where biomass accumulation is to some extent not controlled by natural predation. It was shown that an imbalance between the local development of organic matter and oxygen availability can cause anoxia and the accumulation of hydrogen sulphide in the direct vicinity of a wind farm pile. Data for this study were sampled from fouling plates and a single model pile. Based on the results of these small-scale test fields, the authors set up a hypothesis stating that the impact of an entire large-scale wind farm on oxygen depletion might be similar to the test field results. However, locally important impacts may be irrelevant on regional scales (Erbguth et al., 2013) and studies about the regional impact of multiple wind farms on oxygen depletion are currently missing. Such studies can help shape to Marine Spatial Planning processes, which determine the density and location of wind farms (Jay, 2010).

This paper reports on the findings of a model study that was undertaken to simulate the impact of biomass accumulation caused by secondary hard substrate on regional oxygen conditions. The study is built on the sampling data of Zettler and Pollehne (2006, 2008), which allows a direct comparison of local and regional impacts. This paper is structured in four parts. First, core data on spatial and temporal development of wind farm borne biomass in the southwestern Baltic Sea is described briefly. Secondly, local sampling data is transformed into a biomass scenario for multiple wind farms. This then feeds into a 3D hydrodynamic-biogeochemical model simulating the impact of wind farm borne biomass on regional oxygen conditions. Finally, the simulation results are analyzed to identify process details and to advise Marine Spatial Planning.

2. Study site

The southwestern Baltic Sea as considered in this study includes the Kiel Bay, Mecklenburg Bight, Arkona Basin, Pomeranian Bight, and adjacent waters (Fig. 1). Under administrative law these waters belong to Denmark, Germany, Poland, and Sweden. The region is part of a larger transition zone where saline North Atlantic waters and brackish central Baltic waters meet, with saline water entering the deeper layers mainly through the Danish Straits. This causes a halocline and bottom salinity gradients ranging from 25 to 8 PSU from west to east. Entering waters deliver oxygen into the Baltic Sea and are therefore of great importance for the ecosystem, as no other significant oxygen sources are available for bottom layers (Döös et al., 2004). Salinity and oxygen values in deeper layers vary from year to year and season to season, depending on saltwater inflows. Especially the Arkona Basin shows a large variability in bottom salinity and oxygen values caused by the temporal imbalance between inflow and outflow of the basin (Lass and Mohrholz, 2003). The region is characterized mainly by sandy and muddy sediments including some till, gravel, and single bedrocks.

These geological and hydrographical conditions set the limits for marine organisms (Gogina et al., 2010). Depending mainly on the salinity gradient and sediment characteristics, the macrozoobenthic diversity varies extremely within the investigation area and can range from fewer than 20 up to a few hundred species (Zettler et al., 2008). Many species live close to their limits of tolerance to abiotic factors, while others are relatively robust due to a large range of hydrographical conditions. Especially in the southern and western area of the study site, large sections fall under the protection of NATURA 2000 (FFH & SPA) and under national conservation laws. Shallow waters (in average 20–45 m), relatively short distances to the coast (maximum 50 km), and average wind velocities of more than 8 m/s (EEA, 2009) offer attractive conditions for offshore wind farms. More than 1200 wind farms piles are currently being planned in the southwestern Baltic Sea, but to date only three wind parks are under operation. These wind farms are not suited for this study's multi-annual data sampling because two of them are located in shallow waters with specific coastal conditions and the third has only recently been completed.

3. Methodology

For the following assessment MOM3, a three-dimensional, numerical circulation model was used (Pacanowski and Griffies, 2000). The horizontal grid resolution was 3 nautical miles (nm) in longitude as well as latitude. Vertically 77 layers were resolved with resolution decreasing with increasing depth, from 1.5 m in the top layer up to 5 m in the lowest layer. A partial cell scheme was used for better representation of the bottom circulation. The prognostic variables were defined on an Arakawa-B-grid (Arakawa and Lamb, 1977). The horizontal velocity components as well as temperature and salinity were calculated for every time step at the grid points. The model time step was 9 min. The fluid movement was calculated using the Navier–Stokes-equation with a Boussinesq approximation.

The circulation model was coupled to the ecosystem model ERGOM (Neumann, 2000) in which nine state variables are calculated. Three functional groups of phytoplankton, cyanobacteria, diatoms, and flagellates, are distinguished. The upper-most trophic level is represented by zooplankton. Dead phytoplankton and zooplankton are combined in the state variable detritus. During sedimentation detritus is partly mineralized into dissolved ammonium and phosphate. Those detritus portions which reach the bottom can be buried in the sediment, mineralized, or resuspended, depending on the velocity of the near-bottom currents. Nutrients are grouped in ammonium, nitrate and phosphate. Parts of the mineralized phosphate may bind iron oxides under oxic conditions and are stored in the sediment from where they will dissolve again if anoxic conditions occur. The consumption and production of oxygen are coupled with biogeochemical processes via stoichiometric ratios. Oxygen levels also steer denitrification and nitrification processes in both the water column and the sediment. All the state variables mentioned above are coupled with different biological or geochemical processes. The detailed model equations can be found in Neumann et al. (2002). ERGOM is a nitrogen-based model. All state variables are expressed using the Redfield-ratio in terms of mmol[N] m^{-3}. Oxygen is expressed in mg l^{-1}.

3.1. Meteorological forcing

ERA-Interim reanalysis data was used for the atmospheric forcing. ERA-Interim is a continuously updated reanalysis of the global