

## ***Interactive comment on “Hypoxia and cyanobacterial blooms are not natural features of the Baltic Sea” by L. Zillén and D. J. Conley***

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Zillén and Conley (2010) examine the impacts of population density, technological development and land-use changes on the Baltic Sea ecosystem health during the past two millennia, with a special emphasis on the seafloor oxygen deficiency and cyanobacterial blooms. Their attempt is laudable and timely, inasmuch as eutrophication and associated hypoxia, as well as pollution, fishing, physical modifications and other human activities are placing increasing pressure on the Baltic Sea environment (HELCOM, 2009).

Zillén and Conley use data on laminated sediment intervals that they compiled from a number of earlier works in their previous review (Zillén et al., 2008) in order to identify time intervals of widespread oxygen deficiency in the sub-basins of the Baltic Sea. Zil-

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lén et al. (2008) concluded that seafloor hypoxia became common in the Baltic Sea deep areas at the onset of the present brackish-water phase (so-called Littorina Sea phase) at c. 8500–7800 calendar years before present (cal. BP), and that better oxygenated seafloor conditions took place at c. 7000–6000, 4000–2000 and 800–200 cal. BP. The deterioration of seafloor oxygen conditions at the transition to brackish-water setting has been documented by a number of workers (e.g. Ignatius, 1958). Also changes in the seafloor oxygenation after this transition are known to occur, but their timing is being discussed. None of the studies reviewed by Zillén et al. (2008) are specifically targeted for studying the occurrence of laminated sediments, and, perhaps therefore, sediment-core descriptions provided in those studies are not particularly sophisticated in most cases. In addition, chronologies for those sediment cores are predominantly based on the  $^{14}\text{C}$  determinations of bulk sediment that are biased by undetermined reservoir effects and redeposition of older carbon from shallower areas, which are likely to differ between the Baltic Sea sub-basins. Finally, there is a considerable scatter in the occurrence of laminated sediments in the studied cores. These problems were duly acknowledged by Zillén et al. (2008), and it would be appropriate to include a few cautionary words on the robustness of the chronology of these proposed better-oxygenated time intervals in the current review, as well. Zillén et al. (2008) may be correct with their conclusion, but the occurrence of better-oxygenated time intervals still needs to be properly investigated, documented and accurately dated. Indeed, Virtasalo et al. (2010) show that laminated sediment intervals in Gotland Deep are not as regularly laminated as generally thought, but punctuated by thin biodeformed interbeds, which implies that it is more appropriate to consider these laminites as representatives of time intervals of a higher tendency for oxygen deficiency rather than of continuous hypoxia.

In chapter 2, Zillén and Conley propose that because there is no increase in surface-water salinity during the warm Medieval Period, natural processes cannot explain the reconstructed primary-productivity increase and the accumulation of laminated sediments in the Baltic Proper during that time. They consider the contemporaneous

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anthropogenic expansion, technological development and land-use changes as more likely drivers for the enhanced productivity and consequent hypoxia. However, Zillén and Conley base their proposition on proxies that record surface-water conditions, while the most important process transporting saline water into the modern Baltic Sea is the episodic inflow of oxygen-rich dense water as near-bottom currents from the North Sea (e.g. Matthäus and Franck, 1992). Changes in the occurrence of these inflows have only indirect and substantially attenuated effects on the surface waters of the deep basins. These inflows sustain the salinity stratification of the modern Baltic Sea, which is a prerequisite for hypoxia and the accumulation of laminites. The North Atlantic climate nowadays modulates these inflows (Hänninen et al., 2000; Zorita and Laine, 2000), and the spectral analysis of sedimentary Mn-rich laminae in Gotland Deep indicates that these climatic influences may have been dominant for the past four millennia, i.e. after the glacio-isostatic adjustment in the threshold area (Kattegat) to the North Sea levelled out (Burke and Kemp, 2004). Leipe et al. (2008) argue convincingly that the sustained salinity stratification resulted in the laminite accumulation in the medieval Baltic Proper, similar to the present situation.

On the other hand; the medieval warmth must have been as favourable for primary productivity at the sea (Paerl and Huisman, 2008) as it was for the human population. The medieval warmth was likely accompanied by a precipitation increase in the northern Baltic Sea area as indicated by a recent NAO reconstruction (Trouet et al., 2009) and regional climate models (Räisänen and Alexandersson, 2003; Jylhä et al., 2004; The BACC Author Team, 2008). The consequent increase in runoff and nutrient influx can have further enhanced primary productivity, organic deposition and seafloor oxygen deficiency (Virtasalo and Kotilainen, 2008). Sedimentary microfossils (Andrén et al., 2000) and  $\delta^{13}\text{C}$  values of organic carbon (Lepland and Stevens, 1998) indicate higher primary production and organic deposition in the central Baltic Sea during the medieval times. Thus, there are at least two independent potential natural explanations for the amplified primary productivity and seafloor oxygen deficiency during the medieval times.

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In chapter 4, Zillén and Conley claim that “there are no studies that have compared fossil pigment concentrations in the Baltic with periods of hypoxia recorded in the sediments”. They seem to have forgotten the works by Kowalewska et al. (1999), Kowalewska (2001), Kowalewska and Szymczak (2001), Szymczak-Åżyła and Kowalewska (2007, 2009), at least. Those works consistently show that seafloor oxygen deficiency improves the pigment preservation in the Baltic Sea sediments. Furthermore, fossil pigments indicate amplified primary production and hypoxia during the medieval times in the studied Baltic Sea sub-basins: Gdańsk Deep, Gotland Deep and, possibly, North Central Basin (Kowalewska et al., 1999; Szymczak-Åżyła and Kowalewska, 2009).

The main conclusion of Zillén and Conley is that hypoxia and cyanobacterial blooms are not natural features of the Baltic Sea. The same conclusion was reached already by Zillén et al. (2008). This conclusion is based on two arguments: 1) the shallowing and morphological changes in the threshold area (Danish Straits) to the North Sea more or less came to an end by c. 4000 cal. BP, and resulted in reduced salinity, weaker salinity stratification and improved seafloor oxygenation in the Baltic Sea (Gustafsson and Westman, 2002); 2) there were no natural causes for hypoxia and associated cyanobacterial blooms after c. 4000 cal. BP. The latter argument is problematic because Zillén and Conley inadequately address the natural processes that have had the potential to regulate the seafloor oxygenation during those past millennia. The major contribution by Zillén and Conley is the suggestion that human activities have influenced the Baltic Sea environment over the last two millennia, which certainly is worth pondering, but still remains to be proven, preferably by original data.

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