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Review

Seasonal oxygen depletion in the North Sea, a review

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ABSTRACT

Seasonal mean oxygen depletion in offshore and coastal North Sea bottom waters was shown to range between 0.9 and 1.8 mg/L, corresponding to 95–83% saturation, between July and October over a 30-year assessment period (1980–2010). The magnitude of oxygen depletion was controlled by thermal stratification, modulated by water depth and nitrogen availability. Analyses were based on about 19,000 combined data sets. Eutrophication problem areas were identified mainly in coastal waters by oxygen minima, the lower 10th percentile of oxygen concentrations, and deviations of oxygen depletion from correlated stratification values. Connections between oxygen consumption and nitrogen sources and conversion, including denitrification, were indicated by correlations. Mean oxygen consumption reflected a minimum seasonal turnover of 3.1 g N/m^2 in the south-eastern North Sea, including denitrification of 1 g N/m^2. Oxygen depletion was underestimated in shallow coastal waters due to repeated erosion of stratification as indicated by local high variability.

Contents

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1. Introduction

The occurrence of oxygen depletion has increased globally (Diaz and Rosenberg, 2008) and is predicted to increase further due to climate change and increases in nutrient loadings (Meire et al., 2013). Depletion of oxygen is not limited to deep offshore sedimentation areas with long lasting enclosure of bottom waters (Karlson et al., 2002), but is also seasonally occurring at shallow eutrophic coastal sites (Middelburg and Levin, 2009; Kemp et al., 2009; Conley et al., 2007, 2011), causing kills of benthic organisms and fish throughout the world (Diaz and Rosenberg, 1995), including the North Sea (von Westernhagen and Dethlefsen, 1985).

Seasonal oxygen depletion is a natural process, mostly controlled by the extension (time and space) of seasonal thermal stratification and can be elevated by increased discharges of nutrients and organic matter. Despite the difficulty in differentiating between natural and anthropogenic causes, oxygen depletion can be used as an indicator of eutrophication in coastal waters (Best et al., 2007; Vaquer-Sunyer and Duarte, 2008; Topcu et al., 2009; Conley et al., 2009), as it integrates the annual turnover of organic matter in the water column resulting from the production of plankton.

In the eutrophication assessments of OSPAR (2008) or HELCOM (2013) oxygen depletion is a significant parameter which is used in the EU Marine Strategy Framework Direction (MSFD) assessments, due to its far reaching ecosystem effects. A compilation of effects by oxygen depletion has been presented within OSPAR (OSPAR, 2006) including proposals for thresholds of 80% saturation. 85% saturation had been proposed for the threshold of good/moderate ecological status to be applied by the EU Water Framework Directive (WFD), based on compiled effects and related to natural nutrient levels (Topcu et al., 2009, 2011). Ecological quality standards (EQSs) of 70–80% saturation are reported by Best et al. (2007) as mandatory standards or guideline values. Sub-lethal effects have been observed at 5 mg/L and lethal effects at 2 mg/L oxygen already within 5 days (Vaquer-Sunyer and Duarte, 2008). Besides of oxygen concentrations, extensions and durations of oxygen depletion are important for assessing ecosystem effects, but have not yet been considered for thresholds due to missing data and the variable sensitivity of affected organisms (Gray et al., 2002). Additionally, effects by ammonium and hydrogen sulphide may interfere with effects of oxygen deficiency which starts with increased respiration, less conserving energy and finally cause complete ecosystem change (Wu, 2002).

A main task for reduction of eutrophication effects is to quantify anthropogenic contributions to oxygen depletion and as a first step the identification of connections to nutrient availability. Despite evidence that eutrophication contributes to the expansion of oxygen depletion, it remains difficult to identify and quantify specific causes (Caballero-Alfonso et al., 2015; Conley et al., 2009). For semi-enclosed coastal areas dominated by single river discharges, effects of different nutrient loadings on the extension of hypoxia could be quantified by modelling (Scavia et al., 2003). Connections between oxygen concentrations and nutrient discharges have been modelled for estuaries (Lee and Jones, 1981), including some North Sea rivers and estuaries (Kemp et al., 2009), but are difficult to identify in coastal waters, affected by different sources and increasing interfering processes offshore. Historical oxygen data are mainly related to the central North Sea which can be assumed to be still undisturbed, if atmospheric nutrient precipitation is neglected. Oxygen saturation values from these areas are mostly above 90%, with the exception of minimum values reported (50–60%) during November 1902–1908 (Gehrke, 1916). These are probably artefacts as they were measured outside the seasonal period of stratification when the water column is likely to have been vertically well mixed and ventilated.

Since 1982 repeated oxygen measurements by the BSH (Bundesamt für Seeschifffahrt und Hydrographie) and other German institutions (Rachor and Albrecht, 1983; Brockmann and Eberlein, 1986; Brockmann et al., 1990, 1999) have been undertaken, partly focused on continental coastal waters (CCW). In addition to the regular monitoring, surveys have been performed in the northern CCW during July and August 1994 (Pohlmann et al., 1999) and during August 2010 (Queste et al., 2013), covering main parts of the North Sea. Continuous measurements at moored in situ systems allow a comparison of parallel changes in oxygen and chlorophyll a (Greenwood et al., 2010), however, these local time series indicated only partially connections between production and decomposition because organic matter is advected from surrounding areas as well. Additionally, the significance of point measurements is regionally limited.

Oxygen consumption in bottom waters, permanently exchanged with sediment surfaces, is not restricted to decomposition of organic matter but includes also nitrification and denitrification (Seitzinger et al., 2006), which is controlled by the availability of nitrate and organic matter (Lohse et al., 1993; Brettar and Rheinheimer, 1992). For this reason, connecting sinks and sources, oxygen consumption and nitrogen turnover have been linked, reflecting that nitrogen is the growth limiting nutrient in the North Sea (Loebl et al., 2009). Differences between remineralised nitrogen-equivalents of oxygen depletion and dissolved inorganic nitrogen in bottom waters were used to estimate the degree of net-denitrification and correlation-equations allow the calculation of possible turnover rates. One main objective of this paper is to quantify connections between seasonal thermal stratification and oxygen depletion in enclosed North Sea bottom waters, considering topographic structures and the main sources for nutrients and organic matter enhancing oxygen depletion. For this reason another focus are the relations between sources of nutrients and organic matter and remineralisation in bottom waters, combined with oxygen consumption and denitrification. This coupling will be quantified especially in frequently sampled northern continental coastal water (NCCW), to identify anthropogenic contributions to oxygen depletion by correlations with nutrient discharges. Stability of stratification in shallow areas and its effects on oxygen depletion will be considered. The analyses will be based on gradients with different resolutions, annual cycles, and trends, considering maximum oxygen depletion. Based on compiled data between 1980 and 2010, problem areas with elevated oxygen depletion (hot spots) will be identified within the whole North Sea.

2. Methods

Bottle data for temperature, salinity, nutrients, organic matter, chlorophyll a and oxygen have been compiled from data banks (ICES: International Council for the exploration of the Sea, Copenhagen, DOD: German Oceanographic Data centre) and other national sources (BSH, IBMC: Institute for Biogeochemistry and Marine Chemistry, RIKZ: Rijksinstituut voor Kust en Zee) which are mainly also stored in the ICES data bank. Compiled oxygen data are mostly based on Winkler titration, supplemented in few cases by single inter-calibrated probe measurements. Collection of oxygen data from the bottom layer has been focussed on 1980–2010, due to restricted regional nitrogen data (including TN) in the southern North Sea or diverging methods before. For oxygen concentration in the bottom waters about 14,000 data, paired with surface data, were collected between 1980 and 2010 (all seasons), covering large parts of the North Sea. Most data are stemming from the NCCW (about 40%), Skagerrak (until 11°E) and middle UK coast.