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Past occurrences of hypoxia in the Baltic Sea and the role of climate variability, environmental change and human impact

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ABSTRACT

The hypoxic zone in the Baltic Sea has increased in area about four times since 1960 and widespread oxygen deficiency has severely reduced macro benthic communities below the halocline in the Baltic Proper and the Gulf of Finland, which in turn has affected food chain dynamics, fish habitats and fisheries in the entire Baltic Sea. The cause of increased hypoxia is believed to be enhanced eutrophication through increased anthropogenic input of nutrients, such as nitrogen and phosphorus. However, the spatial variability of hypoxia on long time-scales is poorly known: and so are the driving mechanisms. We review the occurrence of hypoxia in modern time (last c. 50 years), modern historical time (AD 1950–1800) and during the more distant past (the last c. 10 000 years) and explore the role of climate variability, environmental change and human impact. We present a compilation of proxy records of hypoxia (laminated sediments) based on long sediment cores from the Baltic Sea. The cumulated results show that the deeper depressions of the Baltic Sea have experienced intermittent hypoxia during most of the Holocene and that regular laminations started to form c. 8500–7800 cal. yr BP ago, in association with the formation of a permanent halocline at the transition between the Early Littorina Sea and the Littorina Sea s. str. Laminated sediments were deposited during three main periods (i.e. between c. 8000–4000, 2000–800 cal. yr BP and subsequent to AD 1800) which overlap the Holocene Thermal Maximum (c. 9000–5000 cal. yr BP), the Medieval Warm Period (c. AD 750–1200) and the modern historical period (AD 1800 to present) and coincide with intervals of high surface salinity (at least during the Littorina s. str.) and high total organic carbon content. This study implies that there may be a correlation between climate variability in the past and the state of the marine environment, where milder and dryer periods with less freshwater run-off correspond to increased salinities and higher accumulation of organic carbon resulting in amplified hypoxia and enlarged distribution of laminated sediments. We suggest that hydrology changes in the drainage area on long time-scales have, as well as the inflow of saltier North Sea waters, controlled the deep oxic conditions in the Baltic Sea and that such changes have followed the general Holocene climate development in Northwest Europe. Increased hypoxia during the Medieval Warm Period also correlates with large-scale changes in land use that occurred in much of the Baltic Sea watershed during the early-medieval expansion. We suggest that hypoxia during this period in the Baltic Sea was not only caused by climate, but increased human impact was most likely an additional trigger. Large areas of the Baltic Sea have experienced intermittent hypoxic from at least AD 1900 with laminated sediments present in the Gotland Basin in the Baltic Proper since then and up to present time. This period coincides with the industrial revolution in Northwestern Europe which started around AD 1850, when population grew, cutting of drainage ditches intensified, and agricultural and forest industry expanded extensively.

Contents

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1. Introduction

Hypoxia, defined as <2 mg/l dissolved oxygen, occurs in aquatic environments when dissolved oxygen becomes reduced in concentration to a point harmful to aquatic organisms living in the environment. Hypoxia is a globally significant problem with over 400 reported sites suffering from its effects (Diaz and Rosenberg, 2008). Hypoxia not only causes severe ecosystem disturbances (Diaz and Rosenberg, 1995) but alters nutrient biogeochemical cycles (Vahtera et al., 2007) and forms hydrogen sulfide which is hazardous to numerous fauna and flora communities (Diaz and Rosenberg, 1995). Widespread oxygen deficiency has for that reason severely reduced macrobenthic communities below the halocline in the Baltic Sea over the past decades (Laine, 2003) and produced benthic "ecological deserts" that annually cover over 30% of the seafloor (Karlson et al., 2002). Hypoxia also affects food chain dynamics, fish habitats and fisheries (Karlson et al., 2002; Bonsdorff, 2006).

The hypoxic zone in the Baltic Sea has increased about four times since the 1960s (Jonsson et al., 1990), and currently covers an area averaging 41 000 km^2 annually (e.g. Conley et al., 2002). Hypoxia has for that reason developed into a serve environmental problem for the Baltic Sea and its dependents. The increasing trend in hypoxia is thought to be caused by enhanced eutrophication due to excess load of waterborne and airborne nutrients (nitrogen and phosphorus) to the sea from anthropogenic sources (Wulff et al., 2007). Eutrophication has been of great concern for the countries in the Baltic region at least since the 1980s, with ministerial level commitments to reduce nutrients and improve water quality (Johansson et al., 2007).

The debate about improving the present state of the Baltic Sea through implementation of the European Water Framework Directive often refers to conditions prior to the turn of the last century (1900) as an environmental reference status, when the Baltic is suggested to have been an oligothrophic clear-water body with oxygenated deep waters (Österblom et al., 2007). However, geological records show that the Baltic Sea is a dynamic ecosystem that has undergone many environmental changes over the last c. 16 000 years (Björck, 1995; Andrén et al., 2000a,b; Berglund et al., 2005). Studies of the more recent past, for instance, reveal that hypoxia has been present in some basins for at least the last 100 years (Jonsson et al., 1990). Furthermore, analyses of long sediment cores suggest that hypoxia in the Baltic Sea has occurred intermittently in deep basins in the Baltic Proper over thousands of years (Andrén et al., 2000a,b; Sohlenius et al., 2001; Emeis et al., 2003) and that cyanobacterial blooms have occurred during the last c. 7000 years (Bianchi et al., 2000; Kunzendorf et al., 2001; Poutanen and Nikkilä, 2001). Various investigations also imply that there may be a correlation between climate variability in the past and the state of the marine environment, where warmer periods correspond to increased primary production and higher salinities resulting in amplified hypoxia and enlarged distribution of benthic mortality and laminated sediments (e.g. Thorsen et al., 1995; Fjellså and Nordberg, 1996; Andrén et al., 2000a; Bianchi et al., 2000; Nordberg et al., 2000; Emeis et al., 2003). In addition, the occurrence of hypoxia in the deeper basins today need not necessarily be attributed to human activity but could be naturally driven by oceanographic, environmental and climate forcing (Filipsson and Nordberg, 2004a,b).

In addition, both climate variability and human impact have the potential to greatly affect the environment in the semi-enclosed Baltic Sea and its catchment. However, the long-term spatial and temporal extent of hypoxia and its possible connections to these parameters are poorly known. Anthropogenic forcing in the drainage area, such as, changes in land use and population density, could indirectly have affected the marine/brackish environment already in the Late Holocene. It is known from numerous long-term studies of lake sediments in Northwest Europe that population growth and agricultural development have impacted lakes for thousands of years and that cultural eutrophication of lakes has a history longer than just decades or centuries (e.g. Fritz, 1989; Renberg et al., 2001; Bradshaw et al., 2005). Furthermore, the International Panel on Climate Change (IPCC) has recognized that hypoxia is a problem of growing concern with projected climate change (www.ipcc.ch) and recent studies predict that cyanobacteria blooms will magnify with global warming (Pearl and Huisman, 2008). It is thus essential to improve our understanding about the timing, extent and mechanism(s) causing hypoxia on millennial time-scales in order to understand the full range of the natural variability and to put forward realistic measures to improve the future environment of the Baltic Sea. It is also important to put the recent human impact in a time-perspective in order to understand the modern environmental issues.

This paper aims to review and synthesize the current knowledge in the Baltic Sea about the appearance of hypoxia in modern time (last 50 years), modern historical time (50–200 years ago) and in the geological past (last c. 10 000 years), based on previous publications. We examined a large number of papers about Baltic Sea sediments, but only present here papers which report or address hypoxia. We present a compilation of several long sediment records covering most of the Holocene (i.e. the last c. 10 000 years) and explore possible connections with the presence of past hypoxia and the role of climate and environmental variability and human impact. With the purpose to spatially and temporally reconstruct the occurrence of hypoxia our main objective is to answer three basic questions: where, when and why was the Baltic Sea hypoxic in the past?