Manuscript “Global climate change and the Baltic Sea ecosystem: direct and indirect effects on species, communities and ecosystem functioning”
by Markku Viitasalo and Erik Bonsdorff, submitted to Earth System Dynamics.

Author comments for reviewer no. 2 (esd-2021-73-RC2-supplement.pdf).

All author replies to reviewer comments in red font.

Anonymous reviewer #2

General comments

The review provides a valuable overview of past decades scientific studies with relation to climate change projection and the Baltic Sea.

I miss data synthesis in terms of figures and statistical tests on cross-experimental and cross-ecosystem data, proving significance of made conclusions.

More attempts to weight the importance of different factors would make some scenarios to be presented as more likely than others. Several sections is now a list of different outcomes with seemingly similar probability to occur.

A more critical view on the ability to prove climate effects would enhance the scientific value of the manuscript. The same is true for lack of understanding of adaptive and evolutionary processes for the outcome of projected climate change.

We find these comments valid and agree that more analysis of the published results will improve the value of the manuscript. We have made a serious attempt for a data synthesis and evaluation of the attribution of the found effects to climate change in light of the evidence published since 2010 (see replies to Detailed comments, below).

Detailed comments

r. 20 Effects of climate would explicitly require statistically significant changes attributed to climate factors. Since this type of data are scarce, scientific “evidence on effect of climate“ is unlikely to be found. I suggest a rephrasing.

A valid point. New text: “Studies investigating species-, population- and ecosystem-level effects of abiotic factors that may change due to global climate change, such as temperature, salinity, oxygen, pH, nutrient levels, and the more indirect biogeochemical and food web processes, are reviewed, primarily from published literature after 2010.”

r. 22 Please specify “responses” of what effectors? By which type of species?

Edited text: “The responses to the studied abiotic factors vary within and between taxonomic groups, (microbes, phytoplankton, zooplankton, benthic algae and vascular plants, macrozoobenthos and fish), species, and even between sibling species (as is the case with the brown alga *Fucus vesiculosus*).”

r. 25 “will improve “ is ambiguous. Increase or decrease cyanobacterial blooms? Reduced blooms would be an improvement.

Edited text: “It is likely that the combined effects of increased external nutrient loads, stratification and internal loading will favour formation of cyanobacterial blooms in large parts of the Baltic.”

r.26 The impact of allochthonous carbon is primarily influenced by the specific loading of organic matter. Not the latitude.

Edited text: ”In areas strongly influenced by allochtonous DOM, such as the northern parts of the Gulf of Bothnia, increasing freshwater runoff may further complicate the process by increasing heterotrophy and by decreasing food web efficiency.”

r. 29 Influence of organic matter is primarily hampering photosynthetic production. That cannot be counteracted by the proposed food chain. Please remove or adhere hypothesis better to current knowledge.

Yes, the text was not clear. We edit the text in abstract and in the respective chapter, “Complex food web responses in the microbial loop.”

New text (in Abstract): Warming of seawater in spring also speeds up zooplankton production and shortens the time lag between phytoplankton and zooplankton peaks, which may lead to zooplankton controlling phytoplankton and reduced phytoplankton biomass in spring.

r. 44 To uncertainties the adaptation and even evolution of organisms in most trophic levels driven by changed climate should be pointed out. This is not possible to study in short term experiments or modelling.

We agree. New/edited text: “Experimental studies can indicate how species and populations respond to projected levels of abiotic variables, such as temperature, salinity, oxygen or pH, but they cannot show how much species can adapt to slow shifts in the environment, in the time scale of 50 to 100 years. Short-term experiments are also weak in demonstrating the long-term effects of potential changes in the structure of the food web. Experimental work should therefore be better integrated into field and modelling studies of food web dynamics, to get a more comprehensive view of the responses of the pelagic and benthic systems to climate change, from bacteria to fish.”

r.60 The shortcoming of not covering meteorological definition of climate change should be mentioned (i.e., significant differences between 30 year periods). One may even question of it is meaningful to make scientific conclusions of climate effects on chemistry and biology.

Yes, we agree, and we have now added an entire new chapter 2 – Definitions and review methods in the beginning of the ms. We hope this will help the reader to better follow the reasoning between climate issues raised. We also better define where we speak of NAO and other climate fluctuations, and when of global climate change. As suggested in the general Comments by the reviewer, we have tried to clarify this distinction throughout the ms., and also increased our analysis of attribution of the observed effects to either “natural” variations in climate and the global climate change

We do think that it is meaningful to review published literature on responses on *climate related parameters*, i.e., parameters that have been projected to change due to global climate change, at different spatial and temporal scales. By reviewing past changes in pelagic and benthic communities, and short-term experiments, we consider effects of short/medium term changes in such parameters.

r. 88 OAW is defined as abbreviation but OA used below. Please harmonize.

Edited text: “The effects of projected ocean acidification (OA) on microbes have been studied alone, and together with other abiotic variables, such as temperature and salinity.”

r. 104 Please present the duration of those experiments in relation to organism generation time and discuss its influence on the conclusions that can be made.

A valid comment. We have now added notions of the sizes if the micro- and mesocosms, as well as duration of the experiments. They vary from 12 to 1400 litres, and from 12 to 24 days. We have also added in the knowledge gaps a note on the limited temporal and spatial scales of most experimental work.

r. 109 This could primarily be associated with weather changes given the periods investigated (i.e., mainly within a 30-year period).

Yes, that is a valid point, and the same time scale factor was pointed out by Reviewer #1. We have thoroughly rewritten this chapter, and also added more scrutiny to the attribution of the observed phenomena to global climate change, elsewhere in the ms. (see response to the General Comments, above).

The chapter "Phytoplankton and Cyanobacteria" are also divided in two separate chapters, "Phytoplankton" and "Cyanobacteria", for increased clarity.

New text: "Some studies have attributed these shifts to changes in environmental conditions associated with global change (Groetsch et al., 2016), while others have indicated a connection with the North Atlantic Oscillation (NAO); a decline in the intensity of NAO in the 1990s caused less cloudy conditions (more irradiance), and less windy conditions induced stronger stratification of surface water (Hjerne et al., 2019). Such shifts, if caused by variations in NAO, may be temporary and reversable, whereas shifts caused by changes in global climate may be more enduring. It has been suggested that, in the future climate, higher temperatures and less ice will cause an earlier bloom of both diatoms and dinoflagellates, with increased dinoflagellate dominance, but this development may be counteracted by increasing windiness and cloudiness, which have also been projected by certain modelling studies (Hjerne et al., 2019). However, more recent studies have suggested that, while the winter conditions will most probably become more cloudy and windy, the projections for spring and summer are more uncertain (Christensen et al., 2021). The exact nature of the changes in the structure of spring phytoplankton communities in the next 60 to 80 years cannot be projected with certainty."

r. 188-190 This firm conclusion would merit from a presentation of a strong relationship between eutrophication and "shallow coastal water areas". Please specify what quantities that is used to indicate both factors and the strength of the statistical relationship.

Yes, we have edited the text and added some relevant references. Olsson et al. (2015) did not explicitly report statistical significances between macroalgal communities and nutrients, or climate related factors (only relationships between food web structure and principal component axes were reported), so we do not cite any statistics here.

Edited text: "For many shallow coastal ecosystems of the Baltic Sea, it has been concluded that eutrophication, whether being caused solely by anthropogenic nutrient loads, or amplified by climate change, has been the most important pressure affecting the ecosystem components (Olsson et al., 2015). This is plausible, because of the strong influence of anthropogenic nutrient loading in coastal areas, especially those that are prone to hypoxia due to topography (Virtanen et al., 2018), and which often are affected by internal loading of phosphorus from the sediment (Puttonen et al., 2014; Puttonen et al., 2016)."

r. 195-196 The presented ranges of temperatures investigated does not appear to include the natural variation observed of the annual cycle. Please comment.

The temperatures used by Graiff et al. (2015) and Takolander et al. (2017), which were intended to simulate heat waves, 27 to 29 °C, do cover the possible natural variation observed during an annual cycle. We do not think it is necessary here, in the context of SST warming, to comment on the lower end of the temperature range (ca 0 °C). No change is made in the ms.

r.221 Good that also adaptation is discussed here. Please also include in the introduction.

We have now amended the text on the issue of adaptation in several places in the ms.

New text [Abstract]: "Experimental studies can indicate how species and populations respond to projected levels of abiotic variables, such as temperature, salinity, oxygen or pH, but they cannot show how much species can adapt to slow shifts in the environment, in the time scale of 50 to 100 years."

New text [Introduction]: "It is also challenging to assess the capacity of species to genetically evolve and adapt to the relatively small and very slow changes in abiotic parameters, and associated changes in species interactions."

New text [Conclusions]: ”While it has been suggested that Baltic marine species may have, due to isolation and genetic endemism, diminished potential for adaptation, several recent studies have pointed out that, e.g., macroalgae have phenotypic plasticity and potential for adaptation against gradual changes in the abiotic environment.”

r. 255-258 This is one of several examples where direct or indirect effect by climate change on biota is not part of the conclusion (cf. title of the MS). The statement is just a list of factors influencing the organisms today and is assumed to do so in the future, however, without proposing the net outcome of this (i.e. the effect).

Yes, we agree that, from correlative studies, little can be projected for the future. We have modified this paragraph accordingly, and we have also added analyses on attribution to climate change in several places in the ms. (see also response to General Comments, above).

Edited text: “While such correlative studies provide evidence on the factors that have driven past changes, they cannot be used to deduce how species, populations, and benthic biomass, would change in the future. Several studies using ecosystem modelling have however suggested that climate-induced changes in salinity, temperature and eutrophication (affecting both food availability and oxygen levels), will also be of importance for development of benthic communities and their biomass (Timmermann et al., 2012; Ehrnsten et al., 2019a; Ehrnsten et al., 2019b).”

r. 267-269 Do you mean that projected climate driven temperature (increase) may lead to a rapid increase in hypoxia? increase in temperature? Please rephrase accordingly if so. The conclusion that potential phosphorous release alone will cause eutrophication is premature. Projected enhancement of precipitation and river discharge of organic matter may counteract this by reducing light irradiance to the water column.

Yes, we refer to the strengthening temperature stratification to summer. We rephrase and add relevant references.

Thank You for the comment on eutrophication. We do think that it is worth suggesting that increased temperature stratification may increase the risk of eutrophication in shallow areas with poor water exchange. We however add a notion on the uncertainties concerning the speculated process.

New/edited text: “As increasing sea surface temperature will strengthen stratification, late summer hypoxia may increase in such coastal areas. This may increase the release of phosphorus from anoxic sediments (Puttonen et al., 2016) and lead to a “vicious circle of eutrophication” (Vahtera et al., 2007), that will bring generate more nutrients to the system and impede the success of nutrient reductions from land (Stigebrandt et al., 2014). However, several processes may counteract this process. Decreasing ice cover and changes in future wind conditions (of which no consensus exists) may affect both seasonal nutrient dynamics and stratification. Also, changes in benthic species composition may affect the oxygen dynamics of muddy sediments via species specific bioirrigation patterns (Norkko et al., 2012). Such processes that are dependent of traits of a few species may be of particular importance in low-diversity systems such as the northern Baltic Sea (Gladstone-Gallagher et al., 2021).”

r. 305 Please specify what analysis you refer to? The modelling?

Now clarified. Edited text: ”Modelled scenarios of temperature and salinity have also been used to project how the change in the abiotic environment could affect NIS already present in the Baltic Sea (Holopainen et al., 2016). The modelling suggests an increase of Ponto-Caspian cladocerans in the pelagic community, and an increase in dreissenid bivalves, amphipods and mysids in the coastal benthic areas of the northern Baltic Sea until 2100 (Holopainen et al., 2016).”

r. 331-335 The main sentence and the subordinate cl(a)use appear contradictory. If the factors are difficult to disentangle, how can you then derive significant climate factors? Please clarify and rephrase.

Yes, we delete the subordinate clause for clarity.

Edited text: ”A long-term study (over four decades) made at different coastal areas of the Baltic Sea illustrates that it is hard to disentangle the abiotic and biotic interactions, e.g. between fish and their food-sources (benthos) (Törnroos et al., 2019). The study also highlights possible decoupling of benthic-feeding fish from long-term changes of zoobenthos.”

r. 501 Or could it be referred to as a shift in weather conditions?

The event was in several studies called "a regime shift", so we retain this wording. No change in text.

r. 571 As pointed out above few if any studies including biological variables cover at least 2 climate periods. Most also lack coverage of adaptive and evolutionary processes. This should be recognized and the statements rephrased accordingly.

We agree. Text on the uncertainties and on the difficulty of attribution is added here and elsewhere in the ms.

New text: "The purpose of most studies has been to analyse the observed changes in terms of observed or projected climate change in the Baltic Sea, or to simulate the projected changes (often until the end of the 21st century) in experiments. It is however very difficult to attribute the long-term responses observed in field populations, or responses of individual organisms in small- or medium scale experiments, to global climate change. Not much is known of the adaptation potential of species, and attribution to the anthropogenic climate change is difficult also because of overlapping climatic cycles, like the NAO and, e.g., stochastic inter-annual variations in temperature. Correlative studies using field data cannot be used for projecting future changes, especially since very few studies have considered more than one climate period caused by cyclic phenomena such as NAO."

r. 575 Please correct and shorten the sentence. Message is unclear.

Edited text: "Responses of individual species to single parameters may be relatively straightforward, but when effects of several parameters on multiple species or trophic levels are studied, the results are challenging to interpret and become increasingly difficult to attribute to the global climate change, or to climate variations in general."

r.583 "…will promote cyanobacterial blooms…". "Improve" is ambiguous.

Yes, we agree. Edited text: Several recent modelling studies project that the combined effects of increased nutrient loads, increased stratification and increased internal loading will increase the frequency and intensity of cyanobacterial blooms in the central basin of the Baltic Sea, as well as the Gulf of Finland – unless nutrient loading from land will be drastically reduced."

r. 585 The dominating effect of reducing photosynthesis is overlooked (reduced light irradiance and intensified competition for the limiting nutrient with bacterioplankton). Please include and rephrase. Again, the proposed food chain cannot counteract this. The sentences are also close to repetition of what is said in the abstract. Consider replacing by complementing text.

Yes, we agree that the text was not self-explaining. We have rewritten the paragraph, and also add a notion on the uncertainties involved. We however retain the hypothesis that top-down control may increase if warming reduces time lags between functional groups.

Edited text: "In the northernmost areas – the Quark and the Bothnian Bay – in turn, the increasing allochtonous DOM may complicate the picture by reducing light availability for photosynthesis and due to intensified competition for the limiting nutrients with bacterioplankton. Also here, many open questions remain. If the projected warming results in shortened time lags between bacteria, phytoplankton, microzooplankton, suspension feeding cladocerans and microzooplankton-eating copepods, the system may change from a bottom-up controlled one to top-down controlled one, with potential effects on food web dynamics."

r. 604. I am sceptic that cyanobacterial bloom would be markedly reduced as they are also found in sediment records representing pre-industrial conditions. Consider rephrasing sentence.

Yes, there are differing opinions whether cyanobacteria will increase or decrease in the Baltic Sea in the future. We here refer to a modelling study, Meier et al (2019), which uses the term "record-breaking blooms" and claims: "*Under the BSAP, record-breaking cyanobacteria blooms will no longer occur in the future*." We change our wording and, in several places in the ms., highlight the uncertainties

concerning projecting the cyanobacteria blooms. Here we highlight the difference between a situation where only climate change affects the system, and where both climate change and nutrient reductions would take place.

Edited text: “It has also been suggested that, with successful nutrient reductions, record-breaking cyanobacteria blooms seen in the past few decades will no longer occur, despite the proceeding climate change (Meier et al., 2019).”

Table 1. Effects by increased precipitation and discharge of organic matter is overlooked. This primarily influence phytoplankton carbon dioxide fixation but also bacterioplankton and other parts of the food web. This is demonstrated both in long-term field data and controlled mesocosm experiments.

Suggested papers and some others are included in text and added into the Table 1.

AC2 references

Christensen, O. B., Kjellström, E., Dieterich, C., Gröger, M., and Meier, H.: Atmospheric regional climate projections for the Baltic Sea Region until 2100, Earth System Dynamics Discussions, 1-53, 2021.

Ehrnsten, E., Norkko, A., Timmermann, K., and Gustafsson, B. G.: Benthic-pelagic coupling in coastal seas–Modelling macrofaunal biomass and carbon processing in response to organic matter supply, Journal of Marine Systems, 196, 36-47, 2019a.

Ehrnsten, E. S., Bauer, B., and Gustafsson, B. G.: Combined effects of environmental drivers on marine trophic groups-a systematic model comparison, Frontiers in Marine Science, 6, 492, 2019b.

Gladstone-Gallagher, R. V., Hewitt, J. E., Thrush, S. F., Brustolin, M. C., Villnas, A., Valanko, S., and Norkko, A.: Identifying "vital attributes" for assessing disturbance-recovery potential of seafloor communities, Ecology and Evolution, 11, 6091-6103, 10.1002/ece3.7420, 2021.

Groetsch, P. M. M., Simis, S. G. H., Eleveld, M. A., and Peters, S. W. M.: Spring blooms in the Baltic Sea have weakened but lengthened from 2000 to 2014, Biogeosciences, 13, 4959-4973, 10.5194/bg-13-4959-2016, 2016.

Hjerne, O., Hajdu, S., Larsson, U., Downing, A. S., and Winder, M.: Climate driven changes in timing, composition and magnitude of the Baltic Sea phytoplankton spring bloom, Frontiers in Marine Science, 6, 15, 10.3389/fmars.2019.00482, 2019.

Holopainen, R., Lehtiniemi, M., Meier, H. M., Albertsson, J., Gorokhova, E., Kotta, J., and Viitasalo, M.: Impacts of changing climate on the non-indigenous invertebrates in the northern Baltic Sea by end of the twenty-first century, Biological invasions, 18, 3015-3032, 2016.

Meier, H. E. M., Dieterich, C., Eilola, K., Gröger, M., Höglund, A., Radtke, H., Saraiva, S., and Wåhlström, I.: Future projections of record-breaking sea surface temperature and cyanobacteria bloom events in the Baltic Sea, Ambio, 48, 1362-1376, 10.1007/s13280-019-01235-5, 2019.

Norkko, J., Reed, D. C., Timmermann, K., Norkko, A., Gustafsson, B. G., Bonsdorff, E., Slomp, C. P., Carstensen, J., and Conley, D. J.: A welcome can of worms? Hypoxia mitigation by an invasive species, Global Change Biology, 18, 422-434, 10.1111/j.1365-2486.2011.02513.x, 2012.

Olsson, J., Tomczak, M. T., Ojaveer, H., Gårdmark, A., Pöllumae, A., Müller-Karulis, B., Ustups, D., Dinesen, G. E., Peltonen, H., Putnis, I., Szymanek, L., Simm, M., Heikinheimo, O., Gasyukov, P., Axe, P., and Bergström, L.: Temporal development of coastal ecosystems in the Baltic Sea over the past two decades, Ices Journal of Marine Science, 72, 2539-2548, 10.1093/icesjms/fsv143, 2015.

Puttonen, I., Kohonen, T., and Mattila, J.: Factors controlling phosphorus release from sediments in coastal archipelago areas, Marine Pollution Bulletin, 108, 77-86, 10.1016/j.marpolbul.2016.04.059, 2016.

Puttonen, I., Mattila, J., Jonsson, P., Karlsson, O. M., Kohonen, T., Kotilainen, A., Lukkari, K., Malmaeus, J. M., and Rydin, E.: Distribution and estimated release of sediment phosphorus in the northern Baltic Sea archipelagos, Estuarine Coastal and Shelf Science, 145, 9-21, 10.1016/j.ecss.2014.04.010, 2014.

Stigebrandt, A., Rahm, L., Viktorsson, L., Odalen, M., Hall, P. O. J., and Liljebladh, B.: A new phosphorus paradigm for the Baltic proper, Ambio, 43, 634-643, 10.1007/s13280-013-0441-3, 2014.

Timmermann, K., Norkko, J., Janas, U., Norkko, A., Gustafsson, B. G., and Bonsdorff, E.: Modelling macrofaunal biomass in relation to hypoxia and nutrient loading, Journal of Marine Systems, 105, 60-69, 10.1016/j.jmarsys.2012.06.001, 2012.

Törnroos, A., Pecuchet, L., Olsson, J., Gårdmark, A., Blomqvist, M., Lindegren, M., and Bonsdorff, E.: Four decades of functional community change reveals gradual trends and low interlinkage across trophic groups in a large marine ecosystem, Global Change Biology, 25, 1235-1246, 10.1111/gcb.14552, 2019.

Vahtera, E., Conley, D. J., Gustafsson, B. G., Kuosa, H., Pitkänen, H., Savchuk, O. P., Tamminen, T., Viitasalo, M., Voss, M., Wasmund, N., and Wulff, F.: Internal ecosystem feedbacks enhance nitrogen-fixing cyanobacteria blooms and complicate management in the Baltic Sea, Ambio, 36, 186-194, 10.1579/0044-7447(2007)36[186:iefenc]2.0.co;2, 2007.

Virtanen, E. A., Norkko, A., Nyström Sandman, A., and Viitasalo, M.: Identifying areas prone to coastal hypoxia – the role of topography, BIogeosciences, 16, 3183-3195, https://doi.org/10.5194/bg-16-3183-2019, 2018.