Comment on esd-2021-67
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Referee comment on "Climate Change in the Baltic Sea Region: A Summary" by H. E. Markus Meier et al., Earth Syst. Dynam. Discuss., https://doi.org/10.5194/esd-2021-67-RC1, 2021

1. General comments

This review summarizes our current knowledge on climate change in the Baltic Sea region, both for the pre-instrumental past, the instrumental era, and the rest of the 21st century. It also covers other environmentally and societally important topics such as biological changes in the Baltic Sea and coastal erosion, considering other anthropogenic drivers such as nutrient input in addition to the effects of climate change. It consolidates the work done by several tens of scientists in the Baltic Earth Assessment Reports (BEAR) project, building on nine more specialized BEAR review articles as well as a large volume of other recent literature.

This review is a highly valuable body of work. It will most likely become the new default source of information on climate change in the Baltic Sea area, similarly to the first (2008) and second (2015) Baltic Sea basin climate change assessments that were published in book format. Furthermore, the review was a pleasure to read because the structure is well organized, and most parts of the text are very well written.

Due to my own background in meteorology and atmospheric climate change, I am in a better position to evaluate the substance on these parts of the text than, for example, marine biochemistry. Where I am not an expert I have largely focussed on the presentation, commenting on text where I suspect that my difficulties to understand are affected by unclear writing.

Even for the atmospheric part, I have few general comments on the substance, except for two that may be somewhat difficult to address in practice:

- With respect to the IPCC assessment cycle, this review comes out at a slightly unfortunate time. In a few months from now, the natural science part of the IPCC 6th assessment report will be fully available, and this may make the readers of this review feel that some of the results are already outdated. Fortunately, based on the IPCC Summary for Policymakers published in August 2021, the main conclusions on future climate change will not change. However, I will point in my detailed comments a couple of new results and other features in the new IPCC assessment that should be
The analysis of projected future climate changes builds heavily on regional climate model (RCM) simulations in the EURO-CORDEX project. This is a pragmatic choice since global climate model simulations are too coarse to give geographically detailed information (e.g., differences in warming between land and the Baltic Sea) on climate change in the area. Nevertheless, a larger-scale (whole Baltic Sea drainage basin) comparison between the EURO-CORDEX simulations and the wider set of CMIP5 (or CMIP6) simulations would have been of interest, to check how well the uncertainty implied by the variation between the CMIP5 models is captured in EURO-CORDEX, as well as for any systematic differences between the global and regional models.

Considering the reader-friendliness of this extensive review, I have two suggestions:

- If technically possible, a table of contents in the beginning of the article would make the orientation easier.
- A list of acronyms might also help the reader. Most (although not all) acronyms are defined appropriately in the text but, as the review is long, it would be useful to have them all in the same place.

More detailed comments on the substance and presentation follow below. After them, minor technical comments (language, typos etc.) are presented. Naturally, the division between the two categories is not always clear-cut.

2. Comments on substance and presentation

- L227: occurred more than two thousand years ago OR started more than two thousand years ago?
- L256: a forced component related to, inter alia, volcanic eruptions ( ) and anthropogenic aerosols? See, for example: Watanabe, M. and Tatebe, H. 2019: Reconciling roles of sulphate aerosol forcing and internal variability in Atlantic multidecadal climate changes. Climate Dynamics, 53, 4651–4665 https://doi.org/10.1007/s00382-019-04811-3
- L266-267: observed shift in the storm tracks - to which direction?
- L279-280: ... may influence the atmospheric circulation in a way that leads to additional precipitation over the Baltic Sea region - in its positive or negative phase?
- L362-364: IPCC AR6 summary of policymakers was published in August 2021. It might be a good idea to read it and check whether anything in Section 1.5 needs to be updated based on it, in addition to the couple of examples mentioned below.
- L369: 1981-2005 is a somewhat unusual choice for a baseline (e.g., 1981-2010 and 1986-2005 are more common). Does it have a specific meaning here?
- L385-391: It might be good to note that the RCP scenarios have been replaced by SSP (Shared Socioeconomic Pathways) scenarios in IPCC AR6. The lowest of these, SSP1-1.9, which was designed to limit the global warming to 1.5°C above the preindustrial, has lower radiative forcing than RCP2.6. For the other SSP scenarios, the effective radiative forcing tends to be slightly higher than for the nominally corresponding RCP scenarios (e.g., SSP5-8.5 is slightly higher than RCP8.5). Thus, the range covered by the SSP scenarios is even wider than that for the RCPs. See the draft of IPCC AR6 Technical Summary, p. 21-23.
- L405: by a factor of 2.2 to 2.4, as a multi-model mean value?
- L413: Although the difference in heat capacity plays some role in the land-sea warming
contrast during the transient phase of warming, it is not its main reason. As first shown by Joshi et al. (2008), the overall land-sea contrast is to a large extent caused by the dryness of land surfaces, which makes it impossible for evaporation to increase as much in a warmer climate as it does over the oceans. The mechanistic pathway involves atmospheric dynamics and is probably too complicated to be described here. Reference: Joshi, M.M., Gregory, J.M., Webb, M.J. et al. Mechanisms for the land/sea warming contrast exhibited by simulations of climate change. Climatic Dynamics 30, 455–465 (2008). https://doi.org/10.1007/s00382-007-0306-1

- L420: Please reiterate that the normalization is by the global mean (and not local) warming.

- L422: I would suggest omitting "Under RCP8.5", although it is present in the IPCC sentence. The basic features of precipitation change are the same for all the RCP scenarios, although the signal-to-noise ratio increases with stronger forcing.

- L439-440: The IPCC SROCC "High mountain" region is very inhomogeneous, covering mountain regions all over the world. Giving an average snow depth decrease for such a heterogeneous area does not seem meaningful.

- L447-461: For sea level change, it would be useful to also give longer-term projections, since many people do not realize that the 21st century sea level rise is just the beginning. Citing IPCC AR6 Summary for Policymakers, p. 28: "In the longer term, sea level is committed to rise for centuries to millennia due to continuing deep ocean warming and ice sheet melt, and will remain elevated for thousands of years (high confidence). Over the next 2000 years, global mean sea level will rise by about 2 to 3 m if warming is limited to 1.5°C, 2 to 6 m if limited to 2°C and 19 to 22 m with 5°C of warming, and it will continue to rise over subsequent millennia (low confidence)".

- L478: global net primary productivity?

- L495-L506: A key result in IPCC AR6 that should be cited here is the narrowed uncertainty range of ECS, allowed by improved scientific understanding and accumulation of new data. Largely based on the review by Sherwood et al. (2020), the IPCC now gives a likely range of 2.5-4 degrees for the ECS. Reference: Sherwood, S. C., Webb, M. J., Annan, J. D., Armour, K. C., Forster, P. M., Hargreaves, J. C., et al. (2020). An assessment of Earth’s climate sensitivity using multiple lines of evidence. Reviews of Geophysics, 58, e2019RG000678. https://doi.org/10.1029/2019RG000678

- L510-513: Divide into two sentences: … were selected (Table 1). Scientific peer-reviewed publications and reports of scientific institutes since 2013 on past, present and future climate changes in these variables were assessed ...

- L576: What does “regionalizations” of Global Climate Model (GCM) or ESM simulations mean? Does it refer to dynamically downscaled GCM / ESM simulations or just regional features of the GCM / ESM simulations themselves?

- L588: internally consistent results

- L618: drivers of climate and environmental variability?

- L668-670: Here the reader gets the impression that, in addition to the global / Northern Hemisphere mean changes, the changes in the Baltic Sea region can also be explained by volcanic and solar forcing, without the need to additionally consider long-term internal variability. Is this what is meant (and if yes, is this well established)?

- L718-720: Is the unit correct? Figures 6 and 9 in Mauri et al. (2014) suggest one order of magnitude larger precipitation anomalies, as does the text (although not the figures) in Mauri et al. (2015).

- L774-776: Suggested rewording: “The temperatures in the Medieval Warm Period and the Contemporary Warm Period are similar within their respective uncertainties”

- L833: considering the last few years of the NAO time series in Fig. 5: from the mid-1990s to the early 2010s, there was ...

- L836-837: Perhaps this article should also be cited: Scaife, A.A., Smith, D. A signal-to-noise paradox in climate science. npj Clim Atmos Sci 1, 28 (2018). https://doi.org/10.1038/s41612-018-0038-4. The article suggests that the atmospheric circulation in climate models might not be sensitive enough to (e.g.) changes in sea surface conditions.
- L868-869: Mention the period: 1979-2018.
- L878-879: influence of the AMO on the warming of Baltic Sea SSTs during 1980-2008?
- L905: annual number of days defined to belong in warm spells?
- L922-923: The wording is unclear. High values in dimming or global radiation? A minimum in dimming or global radiation?
- L928: Rather: The CERA20C reanalysis. Reanalyses are not pure model simulations.
- L983: with the 95th percentile of wet-day precipitation amounts ranging ... (or how were typical amounts defined)?
- L984-985: Simpler language: An index for the annual maximum five-day precipitation
- L991-994: Another concern about wind trends in reanalyses, especially over land: are the effects of land use change on surface roughness appropriately included?
- L1005-1006: 7-11% per decade (if real) would amount to a rather large (22-34%) change in 31 years. I don't think this is a weak trend in an absolute sense, regardless of the signal-to-noise ratio.
- L1026: more attention than what?
- L1027-1028: Should be: a poleward and downstream displacement of precipitation relative to the cyclone centre. However, this was a highly idealized simulation with a globally uniform increase in SST, and its relevance for the current review article seems therefore low.
- L1104: population exposed to a large number of days with high ozone concentrations (or something similar)?
- L1167-1168: Suggested reordering of words: However, the regional impacts of precipitation change on both the observed and projected changes in stream flow are still unclear.
- L1262: Does "emissions of black carbon“ refer to the effect of forest fires? Perhaps this should be clarified.
- L1285-1286: This sensitivity is surprisingly weak. Given that in the Baltic Sea area temperature increases by about 6°C in 30 days in spring, a uniform warming of 1°C should lead to a 5-day advance in the start of the growing season, assuming that this is primarily determined by temperature. One possible explanation is that the spring temperatures in Jin et al. refer to the 3-month period preceding the start of the growing season. The sensitivity (as estimated from interannual variability) would likely be stronger if temperatures just before the start of the growing season were used as the predictor.
- L1287: 0.18 days for each 1 cm decrease in precipitation in the 3-month period preceding the start of the growing season?
- L1287-1292: Do Jin et al. present a plausible mechanism for the apparent effect of summer and winter temperatures on the onset of the following growing season? If not, I would be sceptical, and would rather refrain from discussing these weaker winter and summer effects in this review, particularly as the statistical analysis was based on only 17 years of data.
- L1352-1356: Long sentence, divide to two: ... southwest Europe. However, their analyses also ...
- L1425-1426: It should be mentioned that the study of Irannezhad et al. was based on a temperature-index snowpack model using daily temperature and precipitation as input, rather than directly on snow observations.
- L1449-1453: Long sentence. Divide to two: ... reference glaciers. This means that ...
- L1460-1465: I feel that the summer 2016/2017 case is discussed in unnecessary detail. It would be enough to just write: "For example, slightly positive mass balances were observed for ... in 2016/2017 as a result of a cold summer (references)“.
- L1480: (permafrost p > 0.8). This definition does not seem essential for the text.
- L1502: since the late 19th century, or even earlier for MIB?
- L1545-1546: The sentence implicitly suggests that there is a category between "severe" and "average". Is there, or should "severe" be "extremely severe"?
- L1550: towards low values? "Towards zero” is problematic since no nearly-zero MIB has been observed this far.
L1555: Only one severe or only one extremely severe? Which winter?
L1607: The total volume-averaged warming?
L1638: changes in Baltic Sea marine heatwaves?
L1740: A maximum rate of 10 mm/year was mentioned on L661. It would be great to reach internally consistent numbers.
L1748-1749: from the 1960s to the early 1990s?
L1761: 20 cm sounds like a very modest number.
L1772: about 4 m in St. Petersburg? This number is not representative for the Gulf of Finland as a whole.
L1938: phosphorus released during the MBIs (or more generally)?
L2108: Do "changes" refer to increases in seal population, or a more complicated mix of increases and decreases?
L2202-2209: The essence of future climate change is global greenhouse gas induced warming. Compared with this, changes in large-scale atmospheric circulation will likely be a minor issue for most purposes. Therefore, although it is logical to retain the same order of subsections in 3.3 as in 3.2 (thus starting with the atmospheric circulation), please make it clear that changes in atmospheric circulation are not the primary cause of projected future warming.
L2220: Please mention the periods between which the climate changes are calculated.
L2229-2230: Is there any information on the magnitude of this difference?
L2231-2233: This explanation oversimplifies the dynamics of diurnal temperature range (DTR) changes, which originate from a multitude of factors (e.g., Lindvall, J. & Svensson, G, 2015: The diurnal temperature range in the CMIP5 models. Clim Dyn 44, 405–421). In addition to the processes discussed in the mentioned paper, it should be noted that, in the middle of the winter when there is little solar radiation, the genuine diurnal temperature range in northern Europe is very small. However, differences between the daily maximum and minimum temperatures can still be substantial due to synoptic-scale weather variability. Factors that reduce the temperature variability on synoptic time scales (e.g., reduced temperature gradients between the Atlantic Ocean and Eurasia) therefore also likely contribute to the apparent decrease in DTR.
L2237-2238: What is the origin of this difference? Is there less warming over the Baltic Sea in the uncoupled simulations? Or is there a cold bias in the baseline SSTs, which precludes the uncoupled models to reach warm enough Baltic Sea temperatures to exceed the tropical night threshold even after a greenhouse-gas-induced warming?
L2239-2241: In addition to the magnitude of the warming that is affected by the ice/snow albedo feedback, the baseline climate may also play a role. Further southwest, where the winters are milder, there are less frost days to start with, and therefore less room for a further decrease in the future.
L2242-2250: This article should be cited: Boé, J., Somot, S., Corre, L. et al. Large discrepancies in summer climate change over Europe as projected by global and regional climate models: causes and consequences. Clim Dyn 54, 2981–3002 (2020). https://doi.org/10.1007/s00382-020-05153-1. A quotation from the abstract: "The RCMs generally simulate a much smaller increase in shortwave radiation at surface, which directly impacts surface temperature. In addition to differences in cloud cover changes, the absence of time-varying anthropogenic aerosols in most regional simulations plays a major role in the differences of solar radiation changes". In other words: The RCP scenarios include a decrease in aerosol emissions, which enhances the warming and the increase in solar radiation in the global climate models. However, this effect is absent from many of the RCMs, in which the aerosols stay constant with time.
L2253: Good agreement with each other or with observations?
L2272: Does this also apply to dry spells in the northern parts of the area?
L2288: implying competing lower and upper tropospheric effects on changes in baroclinicity?
L2292: North-South temperature gradient
L2294-2306: Please clarify whether this text refers to the storm track activity in winter, or also in the other seasons?
L2306: What about CMIP6 (cf. Fig. 3 in Harvey et al., 2020)?
L2342-2345: Perhaps it would be good to notify that this is an exception to the general rule (emission changes dominate over the effects of climate change) articulated on L2313-2314.
L2401-2403: Suggested rewording for clarity: the simulated changes were not larger in magnitude than their uncertainty.
L2426: "also" and "similar" are out of context since Hesse et al. (2015) is the first study mentioned.
L2568-2569: By which time? Under which emission scenario(s)?
L2568-2573: Overall, the relative decrease in snow amount is projected to be smaller in the colder (northern and eastern) than in the milder (southern and western) parts of the Baltic Sea region. See, for example: Räisänen, J.: Snow conditions in northern Europe: the dynamics of interannual variability versus projected long-term change, The Cryosphere, 15, 1677–1696, https://doi.org/10.5194/tc-15-1677-2021, 2021.
L2580: at least double: Is this true even under the RCP4.5 scenario? The change by 2071-2100 must be strongly scenario dependent.
L2587-2588: If the first sentence refers to high-mountain areas in general, and not Scandinavia, it seems irrelevant for this review.
L2602-2603: This formulation seems inaccurate. Citing Hock et al. (2019): "Beyond mid-21st century, atmospheric warming in mountains will be stronger under a high greenhouse gas emission scenario (RCP8.5) and will stabilise at mid-21st levels under a low greenhouse gas emission scenario (RCP2.6)." Thus, depending on the scenario, the range of temperature projections varies from a stabilization to mid-century temperatures to accelerated warming.
L2737-2738: It would also be good to mention that ice melt in Greenland has a relatively modest effect on sea level in the Baltic Sea.
L2747: are somewhat lower?
L2754-2757: Are these numbers also for the change from 2000 to 2100?
L2762-2763: Is this estimate also based on the RCP8.5 scenario?
L2873-2874: A confusing sentence. Why does the fact that the BSAP did not take climate change into account imply that the hypoxic and anoxic area may decrease?
L2882-2883: Are these numbers also based on BACC II?
L2885: Should the increased precipitation be also mentioned (cf. increased river runoff on L2887)?
L2934: biases and different future changes?
L2950-2957: Based on L1972-1973, total alkalinity has increased this far. What explains the contrast between the past and projected future changes?
L3047-3049: What was assumed about climate change and anthropogenic nutrient input in this projection?
L3163: between Baltic Sea climate projections, rather than Baltic Sea models?
L3193-3196: Can anything be said about the likely direction (positive or negative) of these changes, or are they too case-specific or uncertain for any generalization?
L3198: Based on this definition, even something that is not affecting anything else could count as a driver. Perhaps something like this: ... is defined as something affecting something else, although a driver itself may be affected by other drivers.
L3212: reflect more solar radiation / solar radiation energy
L3227: atmospheric kinetic energy
L3235-3236: Problem in sentence structure (The efficiency ... eventually ends up)
L3408-3410: Please clarify whether these are annual or seasonal mean (JJA and SON) values.
L3431: Which period does this magnitude of trend represent?
L3483: The strong dependence of even local temperature changes on the evolution of greenhouse gas emissions and the feedbacks that determine the global climate sensitivity should also be mentioned. Another "black swan" uncertainty, of unknown importance, is the extent to which larger-than-expected decreases in the AMOC could potentially counteract the effects of global warming in Northern Europe. As shown by
Fig. 12.9 in IPCC (2014b), there in fact was one model with a cooling of Northern Europe in the CMIP5 ensemble. The recent suggestion that the AMOC may be more sensitive to anthropogenic climate change than current climate models indicate (Boers, N., 2021: Observation-based early-warning signals for a collapse of the Atlantic Meridional Overturning Circulation. Nature Climate Change, 11, 680–688, https://doi.org/10.1038/s41558-021-01097-4) may also be relevant in this context.

- L3492-3493: Also refer to Boé et al. (2020) (cf. comment 65), about the lack of time-varying aerosol forcing in RCMs.
- L3551-3552: Also mention that these increases are not projected to continue, according to climate model projections. Whether or not there is a discrepancy between the observed and projected trends is not known.
- L3764: Please specify "long-term". Does this refer to a positive trend starting before 1950?
- L3776-3777: A positive or negative long-term trend?
- L3780: I could not find this result (shift from later March to February) earlier in the manuscript. Furthermore, I was surprised to learn that the highest snow-melt floods take place so early in spring. Is this representative for the Baltic Sea region as a whole?
- L3934: By which time by more than 70%?
- L3958: Why will increasing westerly winds decrease salinity? If this is just because westerly winds are typically associated with more precipitation and thus runoff, "or westerly winds" is redundant.

Figure 3: Is the unit of precipitation change correct (cf. comment 21)?

Caption of Figure 7: Please mention the baseline period (1961-1990?)

L4144-4145: "measured at Bolin Centre" appears suspicious. The Bolin Centre did not exist in the 18th century and is distributed among several locations.

Caption of Figure 14: Please also explain why there are two red curves and the dashed bars in the early parts of the time series.

L4190-4191: Suggestion for the beginning of the caption: Sea ice thickness distribution in the Bay of Bothnia in five winters ((a)-(e)), and its five-winter average (f), also shown as a red line in (a)-(e).

L4195: In which month, or is this the winter maximum? The values are too large to be annual means as the caption suggests.

L4274-4275: Should be: “Eight different dynamically downscaled Earth System Model simulations are used”

Figure 34: NIS = Non-indigenous species? Is the abbreviation defined somewhere?

Some of the numeric values (e.g., the area of the Black Sea) differ between Tables 2 and 3. Please ensure that the numbers are consistent.

L4341, L4347 and 4353: Does "nine regionalized ESMs" mean "nine dynamically downscaled ESM simulations"?

3. Technical comments

- L98: Reckermann et al. (2021)
- L191: Add the proper reference to BACC II.
- L198: cannot yet be described?
- L237: regime varies / regimes vary
- L385: 8.3 or 8.5?
- L404: Please give a reference entry to IPCC AR4.
- L441: reduction varies / reductions vary
- L448: 2014a or 2014b?
- L479: warming and *changes* in stratification, light etc.
- L506: Delete “that”
- L518: and even in more general terms?
These results are reproduced in Figure 27.

was previously neglected

the response of climate?

continues

the fifth IPCC report. AR6 is already partly published.

CMIP5?

tend to be smaller than those reconstructed

and influence / which influences

the impact ... is still under debate

weak effect

1876-2020 or 1878-2020 (cf. caption of Table 4)?

particularly / in particular

has been observed

except for

... during 2000-2010 ... input to the catchment were exported ...

2 × 10^{-5}, not 2 × 105

Regional and local deviations ... are, however, expected

were the result of a cold summer

Wording: models indicate? Projections typically refer to the future.

latest six? (2015, 2016, 2017, 2018, 2019, 2020)

measurements in plural

built structures

Delete "be"

"process" in singular.

"weakens" is repeated twice.

Please define the acronyms DIN (dissolved inorganic nitrogen?) and DIP (dissolved inorganic phosphorus?)

Bothnian Sea

... algal blooms ... have in some cases caused

number ... is projected to increase

similar to those over the land area

number ... is expected

( is missing from the list of references.

Projections ... are uncertain?

higher wind speeds?

decreased precursor emissions

66-100% (cf. IPCC definitions)?

“global projections” in plural

latent heat flux?

similar to those observed

no significant changes ... were projected / no significant change ... was projected

seem to show

"the interaction off"?

based on CMIP5 simulations

have lost

may increase the hypoxic area by about 30%

of total

scenarios suggest

through sea level rise

through the construction

responses ... are / response ... is

causes ... are not well known

studies ... exist

summer cold spells

that indicate?
L3924: will lead
L3946: Limited number of ensembles or limited number of ensemble members?
L3952: in the end of the century?
L4170: "och" should be "and"
Figure 14: The percentages in the two right-hand panels should be multiplied by 100.
L4251: in $10^4$ km$^2$?
L4257: December through February
L4258: The unit of precipitation change must be per cent, not mm/day.
L4267: The right-hand-side vertical axis?
L4273: December through February
L4327-4328: 1876-2020 or 1878-2020?