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Interactive comment on "Restoration of the Baltic Proper by decadal oxygenation of the deepwater" *by* Anders Stigebrandt

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The author wants to thank Referee #2 for a detailed review with many questions about the validity of the model. This has led to several improvements of argumentation and presentation.

Ref #2, p1, l9 – p2, l1. Unfortunately, however, the paper lacks detailed justification of the assumptions in the model, does not discuss the weaknesses of the model and many statements are made without the inclusion of any references. Furthermore, a direct comparison is made to previous periods of hypoxia but the differences between those periods and the modern period of hypoxia are not discussed. A major assumption is that sediments overlain by oxic bottom waters do not act as an internal source of P. This is not so as is also well known from lake studies. Finally, the transient aspects of

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the processes in the Baltic Sea are not included in the model and the consequences of this are not discussed. I recommend major revision of the manuscript and an inclusion of a discussion of all of these aspects.

Author: Application of a transient mass balance model for P on the Baltic Proper and data on P release from sediments in the Bornholm Basin presented in Stigebrandt et al. (2014) strongly support the hypothesis that oxygen controls the P release from sediments in the Baltic Proper. In situ observations of benthic fluxes reported by Viktorsson et al. (2013) support the model study. Further support was given by Stigebrandt et al. (2014) who presented (their Fig. 3) a striking correlation between the area of anoxic bottoms and the P content in the water mass below 60 m depth in the Baltic Proper. Conley et al. (2002) showed a similar correlation and estimated fluxes from an internal source and Gustafsson and Stigebrandt (2007) estimated the release of P as single doses when bottoms become anoxic. From the extensive evidence presented here, there is no doubt about the oxygen control of P release from sediments in the Baltic proper in its present state. This was not clearly pointed out in the manuscript but will be so, see below. It is clear that the oxygen control of P release from sediments is quite different in different kinds of lakes. Other factors than oxygen may be of greater importance. According to Hupfer and Lewandowski (2008) more than half of North American lakes exhibited an extremely low level of P release from sediment even after the onset of anoxia in the hypolimnion despite their variability in water chemistry, trophic states and geographical locations. These authors also mention additional cases of none or delayed P release under anoxic conditions. An important component of the review of Re #2 rests on an assumed similarity between sedimentary P dynamics in the Baltic Sea and lakes. However, nobody has shown that experience from lakes is valid for the Baltic Proper. Due to several crucial differences like salt in the water, and permanent salinity stratification that is not broken down during autumn/winter, and marine instead of limnic ecology one may expect that different P burial processes are important in the Baltic Sea and in freshwater lakes, why comparisons with freshwater lakes might be inappropriate. Manuscript changes: p.2, l. 16. The following text will be inserted. “Ap-

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plication of a transient mass balance model for P on the Baltic Proper and data on P release from sediments in the Bornholm Basin presented in Stigebrandt et al. (2014) strongly support the hypothesis that oxygen controls the P release from sediments in the Baltic Proper. In situ observations of benthic fluxes reported by Viktorsson et al. (2013) support the model study. Further support was given by Stigebrandt et al. (2014) who showed (their Fig. 3) a striking correlation between the area of anoxic bottoms and the P content in the water mass below 60 m depth in the Baltic Proper. Conley et al. (2002) showed a similar correlation and estimated fluxes from the internal source and Gustafsson and Stigebrandt (2007) estimated the release of P as single doses when bottoms become anoxic. From the evidence presented here there should be no doubt about the oxygen control of P release from sediments in the Baltic proper in its present state." p.9, l.18: the following reference will be inserted: "Conley, D.J., Humborg, C., Rahm, L, Savchuk, O.P., and Wulff, F., Hypoxia in the Baltic Sea and basin-scale changes in phosphorus biogeochemistry. Environmental Science and Technology 36: 5315 – 5320. DOI: 10.1021/Es025763w, 2002." p.9, l.23: the following reference will be inserted: " Gustafsson, B.G. and Stigebrandt, A.: Dynamics of nutrients and oxygen/hydrogen sulfide in the Baltic Sea deep water. Journal of Geophysical Research – Biogeosciences 112: G02023. DOI: 10.1029/2006jg000304, 2007." p.9, l.23: the following reference will be inserted: "Hupfer, M., and Lewandowski, J.: Oxygen controls the phosphorus release from lake sediments – a long-lasting paradigm in limnology. Internat. Rev. Hydrobiol., 93: 415-432, 2008." p.9, l. 21: the following reference will be inserted: "Viktorsson, L., Ekeroth, N., Nilsson, M., Kononets, M, and Hall, P.O.J.: Phosphorus recycling in sediments of the central Baltic Sea. Biogeosciences 10: 3901-3916. DOI: 10.5194/bg-10-3901-2013, 2013" Detailed comments. Re #2:1. p2. Lines 1-5. There are no references in this paragraph. Relevant references should be added (e.g. Conley et al., 2002 ES&T for the internal P source).

Author: I agree. Two references will be added.

Manuscript changes: p.2, l.2 the following text is added after "increases": "(Conley et al., 2002; Stigebrandt et al., 2014)".

Re #2:2. p2. Lines 30-34. The Carstensen et al. (2014; PNAS) study shows that enhanced respiration, which is linked to the increased external supply of P, played a key role in the expansion of the hypoxia since 1950. The text here could be modified to make this clearer.

Author: Text modified, see below.

Manuscript changes: P. 2, l. 32. The following text is inserted between "increased" and "external": "respiration linked to increased". Insert "(Carstensen et al. 2014)" the end of this sentence.

Re #2: 3. P3. Lines 11-16 and further. Here, a steady state model is used whereas the Baltic Sea is in a transient state and the magnitude of the internal P source is a complex function of a large number of factors besides bottom water oxygen, including the previous depositional history of the sediment, the presence of macrofauna, the Fe-chemistry etc. That bottom water oxygenation does not shut-off P fluxes from the sediment as suggested here is well demonstrated in many lake studies (e.g. see for example the work of Katsev and Dittrich, 2013; Ecological Modeling) and also explains why high phosphate fluxes from the sediment to the overlying water are observed in many continental margin systems (see references in Ruttenberg (2003; Treatise of Geochemistry; Elsevier).

Author: Re #2 is wrong about steady state. It should be very clear both from the text on p. 4, l. 3 and the left hand side of Equation (1) that the model is time-dependent when used to estimate the internal source, see also the application of the model in Stigebrandt et al. (2014). I think that it is irrelevant to refer to lake studies unless the studies concern lakes that are similar to the Baltic proper, e.g. they must have a clear oxygen control on P sediment fluxes like the Baltic proper. The influence of macrofauna was discussed in Stigebrandt et al. (2015b). There is an apparent flux from sediments even under oxic conditions as shown for the Bornholm Basin by Stigebrandt et al.

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(2014).But this flux is likely connected to decomposition of fresh organic matter and not part of the internal source.

Manuscript changes: p. 3, l. 12, “time-dependent” is inserted for clarity. The following text will be added at the end of p.6 (just before chapter 4. “It is often argued that bottom water oxygenation does not shut off P fluxes from sediments because this has been seen in many lake studies. However, nobody has proven that experience from lakes is valid for the Baltic Proper. Due to several crucial differences like salt in the water, and permanent salinity stratification that is not broken down during autumn/winter, and marine instead of limnic ecology one may expect that important P burial processes might be different in the Baltic Sea and in freshwater lakes why comparisons with freshwater lakes might be considered inappropriate until the opposite has been proven.” Manuscript change. The change in response to the interactive comment by Andreas Bryhn is also relevant as an answer to the present comment by Re #2. The two sentences on p.8, l. 2 – l.4, are rewritten as follows: ”Keeping the deepwater oxygenated will permit colonization of the deep bottoms of the basin which will increase the food supply to e.g. cod. It will also stop leakage of phosphorus from the earlier periodically anoxic bottoms as discussed above.” After this the following text is added. “ An important task for the EIA is to investigate if increasing leakage of P from sediments may be a long-term effect like it has turned out to be in some artificially oxygenated lakes (Hupfer and Lewandowski, 2008; Katsev and Dittrich, 2013). However, it should be stressed that nobody has shown that lake experience of P leakage is applicable to marine environments with deepwater salinity >10 as in e.g. the Baltic proper.”

Re #2: 4. P4. 16-18. The immediate impact of reoxygenation (time scale of 1-2 years) can be very different from the long-term impact (>2 years to decades) because of recolonization of the sediment by fauna, saturation of the sediment Fe-oxides with P etc. This is relevant when discussing the data for the Bornholm basin and By fjord. Can the author indicate how representative the present-day Bornholm basin is for the Baltic Sea? Is the Bornholm basin recolonized by macrofauna during periods of oxic conditions that are used as a reference here? Can more detailed information on By Fjord be given? How was the P sequestered in these sediments? Was the lack of P released sustained over a period of multiple years to a decade?

Author: Long-term effects regarding the internal source were discussed for the Bornholm Basin in Stigebrandt et al. (2014). It was estimated that the total loss estimated from hydrographic observations in the basin since the 1960s should have used about 20 % of the P stored in the upper 20 cm of the sediment. It was also found that the P supply to the bottom water during oxic conditions was greater than the P supply by decomposition of fresh organic matter as estimated from oxygen consumption. However, it was concluded that the estimates for oxic periods were not sharp enough to exclude contributions from fluxes from anoxic sediments. Effects of recolonization of bottom sediments by fauna in the Bornholm Basin were discussed in Stigebrandt et al. (2015b) who also referred to other published studies in the Baltic proper. It is believed that the Bornholm Basin is representative for the Baltic proper with respect to oxygen control of P release from sediments. Re #2 is right that we do not know answers to all questions regarding long-term effects of oxygenation on P fluxes why this should be an area of continued research.

The long-term impact of oxygenation has not been studied in the By Fjord that cannot be restored in the same way as the Baltic proper. This is because anoxia in the deepwater of the By Fjord is not due to local production driven by internal P load. Anoxia in the deepwater is mainly due to large import of organic matter over the entrance sill in combination with very weak vertical mixing and large long-term components in the variability of density in the coastal water leading to very long residence time for the deepwater. As expected, a few years after the termination of the oxygenation of the deepwater, the By Fjord had returned to a state similar to that it had when the oxygenation started. No study of P in the sediment was undertaken in the By Fjord. A lot of efforts were spent to in situ observations of benthic fluxes using benthic lander chambers; see Stigebrandt et al. (2015a) but the time series were ended shortly after the end of the pumping.

Manuscript changes: p.4, l. 22, the following sentence is added. “Long-term effects of oxygenation on P fluxes have not been studied, e.g. effects of fauna, but were discussed by Stigebrandt et al. (2015b).”

Re #2: 5. P6. Lines 1-2. See earlier comment above. There is no evidence that sustained oxygenation will shut off the internal source of P from the sediment completely.

Author: As discussed earlier, the observations from Bornholm Basin show that there is a flux even during oxic conditions but most, if not all, of this flux is due to decomposition of fresh organic matter.

Manuscript changes: The text added to p. 8 in response to the detailed comment no. 3 covers this aspect.

Re #2: 6. P6. Lines 4. There is no evidence that the internal source will vanish, see above.

Author: I think there is, see the new paragraph above that will be included on p. 2, l.16

Manuscript changes: None.

Re #2: 7. P6. Line 11. The oxygen debt in the sediment (organic carbon, iron-sulfides) is very large. How would the results of the calculations change if this were included?

Author: Oxygen debts in the water mass and in the sediment influence the time it takes to stop the internal P source and of course, the amount of O2 needed to restore. Substances in the sediment that were oxidized during and after water renewal and reduced when the water run out of oxygen were included in the model by Stigebrandt et al. (2015b). The existence of these substances was clearly seen in the results as discussed in that paper. They delay the arrival of anoxia during stagnation and consume some of the oxygen brought in during water renewal. These substances modify but do not change the nature of the response to oxygenation.

Manuscript changes: p.7, l. 11. The following sentence is inserted: “This debt plus a debt due to reduced substances in the sediment were included in the model for the Bornholm Basin by Stigebrandt (2015b). It was found that the sediment debt slightly modified the response to oxygenation.”

Re #2: 8. P6. Line 32. The conditions during the two previous hypoxic periods were very different: there was much less phosphate in the system and, during the hypoxic intervals of the HTM, the salinity was much higher. The author should consider these differences in the discussion in this section.

Author: A comment on this will be included in the manuscript, see below.

Manuscript changes: p. 8, l. 33, add the following text: “The similarity between the Baltic Sea of today and during the anoxic period occurring under the Medieval Climate Anomaly should be quite large but the similarity is less for earlier anoxic periods due to topographic differences caused by sea level changes and relative land rise, c.f. Jilbert et al. (2015). p.9, l.26, add reference: “Jilbert, T., Conley, D.J., Gustafsson, B.G., Funkey, C.P., and Slomp, C.P.: Glacio-isostatic control on hypoxia in a high-latitude shelf basin. Geology. Doi: 10.1130/G36454.1 2015.

Re #2: 9. P7. Lines 2-4. Given the uncertainties, is it really possible to conclude that this restoration can be achieved in 10 years? The model is simple and does not account for the transient state the Baltic Sea is in and the release of P that occurs from sediments below oxic bottom waters, so is this truly justified? The oxygen debt in the sediment is also not included in the calculations (see comment above).

Author: The model is not as simple as described by Re #2. As told before the model is transient and the internal source has been estimated using the transient model. Actually, oxygen debts will prolong the restoration time and they influence the amount of oxygen needed to perform the restoration. A qualified estimate is that the present debts, given on p. 7, l. 15, are of the same magnitude as the oxygen supply during one year that has been discussed for a restoration system. The debts can therefore be estimated to prolong the restoration by one year.

Manuscript changes: No

Re #2: 10. P8. Lines 2-3. See earlier comment. There is no evidence that sediment release of P will stop under oxic conditions.

Author: I think there is strong evidence as described in the new text that will be inserted on p3, l. 16 (see above).

Manuscript changes: No

Re #2: 11. P8. Lines 8-10. No evidence is shown that the trophic state will change from eutrophic to oligotrophic.

Author: This is a model result described in the beginning of Chapter 3 "Model results and discussion", see also Fig. 3. Restoration means that the internal source (about 100 000 tonnes P yr-1) is stopped so that the total P supply decreases from 140 000 to 40 000. The model predicts that the tot P winter surface concentration will decrease from the present concentration of about 1 to a much smaller value in the interval 0.2 – 0.3 (mmol m-3) which I believe means a change from eutrophic to oligotrophic.

Manuscript changes: No.

Re #2:12. P8. Lines 28-29. See earlier comment. The modern Baltic Sea contains much more P than it did during past periods of hypoxia. There were also important other differences, such as the difference in salinity during the hypoxic interval of the HTM. They can thus not be compared directly in this manner.

Author: The text added to the manuscript as a result of the detailed comment no. 8 covers this case also. Manuscript changes: No.

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