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Interactive comment on “Consequences of artificial deepwater ventilation in the Bornholm Basin for oxygen conditions, cod reproduction and benthic biomass – a model study” by A. Stigebrandt et al.

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Received and published: 28 November 2014

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The public review process offered by Ocean Science became the determining factor when considering different scientific journals for possible publication of our manuscript. We wanted a public review process because we feared that our manuscript possibly could be treated unfairly in a closed review process. This because the topic artificial deepwater ventilation has been banned in the public debate based on non-scientific

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arguments, clearly expressed in the non-peer-reviewed personal comment by Conley (2012). Free science and scientists depend on fair review processes based on scientific arguments. Not unexpectedly, Conley concludes in his interactive Comment that he believes that the manuscript is an inadequate description of the consequences of artificial deep water ventilation with the motivation that the authors do not address many of the potentially important changes in circulation, the ecological effects, or the changes in the biogeochemical cycles of P and N. As shown below, the potentially important changes in circulation he believes will occur due to pumping are unfortunately based on his misunderstandings of how the physical circulation in the stratified basins of the Baltic Proper respond to the pumping described in our paper.

Neither the title nor the content of our manuscript suggest that we think that our manuscript describe all important aspects needed in a complete Environmental Impact Assessment (EIA) for a large-scale oxygenation system for the whole Baltic Proper. Of course, such an EIA has to deal with a large number of issues that cannot, and should not, be presented in one single paper.

Below we respond to the comments by Conley and we also present changes in our manuscript brought about by his comments. Comments by Conley are marked by C. Authors' responses, marked by A, are numbered to simplify cross-referring, and changes in manuscript are marked by M.

C: P C775: The manuscript develops a model to estimate the effect of pumping lower salinity water above the halocline deeper into the water column and to examine the effects on oxygen concentrations in deeper waters. The mixing will reduce the salinity stratification in the water column, enhancing mixing and cause increased numbers of salt water inflows into the Bornholm Basin and subsequently into the Baltic Proper.

A: #1: No, Conley has misunderstood the physics. The number of salt water inflows into the Bornholm Basin (i.e. inflows from the Arkona Basin) will not change as can be understood from the mathematical model. However, the number of inflows that

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will penetrate into the basin water, i.e. below the sill depth at 59 m, in the Bornholm Basin will increase due to the increased rate of density reduction due to pumping. The number of inflows shown in Table 2 (P 1820) refers to inflows reaching 90 m depth in Bornholm Basin. Thus, some inflows that under natural conditions would be interleaved in the lower part of the halocline may penetrate into the basin water due to increased rate of density reduction caused by the pumping.

M: To help readers of the manuscript not used to interpret mathematical models, we put in the following sentence on P 1788 L25. “ This implies that the inflow of new deepwater (and salt) to the Baltic Proper is independent of all oceanographic factors other than the sea level inside the entrance area.”

C: P C776: The paper goes on to describe the positive effects of adding oxygen on the ecosystem and calculates the increase in benthic biomass and reproductive volume for cod populations. The paper concludes that bottom sediments will no longer be anoxic and the sediments will act as a phosphorus sink.

While the model describes the effect on mixing on oxygen concentrations in the Bornholm Basin there are a number of important repercussions that greatly affect the Baltic Sea ecosystem both in terms of the circulation and the biological response that are not addressed in this manuscript.

A: #2 The statement that the Baltic Sea ecosystem is greatly affected by repercussions of the suggested pumping in the Bornholm Basin is a pure invention, probably due to the same mistake as explained in Response #1. In Section 4.5 on P 1808 we present results for changes of the salt water inflows to the Baltic Proper due to pumping in the Bornholm Basin. The volume flow increases by 2 %. The saltiest flows decrease and the inflow of oxygen increases. The flow of P with the deepwater will decrease by ca 7500 tonnes yr⁻¹ (Stigebrandt et al 2013). We do not believe that these small changes may greatly affect the Baltic Sea circulation and the biological response as proposed by Conley, see also Response #3, below.

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C: P C775-776: Some important considerations not addressed in the manuscript include: The halocline in the Bornholm Basin has varied between 55-60 m and between 65-80 m in the Baltic Proper over the last 100 years (Carstensen et al. 2014, PNAS). When the vertical salinity stratification (Pg. 1808, line 13) in the Baltic Proper is reduced by lowering the salinity gradient across the halocline, what are the chances that a large winter mixing event will break through the weakened permanent halocline? If so, what are the repercussions on circulation? How far down will mixing occur? Will the halocline be reestablished at the same depth? Or on what timescales will restratification occur?

A: #3: The depth of the halocline in the Baltic Proper is determined by a balance between supply of deepwater (by inflow of new deepwater from the Bornholm Basin) and removal of deepwater by entrainment into the surface layer in autumn and winter when the vertically well-mixed surface layer extends down to the halocline. The level of the halocline is found in a depth interval where the entrainment of deepwater into the surface water integrated over a year equals the annual supply of new deepwater. In periods when the supply of new deepwater decreases, like in the 1980s, the depth of the halocline increases because less horizontal pycnocline area is needed for the entrainment and vice versa (the horizontal area of the Baltic Proper decreases with depth). The dynamics of the halocline in Baltic Proper is discussed in e.g. Stigebrandt (2003).

Adding winter water to the deepwater (by pumping) increases the deepwater flow, in this case by 2% (P 1808), but at the same time, the density difference between deepwater and winter water decreases. The work to lift (entrain) deepwater into the surface layer during wintertime convection does not change if winter water is pumped into the deepwater because the winter water has neutral buoyancy in this context. Thus, pumping winter water into the deepwater should not change the maximum depth of the halocline at the end of the deep vertical convection season why the outcomes of winter mixing events should not be influenced by the pumping! Because of this, the questions

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raised above are not relevant for our manuscript.

C: P C776: How will destratification in the Bornholm Basin effect the Baltic Proper?

A: #4: Pumping in the Bornholm Basin will decrease the salinity span of water flowing from Bornholm Basin into Baltic Proper, see Response #2 above. The numerical experiment in Stigebrandt (1987b) shows that the top of the halocline should stay at the same depth but the stratification within the deepwater, i.e. below the halocline, should decrease in the Baltic Proper if the inflowing deepwater were homogeneous (i.e. zero span in density). It is thus likely that a decrease of the salinity span of the new deepwater, caused by pumping in the Bornholm Basin, would not change the depth of the halocline in the Baltic Proper but cause a slightly less stratified deepwater below the halocline. This also follows from the discussion in Response #3 above.

C: P C776: Probably strong Major Baltic Inflows may enter the deep Baltic proper without being significantly altered by the pumping, while less strong inflows are significantly reduced in salinity. Is there a possibility that a gap in the inflow distribution could increase the risk of long stagnation periods in the deepwater of the Baltic proper?

A: #5: It is the other way around; the salinity distribution becomes narrower due to pumping. This is addressed on P 1808 L10-13. Thus, less strong inflows will pass the Bornholm Basin in the halocline, largely unaffected by the pumping. It is the saltiest parts of stronger inflows that are trapped in the Bornholm Basin where they become diluted with winter water by pumping. The suggested pumping rate will decrease the salinity below the sill level twice as fast as in the natural state as described by Stigebrandt and Kalén (2013). The span in salinity of deepwater leaving the Bornholm Basin will therefore decrease due to pumping and consequences of this in the Baltic Proper are discussed in Response #2 and #4 above.

C: P C776 – C777: Our current understanding regarding the area of hypoxia in the Baltic Sea is that variations in the total amount of salt water brought into the Baltic has a significant effect on hypoxic area. During the 1980s when salinity decreased, the area

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of hypoxia was reduced due to less vertical stability in the water column. When more salt water entered the Baltic Sea in the 1990s the halocline depth shoaled with reduced vertical mixing and more hypoxia was observed (Conley et al. 2002; Carstensen et al. 2014). Both experimental (Byfjorden) results and the model presented here states that pumping leads to increased number of inflow events. What is the effect on the increased salt water inflows on oxygen concentrations in the Baltic Proper? What is the effect on the long-term salinity structure and the salinity content of the Baltic Proper?

A: #6: As explained in Response #1 above, the inflow of new deepwater (and salt) to the Bornholm Sea from the entrance area is not influenced by changes in the vertical stratification in the Bornholm Sea due to pumping, which should be clear from the inflow model developed and used in the present paper. However, as explained on P 1808 and in Response #4 and #5 above, the pumping will decrease the highest salinities of the inflow the Baltic Proper from the Bornholm Basin. The long-term salinity content in the Baltic Proper will not change although the vertical salinity stratification of the deepest part of the Baltic Proper will decrease slightly as explained in Response #4.

C: P C777: Although the model might describe conditions in Bornholm Basin, what is of critical importance is what are the effects on the Baltic Proper? If the physical circulation is modified with reduced vertical stratification, e.g. more deep water mixing, changes in the depth of the halocline, or changes in inflows, what will the effects be on biological populations? If the permanent halocline changes its depth, what will the effect be on phytoplankton, zooplankton and larvae?

A: #7: As already explained above, the depth of the halocline in the Baltic Proper and the number of inflows to the Baltic Proper will not change due to pumping in the Bornholm Basin why the questions are not relevant in the context of the present paper.

C: P C777: The section of the manuscript on increases in benthic biomass is essentially the same calculations that have been made in a previous paper (Karlsson et al. 2010), e.g. if oxygen returned than X amount of benthic biomass would happen (Pg. 1809,

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lines 3-11). There is nothing new here. However, there is a calculation of the effect if *Marenzelleria*, an invasive species, was able to penetrate into the deep waters of the Bornholm Basin at the same magnitude that they have colonized the shallow waters. There is no evidence to suggest that the shallow, coastal *Marenzelleria* species will colonize the deeper waters of the Baltic once oxygen returns. In addition, the following discussion of increases in bioturbation with the possibility of increases in *Marenzelleria* (Section 4.7) is irrelevant unless there is evidence that *Marenzelleria* could colonize the deeper waters.

A: #8: Conley suggests that the calculation of "missing biomass" in the Bornholm Basin (Pg 1809) is from Karlson et al. (2010) the correct year is 2002. This is right, and in that paper we described how the "missing biomass" was calculated. That figure is still valid.

Conley suggests that there is no evidence that *Marenzelleria* could colonize deeper waters of the Bornholm Basin. *Marenzelleria* has a wide distribution in the Baltic and is found in the deep parts of the Bothnian Bay. In the HELCOM Baltic Sea Environment Fact Sheet (2012), the authors Michalec and Werner state that *Marenzelleria* has established in the entire Baltic Sea.

C: P C777: Currently, a large proportion of denitrification in the Baltic Sea occurs in the oxycline (Dalsgaard et al. 2014), as in oceanic oxygen minimum zones. Will total denitrification be reduced in the Baltic Sea when there is not a strong oxycline? The Baltic Sea is currently limited by the availability of nitrogen. What happens to the system when the amount of nitrate increases?

A: #9: Oxygenation of the deepwater in Bornholm Basin will decrease the internal phosphorus load by about 7500 tonnes/year as estimated in Stigebrandt et al. (2013). This will lead to less supply of nitrogen by cyanobacteria in the Baltic Proper. A complete nitrogen budget for the Bornholm Sea is outside the scope of the present paper but should be estimated in future as part of a complete EIA.

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C: P C777: Or what happens when high nutrient concentration in the water below the halocline are mixed upwards into the surface layer?

A: #10: When the top layer of the bottom sediment has been oxidized, there will be much less phosphorus in the deepwater and possibly also less nitrogen like in the By Fjord experiment where the decrease in ammonia content was greater than the increase in nitrate. These changes were due to both less leakage of phosphorus from the bottom sediments when these became oxidized (after about one year of exposure to oxic water) and to more frequent water exchange. The nutrients of the deepwater of the Bornholm Sea are contained in the quite salty (dense) deepwater below the halocline and will therefore be transported to the Baltic Proper during water exchanges and thus not enter the surface layer in the Bornholm Basin. The phosphorus loading of the Baltic Proper thus decreases by 7500 tonnes/year when the deepwater in the Bornholm Basin is kept oxygenized. This reduction is about 15 times larger than the Swedish reduction assignment for phosphorus. The export of nitrogen has not been estimated yet, it is the subject for a future part of an EIA.

C: P C778: Will the sediments actually become oxic? We have built up large stores of organic matter in sediments with the organic carbon concentrations 3-5 times higher today than in the 1950s (Emis et al. 2000). Will oxygen in the water column be able to oxidize the sediment in the face of this large respiratory burden? Will the sediments be sufficiently oxygenated to overcome the respiratory burden to increase P burial and or increase the importance of the sediments in denitrification?

A: #11: The sediments in the Byfjord, which were anoxic for centuries, were colonized by benthic animals soon after the deep water was reoxygenated (Stigebrandt et al., 2014). Similarly, the organically enriched bottoms in the inner part of the Gullmarsfjord (west Sweden) were colonized shortly after reoxygenation, and the succession of the benthic communities were scientifically described (e.g. Rosenberg in Oikos 1976, vol. 27: 414-427). The variations between oxic and anoxic states that have occurred in the Bornholm Basin since the 1960s show that phosphorus leakage from sediments

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is stopped when the sediments become oxidized (Stigebrandt et al. 2013). Again, nitrogen is outside the scope of the present paper.

C: P C778: Overall, I believe the manuscript is an inadequate description of the consequences of artificial deep water ventilation. The authors do not address many of the potentially important changes in circulation, the ecological effects, or the changes in the biogeochemical cycles of P and N.

A: #12: We claim that the consequences of artificial deepwater ventilation described in our manuscript are both important and adequate. As shown above, Conley has severely misunderstood how the circulation of the Baltic proper functions and many of the questions related to the changes expected by him are based on his misunderstanding of physical circulation. As pointed out above, our paper is not meant to be a complete EIA for a system for oxygenation of the whole Baltic Proper. Of course, many additional investigations have to be done before a complete EIA can be presented. C: Pg. 1784, Line 2. The Bornholm Basin is not an isolated basin.

A: #13: We claim that the basin water, below the sill level, is isolated. It has closed depth contours and the water is vertically density stratified which means that it is isolated. Hydrographical observations show that the basin water is isolated for up to several years' long periods.

C: Pg. 1806, Line 14. It would be easy to ... it depends upon what your definition of easy is.

A: #14: Yes, easy compared to building a system for the much larger Bornholm Basin. Once this larger system has been built, the experience gained during the construction work would greatly facilitate further construction of similar systems, and, since the Arkona Basin is much smaller, the pumping system in this basin would also be smaller.

C: Pg. 1807-1808, Lines 27-2. It is not clear from the text the origin of the diverging opinions of Gustafsson et al. (2008) and this manuscript and why contrasting results

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were obtained with pumping.

A: #15: The origin should be clear because it is stated in the manuscript that Gustafsson et al. (2008) reached their conclusion without explicitly modeling pumping in the Bornholm Basin, the only basin with successful recruitment during the last decades.

C: Pg. 1813, Lines 5-10. All of the problems with cod in this manuscript are attributed to changes in the reproductive volume. While I agree that is a very important parameter, there is no recognition of the effects of overfishing on fish populations. What are the expected effects with the large reductions in fishing pressure with passage of the Common Fisheries Policy (CFP) in Europe? At what level will cod populations recover and how do these compare to changes in reproductive volume? In addition, trophic interactions between cod, herring and sprat believed to be important factors affecting cod reproduction (Cassini et al. 2009, PNAS). What is the relative effect of trophic interactions as compared to reproductive volume?

A: #16: It is not true that we attribute all of the problems listed above to changes of the reproductive volume. However, we focus on an increase in reproductive volume as one way of mitigating the recovery of the cod stock, despite the problems with overfishing. The other mentioned problems are certainly important but they do not influence the reproductive volume of cod, the factor that we investigate. It is hard to see why we then should discuss them in the present paper.

List of references not listed in the manuscript.

Conley, D.J., 2012: Save the Baltic Sea, *Nature*, 486: 463-464.

Stigebrandt, A., 2003: Regulation of vertical stratification, length of stagnation periods and oxygen conditions in the deeper deepwater of the Baltic proper. *Meereswissenschaftliche Berichte*, 54, 69-80.

Interactive comment on *Ocean Sci. Discuss.*, 11, 1783, 2014.

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