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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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os-2016-17 Authors response to Interactive comment from Anonymous Referee #1 on "Restoration of the Baltic Proper by decadal oxygenation of the deepwater" by Anders Stigebrandt. By A. Stigebrandt The author wants to thank Referee #1 for a detailed review which has led to several improvements of the presentation. Ref #1, p.1, l.9/14. .. A perhaps novel aspect is the hypothesis that because of positive feedbacks the artificial oxygenation could be terminated after several years without destabilizing the restoration of oxygen and phosphorus to less eutrophic conditions. Still, all quantitative arguments rely on numbers that are just thrown in by the authors, often without reference, justification or error bars/uncertainty estimates. ..

Author: In the introductory section the referee says that the possibility to terminate oxy-

genation after several years without destabilizing the restoration of oxygen and phosphorus to less eutrophic conditions might be a novel aspect of the paper. To the best of my knowledge, it is a novel aspect. Another novel aspect is the coupling of sustained oxygenation of the deep bottoms, due to occasional disappearance of the deepwater, and the rapid termination of anoxic periods as shown in sequences of sediment records. The referee also thinks that numbers in the model is just thrown in. In the revised version of my manuscript I attempt to be more pedagogic and tell how numbers are derived as described below. Ref #1, C2, l.2 – l.6: The manuscript begins with the statement that the "vertical circulation" transports P from the deep to the surface waters. This is needed for the positive feedback on production, export etc. However, vertical circulation would also transport oxygen to depth, thereby acting as a negative feed-back loop, which is not mentioned in the manuscript at all. Author: The situation described by Re #1 is valid for lakes. But the Baltic proper is also salt stratified. Usually, there is a halocline at about 60 m depth (although it sank to 100 m depth during an unusual episode in the 1980s as mentioned in the paper). The halocline rises due to inflow of new deepwater. However, on an annual basis, this is counteracted by erosion during periods of vertical convection in the surface layer in autumn and winter. Thus halocline water is transported to the surface layer by entrainment which basically is a one-way process, why oxygen from the surface layer is not transported to the deep layer by this process. In salt stratified systems, there are thus different agencies for transports of P and O2. Actually, O2 is transported to the deepwater mainly with incoming new deepwater from the entrance area (Kattegat and the Belt Sea). There is thus no negative feedback loop of the type imagined by Ref #1 as long as there is a halocline (pycnocline) separating the upper and lower layers. Manuscript changes: On p.2, l.2. To avoid misunderstanding the sentence is changed as follows. "Vertical convection in autumn and winter transports dissolved P from the deepwater to the surface layer by entrainment." Then I add the following sentence on p.2, l.5. "It should be noted that the entrainment process gives rise to one-way transports, meaning that it does not transport e.g. oxygen from the surface layer to the deepwater, which if it happened,

would counteract the positive feedback loop". Ref #1, p2, l.6 – l.10: Later it is even said that the deep box is assumed well-mixed for P but stratified for O2. Again, this implies different transport agencies for P and O2, which is not correct (and, I believe, not necessary for the main argument). The treatment of P and O2 transport in the argumentation and story line must be perfectly consistent. This needs careful attention in the revision. Author: I regret an unfortunate formulation in the manuscript that may support the interpretation made by Ref #1. The text is revised as described below. Manuscript changes: p.3, l.30 – p.4, l.1. The two sentences are replaced by the following text. "The time-dependent phosphorus model is a mass balance model that only considers sources and sinks, that all can be represented by fluxes through the external boundaries of the water mass, and storage changes in the water mass. The internal dynamics that regulate the exchange between the layers are thus not invoked in the P model." Ref #1: The terminology is not always precise. E.g. what do restoration (e.g. title) or recovery (e.g. p. 2 l. 13 mean? Author: From p.2, l.6 – l.7 in the manuscript it should be clear that restoration means that anoxic episodes are replaced by oxygenated episodes. Manuscript change: p.2, l.6, add at the end of the sentence, "due to anoxia" ; p.2, l. 13: "recovery" is replaced by "restoration". Ref #1: p.3, l.6 & 22/23: Line 3 speaks of water column, line 23 of surface concentrations. This is not the same and thus contradictory to "as already mentioned" in line 22. Author: This apparent contradictory is solved by a change in the manuscript, see below. Manuscript change: p.3, l.6. Text changed to "the winter phosphorus content in the water column, both in the 60 m deep surface layer and in the deepwater, of the Baltic proper" . . . Ref #1: p.3, l.24 This does NOT show that the model lacks a source. It could also mean that the model overestimates some sink(s). Author: Re #1 is correct. This possibility was discussed on p. 35-36 in Stigebrandt et al. (2014). Manuscript change: p. 3, l. 25. The following sentence is added. "The inverse relationship between external supply and winter surface concentration may also be explained as an effect of a decreasing P sink as discussed in Stigebrandt et al. (2014)." Ref #1: p.4, l.2: What is the conceptual two-layer model? Does this include stratification of the deep layer? Author: The conceptual two-

layer model is described in Fig. 2 and the accompanying legend. A halocline separates the upper and the deep layers. This is important because it strongly hampers oxygen supply from above to the lower layer. Manuscript change: p.4, l.2: Insert "c.f. Fig. 2," after "model". Ref #1: p.4, eq. 1, eq 2: explain the different Q's. Int sin k should probable read #Intsink" all in italics. Author: The Q's and all other variables in eq. 1 and eq. 2 are defined in the legend to Fig. 2 on p.12 but that is unfortunately not mentioned in the text in connection with eq.1.Yes, Int sin k should be Intsink, but the equation editor did not allow me to write it correctly. The equation editor apparently believes that sin is the sinus function. Manuscript change: The following line is added to the sentence that ends on p.4, l.9 "Qf is the rate of freshwater supply, Q1the rate of inflow of new deepwater from Kattegat and Qe the flow rate of surface water that is entrained into the inflowing new deepwater, c.f. Fig. 2". I will change Int sin k to Intsink . Ref #1: p.5, l.12 – l.13: Where do the estimates for Extsource and Intsource come from? How well are they constrained? What methods have been used? What are the error bars? Author: As told on p. 5, l.11/12 the figures for Extsource and Intsource are adapted from Stigebrandt et al. (2014) where it is told that data for Extsource is obtained from Gustafsson et al. (2012) which is in the reference list in the manuscript (p.9, l.19/21). There is an immense collective (Helcom, other institutions) work behind the figures in Gustafsson et al. 2012 that is based on long time series of observational data and supporting modeling. This work is the most trusted estimate of the external supply that exists today. Intsource was derived by Stigebrandt et al. (2014) using the extended P model. The data input to the model is Extsource for 1980 and 2005 (from Gustafsson et al. 2012). Furthermore data for the storage change is taken from Fig. 2 in Stigebrandt et al. (2014) which is based on time series of hydrographical observations in several basins of the Baltic Proper. The P model also uses an estimate of phosphorus import with new deepwater. This is also discussed in Stigebrandt et al. (2014). Within the frame of the model used, the error in Intsource should not be very large since the errors in Extsoutce and storage changes are quite small and the estimated import from Kattegat is similar to other estimates as discussed in Stigebrandt et al. (2014). Manuscript

change: p.5, l.11/12: replace the last part of the sentence (from, is determined) with "will be derived here." P.5, l.13: Insert the following sentence: "These numbers are adopted from Stigebrandt et al. (2014) where data sources are described. Within the frame of the model used, the error in Intsource should not be very large since the errors in Extsoutce and storage changes are quite small and the estimated import from Kattegat is similar to other estimates as discussed in Stigebrandt et al. (2014)." Ref #1: p.6, l.4/5: "total P" would be a concentration (perhaps times volume), but the text uses rates. ??? And why now 25 000 – 40 000 tonnes/yr and not 60 000 as used one page above? Author: Sorry, the word "supply" is missing at the end of line 4. Thus "total P" should be "total P supply" which is a rate. The external supply was 60 000 tonnes/yr in 1980. In 2005 it was 35 000 (Gustafsson et al. 2012). The total P supply minus the internal source was 46 000 in 2005 (which includes the Kattegat source). However, the external source has continued to decrease and is at present probably less than 30 000 tonnes/yr. Should the reduction of the external source decrease until restoration is completed, which at the earliest should be 15 years from now, the external supply should certainly have decreased further to maybe 20 000 tonnes/yr. The lower range used for future external supply equals 14 000 tonnes/yr which is maybe unattainable. However, this is not important here. Manuscript change: p. 6, l.4: "total P" is changed to "total P supply". The following sentence is added on P3, l5:"Based on Gustafsson et al. (2012), Stigebrandt et al. (2014) used an external supply of 60 000 and 35 000 tonnes/yr in 1980 and 2005, respectively.". The following sentence is added on p.6, l5:"This includes the contribution from Kattegat, see above." Ref #1: p.7, l. 15: "Where do the numbers come from? What do they mean? Would this the O2 that is required to make the entire deep box of the model oxic? Or does this assume some boundary layer (which would be inconsistent with the P model part). Author: The figures are computed as follows. The amounts of H2S and NH4 in anoxic water in the autumn 2013 were computed from hydrographical data (i.e. in the water column) from several hydrographical stations in the Baltic proper and using the hypsographic volume information from the different basins. The amount of O2 needed to oxidize all H2S and NH4 in the

anoxic water were computed and presented on p.7, l.12. Stigebrandt and Gustafsson (2007) estimated that the rate of O2 supply needed to keep the (already oxygenated) Baltic proper deepwater oxic is about 3Åů109 kg yr-1). This figure was supported by the estimate in Stigebrandt et al. (2015b) who made a model study of oxygenation of the Bornholm Basin by pumping down oxygen saturated so-called winter water. The exact need of oxygen supply during a restoration operation remains to be estimated. Manuscript changes: p.7, l.6, add the following part to the sentence: "They estimated that a flux of 3Åů109 kg yr-1 would be needed to keep the deepwater oxygenated and" . . . P.7, l.11, add the following sentences: "A model pumping experiment by Stigebrandt et al. (2015) showed that the Bornholm Basin can be kept well oxygenated by pumping 1000 m3 s-1 of well oxygenated winter water into the deepwater. The exact oxygen need of a complete restoration of the Baltic proper remains to be estimated." p. 7, l.15, add the following after the word hydrographical: "and hypsographic" p.7, l.16, change (c.f. Fig. 1) to "c.f. Fig. 1 that shows the volume of anoxic water"