Dear Professor Kienast, dear referees,

thank you very much for the helpful comments and suggestions for our manuscript. We can follow most of the arguments of all referees and have thus incorporated almost all suggestions made. In the following, we have listed responses to the different points made. There are only a few cases in which we would prefer not to follow the suggestions made, but we offer compromise solutions in most of these cases. We will attach an extra document showing the changes between the old and the new version of the manuscript. The pages mentioned here are referring to the old manuscript.

Kind regards also on behalf of the co-authors

Ulrich Kotthoff

Comments/replies to the Review by F. Naughton (Referee)
Referee 1: The manuscript "Reconstructing Holocene temperature and salinity variations in the western Baltic Sea region: A multi-proxy comparison from the Little Belt (IODP Expedition 347, Site M0059)" by Kotthoff et al., presents new and a large array of proxy data from IODP Expedition Site M0059 covering most of the Holocene period. The study is methodologically sound, the results are significant, and the interpretation is well justified. The manuscript is very clearly written and supported by good quality figures. The manuscript makes several very valuable contributions to the palaeoenvironmental understanding of the last 8 kyr in the western Baltic Sea by using coupled ocean and atmospheric multi-proxy data. Overall, I would strongly recommend this manuscript for publication in Biogeosciences journal with very minor modifications in response to my comments on the pdf.
Yours sincerely, Filipa Naughton
Please also note the supplement to this comment: http://www.biogeosciences-discuss.net/bg-2017-101/bg-2017-101-RC1-supplement.pdf
Authors: We are thankful for this review of our manuscript. In the following, we respond to the different comments in the text. We are particularly thankful for the detailed checking of our references. In the following we reply in detail to the comments in the supplements.

Page 3
Referee 1: "replace Frenzel et al 2005 by Frenzel and Boomer 2005"
Authors: Has been replaced.

Referee 1: "is this reference Filipsson et al., 2016? if not introduce this reference in the references section."
Authors: Has been corrected.

Page 5
Referee 1: "this reference is not mentioned in the reference section"
Authors: The reference has been replaced.

Referee 1: "references should be in chronological order"
Authors: The references have been re-organized.

Page 6
Referee 1: "Even if this paper is accepted how can we see the age model? In the references we can't see where this mentioned paper will be published. You should have a table with core depth and the radiocarbon ages as well as a figure with the resulted age model. You can cite the Van Helmond et al accepted paper as well."
Authors: The paper is now published and has been added to the references. We have also added a table showing the core depth and the radiocarbon ages. A table giving more information is given in the supplement (Table S3). We have considered adding a figure, but since the Van Helmond paper is now accessible, we decided against it. If it is regarded as necessary, we can add it.

Referee 1: "How? you must say how they were extrapolated: e.g. using clam program? by hand using the last sedimentary rate value?"
Authors: The ages were indeed extrapolated linearly, which we have now explained.

Referee 1: "Although this correlation is very interesting and a good point to reinforce the reliability of your age model, it would be nice to see the age model of site M0059. The temporal resolution of pollen data from Site M0059 is much lower than that of Lake Belau, therefore the last 2500 years of correlation have some slight discrepancies. However it does not seem to affect your interpretation."
Authors: See above. We have added more information on the age model in table 1 and the Helmond et al. paper is now accepted.

Referee 1: "need a reference of the method"
Authors: We have added a reference.

Referee 1: "replace to: ....for diatom analysis were...."
Authors: Done

Referee 1: "include "the" to be consistent with what said in the diatom methodology."
Authors: We have instead removed "the" from the other texts in this context in the framework of generally shortening these sections. We have, e.g. also removed "M0059" and other redundant words in the methodology sections concerning the different proxies.

Page 11
Referee 1 makes several suggestions concerning Fig. 2, we have followed these suggestions by thickening lines and adding the "cereal curve" from Lake Belau. We have also rephrased the sentence concerning maximum *Fagus* percentages.

Page 12
Referee 1: "you should/(could if you have) include the pollen concentration curve next to the TOC curve."
Authors: Curves with pollen and dinocyst concentration have been added to Figs. 2 and 3.

Page 14:
Referee 1: "since you have just isolated points with ammonia beccari i wonder if this is representative"
Authors: *Ammonia beccarii* is present in the surrounding samples too (<3%). We agree that it should be mentioned that the particular high abundance (~15%) is reflected in one sample. We have changed the text accordingly.

Referee 1 makes several suggestions for section 3.3.3 which we incorporated.

Page 15:
Referee 1 mentions a missing reference which we have added.

Referee 1 (correction): "which can be found"
Authors: The sentence has been rephrased.

Referee 1: "include non-heterotrophic taxa in the text here"
Authors: We have included the information that heterotrophic taxa were rarely encountered.

Page 16: Referee 1 made several comments on this page which are now incorporated, except the remark "*at a long term SST is increasing since 1000 yr BP*" which we could not follow completely (the datapoints do not show a clear trend in our opinion). The text concerning clumped isotopes (3.3.6) has been rephrased.

Page 17: We have removed a citation that was not included in the references.

Page 18:
Referee 1: "in figure is until 5.5 ka"
Authors: We have rephrased the sentence.

Referee 1: "As previously mentioned in my comments the single peaks cannot be representative of major changes. "
Authors: We have rephrased the sentence in accordance with the comment Referee 1 made concerning the related aspect on page 14. It is now mentioned that the percentages are below 1 %.

Referee 1: "you could probably also mentioned based in the pollen based temperatures estimates that evaporation was not strong because MTWA did not increase during this interval."
Authors: We had considered to add this aspect here, but since pollen-based MTCO show a slight increasing trend and annual temperatures remain quite stable, we have finally decided against this. The temperature aspect in context with evaporation is however mentioned later.
We have restructured the brackets in this sentence.

Page 19:
Referee 1: "again one single data point is not enough to extrapolate a rapid change in the salinity"
Authors: We have added that it is only one sample, but we regard the signal as important (see above).

Referee 1: "rephrase the end of this sentence"
Authors: Has been rephrased.

Referee 1: "since you do not have a peak in pp at 1700 but rather an increase along the EZ3 it would be better to just mention what happened during the entire interval."
Authors: We have rephrased the related sentences and removed some redundancies in this context.

Referee 1: "If pp increase (and runoff) why there is no signal of that in the TOC and BTI curves? well maybe a slight increase of the TOC could also support this idea?"
Authors: Indeed, diatom based pp often fluctuates in an inverse relationship with soft bodied algae and other forms. Especially where eutrophication is concerned as soft algae will replace diatoms. The lack of signal in TOC curves likely reflects trade-offs between diatom and soft algae productivity (i.e. diatom productivity replaces or is replaced by other pp groups, so a change in TOC may not always be seen).
The related part of section 4.1 has partly been rewritten, so the sentence marked by referee 1 has been removed. We hope that the more condensed rewritten version is clearer.

Page 20:
Referee 1: "i think that you can also do not have enough resolution in your record to show that linkage. so you can also propose that."
Authors: We have mentioned that the temporal resolution may hamper the related interpretation and that higher resolution studies should be undertaken.

Page 21:
Referee 1: "at a long-term sst seems to decrease gradually as the LDI and even more similar to the MTWA decrease trend, even if the signal of TEX is noisy!"
Authors: We are not sure what the question is in this case. We have rephrased parts of section 4.2 (see below) so that we hope the discussion is improved.

Referee 1: "I do not see any similarities between the TEX and the clumped isotope record for this period. Maybe you should look to the data at long term and forget the rapid reversal episodes."
Authors: We have to agree with referee 1, we cannot really suggest a common trend. We have regarded this comment also that way that the clumped isotope record is not shown as line anymore in Fig. 4. We have, in context with points made by referee 3, rewritten section 4.2, so that the sentence related to Referee 1's comment has been rephrased.

Referee 1: "the pattern is from 19° to 17.5 and not from 17.5 to 19. please change"
Authors: Has been corrected.

Page 23:
Referee 1: "this reference is in press in the reference section"
Authors: The Krossa et al. paper has now been published, references are updated.

References:
Referee 1 has marked several corrections to be made in the references, we have incorporated them.

Comments/replies to the review by R. Limoges.

Referee 2: "This paper compares and uses the signals provided by multiple biogenic proxies to interpret the hydrologic evolution in the western Baltic Sea region during the past 8000 years. Inter-comparison of the proxy-data and quantitative reconstructions allow for robust reconstructions and time constraint of the major regional hydrological transitions (salinity and temperature). This paper is a good contribution and I suggest it is accepted with minor modifications. I kindly refer to the attached pdf (supplement)."
Authors: We are thankful for this review of our manuscript. In the following, we respond to the different comments in the additional text file provided.

Referee 2: "General comments
The information provided in this paper is highly relevant and the interpretations are well justified. However, although I understand it is difficult to be concise when reporting on so many proxies, the manuscript is long and should be thoroughly reviewed to remove repetitive sections, and to restructure certain sentences and paragraph sections (particularly lines 532-556 present one long section in which the reasoning is jumping around a bit between proxies and from one time interval to another). Furthermore, there are a lot of abbreviations and this makes the reading unnecessarily challenging."
Authors: We agree. The MS already went through several "shortening cycles", but we have found additional redundancies and removed them. We removed several abbreviations, e.g. "DI" (Diol Index) and "LDI" (long chain diol index) from the text (except equations in the method section, see below!) and several abbreviations in Fig. 4 and Supplementary Fig. S02. We have reorganized the lines mentioned by referee 2. We have furthermore generally tried to remove redundancies.

Referee 2: "I would be cautious with the discussions concerning the performance of the different proxies. Although many proxies are used, only a very few amongst them are used in an optimal way (e.g. not statistically robust dinocyst counts; a noncalibrated foraminifer species used for Mg/Ca-based estimates, contamination of foraminifer test used for Mg/Ca ratios, and assemblage and geochemical analyses on foraminifera that are suspected to be affected by dissolution - which probably also is the same for the ostracodes, etc) – this is okay if trying to answer a scientific question, but I would have some reservations when the authors evaluate the performance of these proxies. Their applicability can be evaluated, but not their performance (question of using the right term)."
Authors: This aspect is indeed very important. It is true that we cannot evaluate the "performance" of some of the proxies. We have rephrased related sections and avoided the term "performance".

Referee 2: "Specific comments
Figure 1. The « Little Belt », « Great Belt » and « Öresund » should be added to this figure so the readers that are not familiar with the region can refer to this map. Perhaps also « Lake Flarken », also mentioned in the text."
Authors: Figure 1 has been changed accordingly.

Referee 2: "Figure 3. What species of diatoms were considered F, BF, BM, etc?"
Authors: We have prepared a table with all encountered species (Table S5), and which category they were included in. This table (comprising more than 170 species) has been added to the supplementary data. We have mentioned this in the figure caption for Fig. 3 and in section 2.2.4.

Referee 2: "Figure 3. Add dinocyst concentrations."
Authors: Dinocysts concentrations have been added to Fig. 3.

Referee 2: "Replace "non-heterotrophic dinocysts" by "phototrophic".
Authors: Has been replaced.

Referee 2: "Introduction
Lines 54-59. These sentences are somewhat unrelated to the remainder of the manuscript and the objectives of this study."
Authors: We have removed these sentences.

Referee 2: "Line 77. Can you be more specific here? What conditions can influence the application of Mg/Ca in the Baltic Sea?"
Authors: The sentence has been re-written to include the following "large gradients in salinity (and low absolute salinity) as well as parameters related to the carbonate system (e.g. alkalinity and carbonate saturation state) in the Baltic Sea may significantly influence the application of Mg/Ca ratios".

Referee 2: "Lines 78-83. Include references here."
Authors: We have added references.

Referee 2: "Lines 86-87. You introduce the TEX86 proxy, but the text further down mentions the TEXL86 proxy; please clarify what the TEXL86 is."
Authors: We now added a description of the TEX^L_{86} to the introduction section.

Referee 2: "Line 89. What does LDI stand for?"
Authors: The abbreviation has been removed from most of the text, and is explained at its few occurrences (Method section/Fig.4).

Referee 2: "Line 94. The term biogenic should be used instead of "biotic"."
Authors: We agree. It has been changed.

Referee 2: "Line 99. The length of the core is not important, it is the sedimentation rates and temporal resolution (it is not because it is long, that the sedimentation rates and temporal resolution are high)."
Authors: We have rephrased the sentence.

Referee 2: "Line 103. […] moreover to Greenland ice core records and marine records from the North Atlantic this sentence seems out of place, since this is not done later in the manuscript."
Authors: We have now removed the related part of the sentence. A comparison with the ice core records would be out of scope of our manuscript.

Referee 2: "Line 103. replace "records" with "cores" (drilling provides cores, analyses provide records)"
Authors: We have now rephrased the text.

Referee 2: "Methods
- The thickness of the samples is only given for forams, but not for other proxies.
- For many proxies, the same amount of samples was analyzed (36). Presumably, these represent the same samples/levels in the core (although this is not that obvious from the manuscript). Instead of repeating this information every time, perhaps a short introducing paragraph can be added to provide

this information (same-sample analyses for which levels, which ones in higher resolution, etc)"
Authors: It is, unfortunately, not the case that all authors could use samples from the same levels due to limited core material. We used closely neighboring samples, in most cases and aimed at at least 35 samples per proxy over the time interval analysed. This information and the sample thickness have now been added.

Referee 2: "2.1. Lines 114-115: is the latitudinal span (numbers) relevant? So why not the longitudinal span, too? But both would not seem relevant to the study, which focuses on a specific, smaller region. The coordinates of the core would seem to suffice."
Authors: We have removed this, and shortened this section.

Referee 2: "2.2.3. What mesh sizes were used for sieving?
● Did you add marker grains for calculating the concentrations?"
Authors: The mesh size (7µm) and information concerning markers has been added (concentration curves have been added to Figs. 2 and 3).

Referee 2: "● Zonneveld and Pospelova, 2015 is not an appropriate reference here – it is a determination key. Perhaps you can refer to de Vernal and Marret, 2007 [de Vernal, A., Marret, F., 2007. Organic-walled dinoflagellates : tracers of seasurface conditions, In Hillaire-Marcel and de Vernal (eds.) Proxies in Late Cenozoic Paleoceanography, Elsevier,pp. 371-408.]"
Authors: We have exchanged the reference.

Referee 2: "● What does "rarity of counted types" mean?"
Authors: We have rephrased the related sentence.

Referee 2: "2.2.4. Line 201: "selected depths": do you mean the same 36 depths, or a selection of these 36?"
Authors: We have rephrased this sentence (the 36 samples are meant).

Referee 2: "2.2.5. The use of heavy liquid separation is understandable, but is this common practice? Could you provide a reference that illustrates the influence - or, ideally, the lack of it – on assemblage composition (selective removing of certain species because of sediment infilling, fragmentation of fragile species, etc.). Ideally, in order to really test the power of the proxy, all samples should have undergone the same preparation method..."
Authors: The residual fraction after heavy liquid separation was checked for foraminifera; only very few specimens were found. The heavy liquid separation thus did not influence the analyses. We have rephrased parts of section 2.2.5 and added this aspect.

Referee 2: "2.2.6. Line 230. A total of 75 30cm3 sediment samples were processed for ostracod analysis (confusing otherwise)."
Authors: We have rephrased this sentence.

Referee 2: "Results
Line 455. Operculodinium centrocarpum (?), Spiniferites spp., Lingulodinium machaerophorum (?)"
Authors: We have added the species names/spp.

Referee 2: "Line 460. When using "Gymnodinium cf. nolleri", it is implied that a cyst type was found with a morphology that looks like G. nolleri, but at the same time very clearly is not G. nolleri. Is this what the authors mean: cysts whose morphology cannot be attributed to a known species? Or, if different species of Gymnodinium are meant (i.e. nolleri, catenatum, microreticulatum), then "Gymnodinium spp." should be used."
Authors: In this case, we cannot completely agree with referee 2 – "cf." does not indicate clearly that the specimens are not *G. nolleri*. Instead, it indicates that they look like *G. nolleri* and probably belong to the taxon, but that the assignment is not completely sure because, while we checked some specimens in detail, we did not check all characteristics like wall structure in detail for every specimen. We have now added in brackets in one of the preceding lines that we use the term "cf.

nolleri" in the sense of "probably *G. nolleri*", and we think that this is in accordance with typical nomenclature.

Referee 2: "Discussion
Transition from line 492 to line 493. Somehow a circular reasoning, as the variations themselves are inferred from the proxies. The first two sentences of this paragraph could be removed."
Authors: We have removed these sentences.

Referee 2: "Line 502. How do the ostracodes indicate low primary production?"
Authors: We have rephrased this sentence (it was meant that they indicate freshwater conditions)

Referee 2: "Lines 501, 504, 506. These sentences could be restructured to avoid repetition. In addition, the sentence "these factors indicate that EZ1 presents a low productivity freshwater environment" should be moved downward, as (the more convincing) arguments are given following this sentence; the low concentrations of marine palynomorphs does not indicate that the setting was one of low total productivity."
Authors: We have slightly shortened and rephrased these sentences. The sentence mentioned by Referee 2 was removed completely to avoid redundancy. We have removed further redundancies in this section.

Referee 2: "Line 526. Add reference after "[…] may indicate more saline conditions"."
Authors: It is not yet clear what these peaks in *Gymnodinium* indicate, this is discussed later in this discussion section. It is rather our suggestion that the peaks are tied to more saline conditions, which we have now indicated. We have also added a related sentence later in the MS in connection to a remark by Referee 1.

Referee 2: "Lines 543-556. This entire section needs a bit of restructuring and rephrasing; now it is sometimes confusing and unclear what periods and water masses (bottom, surface) are compared and discussed."
Authors: We have rephrased this section. We think that it is clearer now.

Referee 2: "- bottom water = increasing salinity (Line 545-546); surface water = decreasing salinity (Line 549-553), correct? This contrasting evolution (if I understood correctly) is worth stressing and discussing further?"
Authors: We assume that this point has become obsolete because we changed the related part of section 4.1.

Referee 2: "- L553: ...regard this as the most… what period exactly (early Littorina, entire Littorina,...)? "most marine" seems in contradiction with decreasing salinity..."
Authors: We have specified that the interval between ~6,500 and ~5,000 cal. yr BP is meant and rephrased the sentence.

Referee 2: "- L554: increased with respect to what? Modern? EZ1?"
Authors: This has been rephrased in context with the other changes in this section.

Referee 2: "Lines 559-601. please rephrase, there seems to be something not entirely correct about this sentence."
Authors: We have divided the particularly long sentence into two and slightly rephrased the text.

Referee 2: "Line 600. The use of "juvenile (percentages)" comes out of the blue here. Also, given the low ostracod counts, how significant are such percentage/relative changes? How many specimens are we talking about here?"
Authors: We have removed the part referring to juvenile specimens. Referee 2 is probably right that this information is not very significant.

Referee 2: "Line 611. Inorganic and inorganic proxies are not the best terms here – perhaps

“geochemical analyses” and “biomarker””
Authors: We have no written “inorganic- and organic-based” to address this (since biomarkers” are also geochemical, we did not follow the suggestion word-for-word).

Referee 2: “Line 637. Not everybody is familiar with the Boreal and Atlantic terminology and timescale; please introduce properly or replace with/add actual dates.”
Authors: Done (we added years in brackets).

Referee 2: “Line 651. When do these eustigmatophyte algae bloom?”
Authors: Currently no information on the annual growth cycle of eustigmatophytes in the Baltic Sea or other brackish-marine settings is available. Previous studies indicate that the LDI-derived surface water temperatures match best with summer surface water temperatures in various oceanographic settings such as the Southern Ocean (Lopes dos Santos 2012). Likewise, the core top sample at Site M0059 shows LDI-derived temperatures that are most similar to surface water temperatures in July, suggesting that eustigmatophytes may show highest productivity during summer in the Little Belt region. We added a brief discussion on the timing of eustigmatophyte blooms and LDI-derived temperatures in the Baltic Sea to the discussion section.

Referee 2: “Line 656. LCD would seem a good candidate to be left out as abbreviation and be written out in full instead (as is done just a few lines above). Other good candidates, since used only very rarely, would surely be BIT (line 679), MWP and MHP (685; the latter only used once, i.e. where the abbreviation is given!?), HTM (line 691), and BWT (line 697).”
Authors: We have removed LCD and BIT as abbreviations (except for the equation section). MHP was removed, too. We left MWP in the text since it is also used in Figs. 2-4. HTM was replaced with HCO (see below). BWT is only used in Fig. 4 now.

Referee 2: “Technical corrections
Line 43. […] changes in salinity, but often do not allow quantitative
Line 44. […] is associated with particularly large uncertainties […]
Line 248. Due to poor preservation
Line 290. A total of 40 sediment samples collected […]
Line 351. […] was divided into four overall environmental zones.
Line 397. A. beccarii
Line 456. G. nolleri
Line 465-467. This information belongs to the method section.
Line 501. “biological” should be replaced by “biogenic”.
Line 647. Same as above. Change different inorganic and organic for “biogenic proxies”.”

Authors: We have incorporated most of these corrections.
Concerning former Line 647, we have instead used the term “-based” as above. This was also changed elsewhere in the manuscript. Concerning Line 397, we think that the genus name should not be abbreviated there since it is mentioned for the first time. Concerning line 351, we are not sure what is meant.

Comments/replies to the review by Referee 3.

Referee 3: “The manuscript by Kotthoff et al. based on a multi-proxy approach is very interesting. However, while combining that much different proxies is not an easy task, some more thorough discussion is needed concerning (1) the climatic forcing possibly explaining the different salinity and temperature trends observed over the Holocene, and (2) the high discrepancies between proxies for the same parameter (temperature). A graphical comparison with previously published records from the study area is also missing. The text suffers from some imprecision in the Results and the Discussion, some parts of the text should be reorganized, some figures should be modified and some new figures should be provided (as supplements). Finally, a calibration issue related to some organic proxies should be addressed. Therefore, I recommend the publication of the present study, but only *after major revisions."*

Authors: We are thankful for this detailed review, particularly of aspects related to the biogeochemical proxies. We agree that it would make sense to discuss the climate forcing and some of the discrepancies in more detail (see below). Concerning graphical comparison with other records, we are not sure if this should be done in the framework of this manuscript, because on the one hand, there are no nearby records covering a similarly long time interval, and on the other hand, the sheer amount of proxies we use would result in numerous additional figures.

Referee 3: "Major comments:
The introduction should be reworked partly. After the second paragraph, it sounds like an enumeration and description of the proxies that will be applied in the study. It is not necessary and belongs rather to the Discussion part."

Authors: We had a long discussion how to handle this. In our opinion, we found a reasonable approach – in an earlier version, we had shifted the proxy description to the subsequent sections, and most co-authors did not like this approach. We would thus prefer not to move these descriptions. This does not mean that we cannot follow referee 3's arguments, but we think in this case it is also a matter of different tastes. We could, however, shorten the related sections.

Referee 3: "Instead, previously published Holocene records from the Baltic Sea and the Skagerrak region should be mentioned and the main results should be described as in lines 97 to 104, but in more details.
In my opinion, at least the following studies on Holocene temperature and salinity changes should be mentioned: Emeis et al., 2003, The Holocene (salinity and temperature); Warden et al., 2016, Organic Geochemistry (salinity); Krossa et al., 2015, Boreas, and Krossa et al., 2017, The Holocene (salinity and temperature); Ning et al., 2015, Boreas (salinity); Butruille et al., 2016, The Holocene (temperature); Zillen et al., 2008, Earth-Science Reviews (climate and hypoxia); Widerlund and Andersson, 2011, Geology (salinity). Based on these previous results, the necessity of a long and continuous record from the Belt Sea as intermediate location linking the Baltic Sea and the Skagerrak region can be introduced (in lines 97-104)."

Authors: We are referring to several of these references, a few of them are mentioned in the introduction as well as in the discussion sections. While we not use all of these, there are further records mentioned. We think, however, that by adding to many of the related results in the introduction, the already long manuscript may become too long.

Referee 3: "Some other parts of the text should be reorganized. As some results are discussed/presented in Section 2.2.1, I would suggest merging it into Section 3.1. The problem related to Mg/Ca contamination is mentioned at least three times in the manuscript (Methods, Results, Discussion). Because of repeating this issue again and again, one could consider removing completely this record from the study as this proxy is not really reliable. It would be a pity however. Therefore, I recommend shortening and grouping the different parts about this contamination issue somewhere in part 4.2, and discussing this issue in more details in the supplements (if necessary). "

Authors: These are reasonable suggestions. We have followed the suggestions concerning the Mg/Ca contamination aspect to put it more into one part. We think it is worth it to keep it in the main text, but have combined the method work in the actual Mg/Ca-method as it does not directly complement the paleo-discussion. The final climate signal from the Mg/Ca is of course still included in the discussion. Concerning section 2.2.1, it is true that results concerning the age model are mentioned, but these are not new results but rather necessary information from other publications (with the van Helmond-Paper presenting the age model now published, see above) which in our opinion should be given before the proxy methods are introduced, so we would rather prefer to leave this here.

Referee 3: "Concerning Section 4.2, while it is possible to discuss the records based on the different environmental zones for the salinity and productivity proxies, it is confusing for the temperature proxies as these latter present completely different long-term and short-term trends. I suggest reworking/reorganizing this part. First, the differences in the temperature proxy records (trends, absolute values, amplitudes, etc) should be discussed, then the temperature trends should be summarized as a function of the environmental zones, and finally the potential forcing behind the *temperature records should be discussed (see below)."*

Authors: We agree that section 4.2 needed to be reorganized and have done so. We have, however, more focused on the possible complications concerning the proxies and the different approaches to gain temperature information and not discussed the possible forcing in detail. The focus of our publication is the multi-proxy comparison. The scope of our study is, even if we cannot test the "performance" of the proxies, as Referee 2 pointed out, to test the applicability of the proxies in such a particular setting as the Little Belt as shelf/coastal area, and to see which issues can occur in future, higher-resolution studies. Referee 3 has made several comments regarding the biogeochemical proxies (discussed below and in most cases incorporated) which also indicate that it is reasonable to discuss the proxy-applicability in our research region in high detail.

Referee 3: "I have a few comments concerning the TEXL86 temperature proxy. First of all, I was wondering if a standard was used for GDGTs quantification. If yes, I suggest using the absolute concentration of the branched GDGTs rather than the BIT index as the BIT index is often mostly function of variability in crenarchaeol (usually the dominant GDGT)."

Authors: We agree with Referee 3 that quantifying absolute concentrations of GDGTs is desirable. Unfortunately, no standard was available for quantification of isoprenoid and branched GDGTs and thus we used the BIT index (Fig. S5) to provide information on the relative changes of the aquatic and terrestrial derived GDGTs.

Referee 3: "Generally speaking, the use of TEXL86 should be avoided because the crenarchaeol regioisomer plays a role in the temperature predictability (relatively more of the regioisomer is observed at higher temperatures)."

Authors : We are somewhat surprised by this comment as the TEX^{L}_{86} has shown best correlations with surface water temperature in low temperature environments (temperatures below 15 °C). Furthermore, the TEX_{86} has been established as a marine temperature proxy. It is of limited use in freshwater and brackish settings though due to the absence or low abundance of the crenarchaeol regioisomer in many lacustrine and brackish systems. In fact, the crenarchaeol regioisomer could not be identified in all of the samples that have been analyzed for isoprenoid GDGTs. Therefore, we consider the TEX^{L}_{86} most suited to reconstruct the temperature variability of the Little Belt. However, we have added an additional graph to the supplements (Fig. S2) showing the TEX^{H}_{86}-temperature record and explain differences in TEX^{L}_{86} and TEX^{H}_{86}-temperature profiles in the discussion section.

Referee 3: "Furthermore, the TEXL86 calibration from Kabel et al. (2012) is only based on the highest correlation with summer SST, but has no "biological grounds". When looking at the supplementary information in Kabel et al. (2012), it appears that the correlation is high ($r2 > 0.7$) for all months from May to November (i.e. not only for the summer months) and not only for TEXL86, but also relatively high ($r2 > 6$ from June to October) for TEXH86. Moreover, the IODP M0059 site location is out of the area covered by Kabel et al. (2012) calibration, what may play a role considering a possible influence of strong salinity gradient on Thaumarchaeota distribution in the western Baltic Sea."

Authors: Referee 3 is of course right that a comparatively high correlation with summer to autumn temperature is also observed for the TEX^{H}_{86}. But it is significantly lower than for the TEX^{L}_{86} and therefore we deem the TEX^{L}_{86}-reconstructed temperatures more reliable. Although the Kabel et al. (2012) calibration does not include the Little Belt region, the vicinity of the studied site to the Baltic Proper and the strong environmental gradients that are observed in the western Baltic region suggest that other calibrations may not be as applicable to reconstruct SSTs. However, we have now also calculated SST based on the TEX^{H}_{86} and will discuss difference between both temperature profiles in the text. The TEX^{H}_{86}-based reconstructions are shown in Fig. S2.

Referee 3: "Another factor potentially complicating the TEXL86 record is the presence of a redoxcline and hypoxic to anoxic conditions. It is known that in the modern, Thaumarchaeota are most abundant at depth near the redoxcline in the Baltic Sea (e.g. Labrenz et al., 2010, ISME Journal; Berg et al., 2014, ISME Journal). Therefore, on the one hand the recorded temperature may rather be from the subsurface, or even the near bottom if anoxic conditions are present near the bottom as in the Bornholm Basin."

Authors: We agree with the reviewer that the TEX^L_{86} (as the TEX_{86} in general) may record subsurface water in certain oceanographic regions. However, comparing our TEX^L_{86}-reconstructed water temperature from the core top sample to measured water column temperatures strongly argues for a synthesis of isoprenoid GDGTs in surface waters of the Little Belt region as ambient subsurface temperatures are much too low and do not explain the proxy-based temperatures. Therefore, we consider it unlikely that Thaumarchaeota growing at the redoxcline were a substantial source of GDGTs. However, we will extend our discussion on the spatiotemporal water column signal of archaeal GDGTs in the Baltic Sea.

Referee 3: "On the other hand, culture experiments have shown that increased O2 limitation may result in increased TEX86 SST estimates (Qin et al., 2015, PNAS). Indeed, van Helmond et al. (2017) have shown that seasonal hypoxia occurred over the last 8,000 years at Site M0059 and intensified during the HTM and, more especially, during the MCA, i.e. when the TEXL86 temperatures are highest. This aspect should be shortly discussed. It would be very interesting to plot also a TEXH86-based temperature record using a global calibration, e.g. Schouten et al. (2013, Organic Geochemistry) or Kim et al. (2012, EPSL) subsurface calibrations on Fig. 4 (or as supplement) as well, and to discuss potential differences."

Authors: O_2 limitation may indeed result in increased TEX_{86}-SST estimates but as GDGTs synthesizing Thaumarchaeota likely inhabited the surface waters of the Little Belt, they were likely little affected by the spread of seasonal hypoxia during the HTM and MCA. Both periods, on the contrary, are well known to be characterized by optimum climate conditions and we thus consider the trends to warmer surface water temperatures reasonable. However, we have included a more detailed discussion on how environmental parameters may affect the TEX_{86} and its interpretation to the "discussion" section. Although at lower resolution, we have now also included a figure in the supplements (Fig. S2) showing TEX^H_{86} temperature trends using a set of different calibrations.

Referee 3: "Moreover, as methanogenic and, more especially, methanotrophic archaea produce GDGTs involved in TEX86 in substantial amounts, it would be interesting to test their potential influence by plotting e.g. the Methane Index (Zhang et al., 2011, EPSL) as supplementary information."

Authors: We thank the reviewer for the comment. To determine the possible effect of GDGTs derived from methanotrophic archaea on the calculation of the TEX^L_{86}, the Methane Index (MI) was calculated and has been added as supplementary information to the manuscript (Fig. S2). MI values are below those considered diagnostic for methanotrophy and thus suggest that the TEX^L_{86} was not confounded by the addition of GDGTs from methanotrophic archaea.

Referee 3: Some imprecision are apparent in the text. Compared to e.g. the LDI record (same samples as for GDGT analysis), the oldest three samples of the TEXL86 record are "missing" (not plotted), without explanation, what makes a true comparison difficult (see e.g. lines 667-668)."

Authors: The missing TEX^L_{86}–based temperatures from EZ1 have now been measured and have been added to the manuscript.

Referee 3: "Furthermore, to be as correct as possible, a global TEX86 calibration for lakes (e.g. Powers et al., 2010, Organic Geochemistry) should be applied for the samples from EZ1, as this latter is characterized by freshwater conditions (lines 510-511)."

Authors: We agree with referee 3. TEX86-based temperatures for this interval were now obtained using the Powers et al. (2010) calibration and added to the manuscript.

Referee 3: "Obviously the TEXL86 record is NOT "... to some degree similar to the clumped isotope record" as stated by the authors (lines 674-676). For examples, the temperatures are equally high in the HTM and the modern in the clumped isotope record, but not in the TEXL86 record. The absolute values are different as well."

Authors: This comment is similar to one of referee 1. We agree that the cited statement cannot be made, we have rephrased related sentences.

Referee 3: "Moreover, if plotting the TEXL86 temperature data of Kabel et al. together with Site

M0059 on Fig. 4 (what I suggest to do), I suspect that these two records are not that similar (lines 685-688) concerning both the temperature amplitudes and the trends."
Author: We are surprised by the comment as we did not state that the Kabel et al. record and our record are similar. The Gotland Basin is significantly deeper than the Little Belt region and elevated temperatures at the latter site may simply be due to a shallower production depth and consequently higher water temperature. Trends in both records, however, are indeed similar. The Kabel et al. record has been added to Fig. S2.

Referee 3: "As for the TEXL86, a calibration based on lake sediments (Rampen et al., 2014) should be used for the samples from EZ1. The strong temperature increase (10 ◦C) at the transition between EZ1 and EZ2 may be an artefact due to the different calibrations as discussed in lines 659-661."
Authors: Unfortunately, this comment is not clearly phrased. We assume that Referee 3 refers to the LDI? In any case, we now applied the lake specific calibration by Rampen et al. (2014) to sediments deposited in the freshwater environment of EZ1 (the putative Ancylus Lake phase) to reconstruct surface water temperatures.

Referee 3: "The Diol Index is not convincing as surface salinity proxy. It suggests similar conditions/salinity during the freshwater lake, as well as in the mid-Littorina Stage (ca. 4,500- 4000 cal. yr BP) and maybe the late Littorina Stage (ca. 1,000-500 cal. yr BP), although the Littorina Stage was marine-to-brackish. While salinity may affect this index together with temperature, I suggest removing this proxy from the study, or discussing it in more details."
Authors: We cannot completely agree with the reviewer. Obviously, it is true that the index suggests that the salinity was similar during the freshwater lake stage and specific intervals during the Littorina Sea stage. Yet, however, the diol index is an empirical measure that does not gradually change with salinity but allows a rough separation of freshwater, brackish-marine and marine conditions with some overlap. The diol index, however, shows a similar trend as *Gymnodinium* suggesting that there was an intermediate interval of "fresher" conditions in the Little Belt region. Based on this observation, we consider the diol index a valuable addition to our proxy records but discuss it potential constraints in more detail.

Referee 3: "Based on the proxy results, it is in my opinion difficult to separate between surface and deep salinity changes, especially at 37 meter water depth. The salinity history reconstructed here concerns probably rather the complete water column. While a precipitation increase (pollen-based record) may explain a salinity decrease between 8,000 and 4,000 cal. yr BP, why is the salinity increasing/high between 4,000 and 1,000 cal. yr BP, while the precipitations are highest? Please, discuss the potential mechanisms for this salinity increase, as well as for the salinity decrease over the last 1,000 years. Considering the high heterogeneity in the different temperature proxies from Site M0059, some previously published, marine-based and pollen-based temperature records as mentioned in lines 626-636 should be plotted in Fig. 4 for comparison."
Authors: We agree, and have now added increased evaporation as a potential mechanism for the salinity increases after 4,000 cal. yr BP. Concerning additional temperature records, see below (e.g. comments concerning Figure 4).

Referee 3: "A discussion concerning the forcing and mechanisms behind the temperature records and the difference in the temperature trends of the proxies is missing, or not thorough enough. Why are the LDI and TEXL86 records that much different although both should reflect summer temperature? Why are the pollen-based and TEXL86-based summer temperature records that much different? Why are the trends in MTCO and MTWA opposite? What are the expected/modeled evolutions of winter and summer temperature in northern Europe during the Holocene? How does seasonality change over the Holocene? What about insolation? Etc . . ."
Authors: This is also in context with the question if other records should be discussed and to what degree forcing should be included in the discussions. As mentioned above, and also enforced by several points of referee 3 discussed above, we think that the applicability of the proxies and related problems should be in the discussion focus and that some of the questions named by referee 3 should be addressed in future studies. In the revised discussion and in the method sections, we have better addressed some of the questions concerning the temperature proxies.

Referee 3: „Minor comments (some redundancy with the major comments is possible):

Lines 124-125: Are those surface or deep currents?
Authors: We have now provided more details here. The outflowing low salinity water surely flows at the surface and remains traceable there to some degree. The saltier, denser water flows along the bottom, sinks when it crosses a sill and only becomes shallower when it mixes with other, lower saline water masses.

Referee 3: "Lines 145-147: What are the time intervals for "a transitional low salinity phase" and "the Littorina Stage"? Please, add."
Authors: We have added information on the time.

Referee 3: "Line 330: Is now published in Marine Geology."
Authors: We have updated the reference.

Referee 3: "Lines 340-343: For consistency, these lines should be moved to Section 3.2. What is meant with "... and between Holes (Fig. 2)."?"
Authors: We have removed the confusing "and between Holes", but we are not sure why this should be moved to 3.2 since we regard the pollen preservation as important for the robustness of the pollen-based stratigraphy and the correlation with the Lake-Belau record.

Referee 3: "Chapter 3.3.2 (font size too small): A reference to Fig. 3 is missing."
Authors: Two references have been added. The font size for the title of section 3 was corrected.

Referee 3: "Line 491: Why not mentioning that this is the Ancylus Lake Stage as in van Helmond et al. (2017)?"
Authors: In opposite to van Helmond et al., there is no agreement among us that this is unequivocally the Ancylus Lake Stage. The related sentence has been removed anyway according to another referee comment.

Referee 3: "Line 502: Why "lowermost part"? The complete EZ1 suggests freshwater conditions."
Authors: The sentence has been rephrased.

Referee 3: "Lines 504-505: But this is in disagreement with van Helmond et al. (2017) suggesting a eutrophic freshwater environment with high productivity..."
Authors: True, the discrepancy is now mentioned.

Referee 3: "Lines 510-511: To be as correct as possible, a TEX86 global calibration for lakes (e.g. Powers et al., 2010, Organic Geochemistry) should be applied for the samples from EZ1, as this latter is characterized by freshwater conditions."
Authors: We agree with the reviewer and now apply the mentioned freshwater TEX_{86} calibration to the samples from unit EZ1.

Referee 3: "Lines 537-538 and 541: Could you develop/discuss these sentences about foraminiferal 18O? It could also be a temperature effect ..."
Authors: Change in $d^{18}O$ indeed could also be a temperature change, but temperatures based on the other proxies mainly decrease during this interval, and the change in salinity would fit with the assemblage based changes. Therefore it seems more likely that the change in $d^{18}O$ is mainly salinity.

Referee 3: "Lines 546-547: On which proxy (proxies) are these salinity values based?"
Authors: It has now been added that they are based on ostracods.

Referee 3: "Line 549: The values of the Diol Index are as low as in freshwater water conditions. This is not so realistic."
Authors: As previously mentioned the diol index does not gradually change with salinity and absolute

values of this proxy should be interpreted with caution. Changes in the diol index, however, indicate a freshening of the Baltic Sea during the Littorina Sea phase, which is in agreement with variations in *Gymnodinium*. However, we agree that absolute diol index values might be somewhat misleading and now provide information on possible pitfalls in the interpretation of this index in the discussion.

Referee 3: "Line 552: I'm not convinced about this decreasing surface salinity as (1) the results based on the Diol Index are not realistic and (2) there is no trend in the diatom assemblages."
Authors: But marine and brackish-marine diatoms are decreasing after ca. 5500 yr BP, too, as we now added. Concerning the "realism" of the Diol Index, also see comment above.

Referee 3: "Lines 562-565 and 576: The peak (one sample ...) in marine diatoms is not synchronous with the high values of the Diol Index that occurred after the transition. These are two distinct events. And the Diol Index values are not "particularly high" compared to the rest of the record."
Authors: We admit that the peak in the Diol Index is around 900 cal. yr BP, not between 1,000 and 1,200 cal. yr BP, but a sample for the Diol Index at around 1,150, if not "particularly high", still shows high values compared to the average value of the whole record. Furthermore, there are three samples between 1.000 and 1.200 yr BP with high marine diatom percentages. While we do thus not completely agree, we have added that the values of the Diol Index are already high since ~3,000 cal. yr BP.

Referee 3: "Lines 569-570: Why is "1,700 cal. yr BP" written here in brackets? While the high productivity together with the high precipitation during EZ3 is apparent, there is nothing particular at ca. 1,700 cal. yr BP."
Authors: The related part of section 4.1 has been rephrased and shortened.

Referee 3: "Lines 571-572: This sentence is not clear. Please, explain."
Authors: This sentences has been removed.

Referee 3: "Line 590: Replace with "between 2,000 and 300 cal. yr BP"."
Authors: The two peaks are at ca. 2,000 and 300 yr BP (so writing "between" would be imprecise), we have added that there are two mass occurrences.

Referee 3: "Line 593: For consistency with van Helmond et al. (2017), please use Medieval Climate Anomaly (MCA)."
Authors: While it is reasonable to be consistent with Helmond et al., we prefer MWP since the term "anomaly" is rather unfortunate in the opinion of several of our co-authors (though others agree with referee 3). We have, however, now added "(also called Medieval Climate Anomaly)".

Referee 3: "Line 599: This sentence is long. Suggestion: "... ostracods. As the assemblage ..."."
Authors: Has been shortened in context with another referee comment.

Referee 3: "Line 611: Why not mentioning the pollen-based transfer function as organic temperature proxy?"
Authors: This is done in the following paragraph.

Referee 3: "Line 618: "... are feasible ..." sounds strange, wouldn't e.g. "... were obtained ..." be better?"
Authors: We have rephrased this sentence.

Referee 3: "Line 622: Change "comprising" to e.g. "representing"."
Authors: We have changed it to "from the interval between", since these two samples neither comprise nor can represent 100 yrs.

Referee 3: "Line 623: Replace "... fits well with ..." with "... are close to ..."."
Authors: Done.

Referee 3: "Lines 624-626: If possible, a calibration based on lake sediments (Rampen et al., 2014) should be used here. The strong temperature increase (10 ◦C) at the transition between EZ1 and EZ2 may be an artefact due to the different calibrations as discussed in lines 659-661."
Authors: As mentioned above, we now applied the lake specific calibration by Rampen et al. (2014) to sediments deposited in the freshwater environment of EZ1 to reconstruct surface water temperatures of the putative Ancylus Lake phase. The data is now presented in the "results section" and discussed in the manuscript.

Referee 3: "Lines 626-636: Some of these records (marine-based and pollen-based) should be shown here for comparison, especially considering the high heterogeneity in the different temperature proxies from Site M0059. A reference to Krossa et al. (2017) alkenone-based records form the Skagerrak is missing."
Authors: We agree only to some degree here – for example, the pollen-based records including temperature data are quite far away and from a terrestrial archive. Furthermore, we want to avoid too many or too complex figure (see above/below). Compare our answers to the comments to Fig. 4 – we have now added a comparison with the Kabel et al record in Figure S2 (plus different calibration methods for the biogeochemical proxies), but we would prefer not to add too many other records. The reference has been to Krossa et al. 2017 has been added.

Referee 3: "Lines 632-633: Because of the extremely low and inconstant sample resolution of the clumped isotope record, no trend can be seen. Remove this part of the sentence. For the same reason, I would further suggest to remove the lines between the dots in Fig. 4. Such an extrapolation is not realistic."
Authors: We agree. The sentence has been rephrased and we have changed Fig. 4 in accordance with the comment.

Referee 3: "Line 641: Change MWP into MCA."
Authors: We prefer MWP but we have now made sure that all texts (also figure captions, see below) use the same terms consistently.

Referee 3: "Lines 655-657: This sentence is not necessary. It could be removed.
Lines 661-663: This sentence is not necessary. It could be removed."
Authors: Here, we do not agree. There are only few studies that have used the LDI in paleotemperature studies yet and the study in referred to in the sentence demonstrates that the LDI reflects summer SSTs in other oceanographic regions which is in agreement with our observation. We, therefore, prefer to leave the sentence as is.

Referee 3: "Lines 667-668: However, the oldest three samples of the TEXL86 record are missing, what makes a true comparison difficult. I suggest removing "...absolute temperatures based on the TEXL86 lipid paleothermometer and ..."."
Authors: The sentences has been rephrased in context with the changes to section 4.2. The three samples are now added.

Referee 3: "Lines 667-668: If not done, add a line break here. The text is much too dense."
Authors: See reply to previous comment.

Referee 3: "Lines 672-674: Remove this sentence. If a summer calibration (Kabel et al., 2012) is used, than the reconstructed SST should be close to summer SST."
Authors: We have left this sentence in the discussion, but we hope that this is all right in context with the generally improved discussion regarding different calibration methods.

Referee 3: "Lines 674-676: No, the TEXL86 record is NOT "... to some degree similar to the clumped isotope record". The temperatures are equally high in the HTM and the modern in the clumped isotope record, but not in the TEXL86 record. The absolute values are different as well. Remove this part of the sentence. And change the end of the sentence in " ... as well as the temperature records based on pollen and Mg/Ca ratios of benthic foraminifera.""

Authors: This has been rephrased accordingly.

Referee 3: "Lines 685-688: Please, plot the TEXL86 temperature data of Kabel et al. together with Site M0059 on Fig. 4. I suspect that these records are that similar concerning both the temperature amplitudes and the trends. Remove "the" before "TEXL86"."

Authors: As mentioned previously, the settings of the shallow, near coastal Little Belt site and the deep, offshore Gotland Basin site are very different. Temperatures are obviously different between both sites, which may be attributed e.g. to a deeper production depth in the Gotland Basin. However, trends between both sites are similar with comparatively high water temperatures during the MCA and MHP.

The sentence has been changed so that the desired change is obsolete. We have added the Kabel et al. data to supplementary Fig. S2.

Referee 3: Lines 713-714: But this concerns only a very little aspect/part of the records ... This is not really convincing. Same comment for the Abstract.

Authors: Here, we do not agree with Referee 3. Significant changes in the lithology and depositional environment occur at the transition from EZ1 to EZ2 and our aim was to document how these changes affect and/or impact the different salinity and temperature proxies used in this study. Although the transition comprises only a small part of the sediment profile it is a highly significant aspect of the presented research.

Referee 3: "Line 718: NO ! This temperature increase is very probably an artefact."

Authors: Considering that we now have also TEX^{L}_{86} datapoints for this interval and that the lake-specific calibration by Rampen et al. (2014) was applied (see above) for the LDI-based temperature reconstructions, we kept this sentence (but added "probably"). Using the lake-specific calibration, the reconstructions for the four lowermost datapoints (EZ1) imply temperatures which are ca. 4 °C higher compared to the calibration for marine conditions. This means that there is still a rapid increase between EZ1 and EZ2, but not as rapid as before.

Referee 3: Line 726: But no quantitative record is shown in this study...

Authors: This might be a misunderstanding: Are the temperature reconstructions not quantitative? We are not sure what is meant here.

Referee 3: "Lines 727-730: These results are based on a figure from the supplements..."

Authors: We are not sure if this is a problem:

We assume that our original approach to discuss this aspect, but to put the related Fig. S1 in the supplement is a good compromise to save space.

Referee 3: "Figures:
Fig. 2: Please change MWP to MCA and HCO to HTM (for consistency with the text)
and explain the acronyms (LIA as well)."

Authors: We have discussed this, most of us prefer "MWP" over "MCA", but we agree that there should be consistency to the text and have thus changed the text accordingly.

Referee 3: "Fig. 3: For consistency with the text, please rename "Diatom abs. Abundance" into "Abs. Diatom Abundance (ADA)". And add "(CRS)" after "Chaetoceros resting spores"."

Authors: We have now done so.

Referee 3: "Fig. 4: Why no GDGT-based data exist for the three deepest/oldest samples although LDI-based data are present? Please change MWP to MCA and HCO to HTM (for consistency with the text) and explain the acronyms (LIA as well). Plot the TEXL86 temperature data of Kabel et al. together with Site M0059. The scale of the BIT index is not readable. The BIT index should be removed and should be plotted correctly (e.g. with a break in the Y axis) with the TEXL86 temperature record as supplementary figure. Add 2 previously published temperature records from the region (1 pollen-based and 1 marine-based record). The text in the topmost part should be turned over."

Authors: Three additional samples from EZ1 have been measured and are now added to the manuscript. We have changed Figs. 4 according to several of Referee 3's suggestions and reorganized the figure text. However, in order to avoid to make the figure even more complex, we use a supplementary figure (new Fig. S2) to show the Kabel et al data vs. our data. The BIT index has been moved to the supplementary figure, as suggested. To Fig. S2, we have also added different calibrations, particularly lake calibrations (following e.g. Powers et al. 2010) for the lowermost samples (EZ1). Concerning pollen-based data, we are not aware that the modern analogues technique has yet been used on a record close to Site M0059. One reasonable approach would be to apply the MAT to the record from Lake Belau, but this should rather be done in the framework of a separate publication which also features a higher resolution for Site M0059. Similarly, a comparison with pollen-based temperature reconstruction based on other methods and from sites which are far away from Site M0059 might be too complex for the scope of our MS, though we agree that this would be a good thing to do. Unfortunately, records like the one from Antonsson et al. (2006) are very far away and far inland, so we do not think that they are directly comparably. In order to show a "validation" of the pollen-based data, we have added a curve to the suggested supplementary figure (Fig. S2) which shows the similarity of the used pollen analogues to the fossil samples.

Referee 3: Supplementary information:
Where are the captions for Tables S1 to S4?
Authors: Captions have been added.

References not listed in the Manuscript

Antonsson, K., Brooks, S.J., Seppä, H., Telford, R.J., Birks, H.J.: Quantitative palaeotemperature records inferred from fossil pollen and chironomid assemblages from Lake Gilltjärnen, northern central Sweden. J. Quaternary Sci. 21, 831-841, 2006.

Reconstructing Holocene temperature and salinity variations in the western Baltic Sea region: A multi-proxy comparison from the Little Belt (IODP Expedition 347, Site M0059)

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Abstract

Sediment records recovered from the Baltic Sea during Integrated Ocean Drilling Program Expedition 347 provide a unique opportunity to study paleoenvironmental and -climate change in central/northern Europe. Such studies contribute to a better understanding of how environmental parameters change in continental shelf seas and enclosed basins. We present a multi-proxy-based reconstruction of paleotemperature (both marine and terrestrial), -salinity, and -ecosystem changes from the Little Belt (Site M0059) over the past ~8,000 years, and evaluate the applicability of inorganic- and organic-based proxies in this particular setting.

All salinitySalinity proxies (diatoms, aquatic palynomorphs, ostracods, long chain diol index— LDI) show that lacustrine conditions occurred in the Little Belt until ~7,400 cal. yr BP. A connection to the Kattegat at this time can thus be excluded, but a direct connection to the Baltic Proper may have existed. The transition to the brackish-marine conditions (more saline and warmer) of the Littorina Sea stage (more saline and warmer) occurred within ~200 yr when the connection to the Kattegat became established (~7,400 cal. yr BP).

The different salinity proxies used here show similar trends in relative changes in salinity, but do often do not allow quantitative estimates of salinity.

-The reconstruction of water temperatures is associated with particular large uncertainties and variations in absolute values by up to 8 °C for bottom waters and even up to 16 °C for summer surface waters. Concerning the reconstruction of temperature using foraminiferal Mg/Ca-ratios reconstruction, contamination by authigenic coatings in the deeper intervals may have led to an over-estimation of temperatures. Differences in results based on the lipid paleothermometers (long chain diol index proxies (LDI and TEX^{L}_{86}) can partly be explained by the application of modern-day proxy calibrations to intervalsin areas which experienced significant changes in depositional settings, in case of our study e.g. change from freshwater to marine conditions. Our study shows that particular caution has to be taken when applying and interpreting proxies in coastal environments and marginal seas, where water mass conditions can experience more rapid and larger changes than in open-ocean settings. Approaches using a multitude of independent proxies may thus allow a more robust paleoenvironmental assessment.

1 Introduction

Recent~~Coastal marine environments are particularly susceptible to global~~ climate change is~~(IPCC, 2014). With ongoing climate change, sea water is warming, and together with circulation changes and human-induced eutrophication this results in decreasing dissolved oxygen concentrations in many areas worldwide (Keeling and Garcia, 2002; Meier et al., 2012). This is particularly the case in semi-enclosed basins such as the Gulf of Mexico (Osterman et al., 2005; Platon et al., 2005), (Scandinavian) fjords (Gustafsson and Nordberg, 2000; Filipsson and Nordberg, 2004), and the Baltic Sea (Diaz and Rosenberg, 2008; Conley et al., 2011; Gustafsson et al., 2012). Climate change in recent decades is also~~ showing a persistent trend to a more positive state of the North Atlantic Oscillation resulting in wetter conditions especially over northern Europe (Hurrell, 1995; Visbeck et al., 2001). Further increased~~Increased~~ westerly winds together with a changed barotrophic pressure gradient may result in ~~would lead to~~ increased inflows of open-marine waters and therewith more saline deep waters in~~water into~~ the Baltic Sea in the future (cf. Meier et al., 2006; Meier, 2015). Concomitantly~~. Furthermore~~, the increase in continental runoff due to increased precipitation may result in a freshening of the surface waters in the Baltic Sea (Matthäus and Schinke, 1999; Gustafsson and Westman, 2002).

Both temperature and salinity changes will thus have important consequences for the Baltic Sea environment (e.g. Meier et al., 2012). To improve our understanding of the impact and magnitude of future environmental changes~~change~~ in the Baltic Sea region, it is essential~~advantageous~~ to generate high-resolution paleo-reconstructions in order to investigate how salinity and temperature varied in the past (e.g. Zillén et al., 2008; Andrén et al., 2015a; Ning et al., 2017).~~).~~ A multi-proxy approach, comprising proxies representative for bottom water, surface water and air (terrestrial) conditions, is used here~~allows us~~ to reconstruct a wide array of environmental change (in particular~~especially~~ temperature and salinity) from the same or closely neighbouring samples, and thus, how conditions simultaneously changed within~~with~~ the same age constraints.

The occurrence of specific species of ostracods and foraminifera are important indicators of bottom water parameters, in case of the Baltic Sea primarily salinity (Lutze, 1965; 1974; Murray, 2006; Frenzel and Boomer~~et al~~., 2005; 2010; Viehberg et al., 2008). Additionally, stable oxygen and possibly carbon isotopes in foraminifera are commonly related to changes in salinity, though stable oxygen isotopes are also influenced by temperature and global ice volume, while productivity is another control factor for carbon isotopes (Kristensen and Knudsen, 2006, Filipsson et al., 2016~~in press~~). Bottom water temperatures ~~(BWT)~~ can be reconstructed using Mg/Ca in benthic foraminifera (Raitzsch et al., 2008), but large gradients in salinity (and low absolute salinity) as well as parameters related to the carbonate system (e.g. alkalinity and carbonate saturation state)~~the specific conditions~~ in the Baltic Sea may significantly influence the application of Mg/Ca ratios (Groeneveld and Filipsson, 2013).

Due to the low salinity and overall shallowness of the Baltic Sea, planktonic foraminifera are absent from the Baltic Sea region (Seidenkrantz, 1993; Andrén et al., 2015a). Diatoms and marine palynomorphs like dinoflagellates, however, are common and often very good indicators of changes in salinity (Andrén et al., 2000; Snoeijs and Weckström, 2010; Ning et al., 2015).

A proxy which appears to be only dependent on temperature and may therefore be ideal for the Baltic Sea are clumped isotopes on molluscs (Henkes et al., 2013; Wacker et al., 2014).~~.~~ This proxy has not yet been applied to samples from the Baltic Sea. 'Clumped isotopes' (~~,~~ or, more correctly, 'clumped isotopologues')~~,~~ are isotopic molecules that contain more than one rare isotope (e.g.~~for example,~~ the carbonate isotopologue $Ca^{13}C^{18}O^{16}O_2$). The abundance of these molecules in carbonate is determined by the formation temperature of the mineral.

~~Due to the low salinity and overall shallowness of the Baltic Sea, planktonic foraminifera are absent from the Baltic Sea (Andrén et al. 2015a). Diatoms and marine palynomorphs like dinoflagellates, however, are common and often very good indicators of changes in salinity (Andrén et al., 2000; Snoeijs and Weckström, 2010; Ning et al., 2015).~~

The lipid paleothermometer TEX_{86} (TetraEther index of tetraethers consisting of 86 carbon atoms), based on the sedimentary distribution of isoprenoid glycerol dialkyl glycerol tetraethers (GDGTs) produced by pelagic Thaumarchaeota, has been successfully used in the reconstruction of sea water temperatures in numerous paleoceanographic settings~~) and its derivatives~~ (Schouten et al., 2002; 2013). A derivative of this proxy is the TEX^{L}_{86}, which in low temperature environments (generally below 15 °C) shows a high correlation with sea surface temperature (SST; Kim et al., 2010).~~) is frequently used to reconstruct SSTs.~~ In the Baltic Sea, the TEX^{L}_{86} has been shown to be best correlated~~correlate well~~ with late summer SSTs and ~~it has been~~ used to investigate climate-induced variations in water temperature~~-driven changes in SST~~ over the past ~1,000 yr (Kabel et al., 2012), while complete TEX^{L}_{86} records of Holocene climate change are yet missing.~~).~~ A more recently introduced proxy that shows promise in paleoenvironmental studies is the long chain diol index~~LDI~~ (Rampen et al., 2012). This proxy makes use of the sedimentary distribution of long chain diols ~~(LCDs)~~ synthesized by eustigmatophytes and ~~in different marine settings~~ has been suggested to either reflect an annual (Rampen et al., 2012; de Bar et al., 2016) or a summer SST signal (Lopes dos Santos et al., 2013) in marine settings.~~).~~ In addition to SST, however, salinity has been observed to also affect the distribution of long chain diols~~LCDs~~ in aquatic environments and consequently the diol index has been proposed as a tool to qualitatively assess relative changes in freshwater input to marine environments (Versteegh et al., 1997). An alternative mean to investigate past climate dynamics is provided by terrestrial~~Terrestrial~~ palynomorphs such as pollen grains. The ~~are ideal biotic proxies for the reconstruction of continental environmental and climate dynamics. Techniques such as the~~ modern analogues technique (MAT) and similar approaches furthermore allow calculating quantitative climate data (e.g. temperature, precipitation, seasonality) from pollen assemblages (e.g. Guiot, 1990; Kotthoff et al., 2008;~~,~~ 2011).

Despite a large amount of proxy-based research performed in the Baltic Proper (e.g. Zillén et al., 2008; and references therein, Kotilainen et al.,~~,~~ 2014), there are no continuous ~~high-resolution~~ records from the Baltic Sea and its connections to the Kattegat (Little Belt, Great Belt, and Öresund) enabling~~surpassing ~20 m sediment length (Andrén et al., 2009; Bennike and Jensen, 2011). Such records would enable~~ multi-proxy studies in high temporal resolution for the entire Holocene (Andrén et al., 2015a), and particularly the Holocene history of the Little Belt has not been~~and possibly further back~~ in the focus of research (Bennike and Jensen, 2011). ~~time.~~ Continuous high-resolution records would not only allow correlation between the different basins in the Baltic Sea region but also provide a connection to terrestrial archives~~ and moreover to Greenland ice core records and marine records from the North Atlantic~~.

In the framework of International Ocean Drilling Program (IODP) Expedition ~~(Exp.)~~ 347, ~~drilled~~ a series of long, continuous sediment records in the Baltic Sea region was recovered that allows reconstructing environmental change in central/northern Europe in an unprecedented manner (Andrén et al., 2015a, b). Here we present a centennial-resolution multi-proxy study of IODP Expedition~~Exp.~~ 347 Site M0059 from the Little Belt, one of the connections between the Baltic Sea and the North Sea, using a variety of different proxies which are commonly used in paleoceanography to reconstruct past sea water temperature and salinity. We investigate how these proxies perform in a proximal setting like the Little Belt and how they link to seasonality. We selected the last ~8,000 yr at~~of~~ Site M0059 (top ~53 m of sediment) which~~to~~ include the transition from freshwater to brackish/marine conditions.~~, creating the connection between the Baltic Proper and the Kattegat.~~ We show that a multi-proxy approach allows unravelling~~to unravel~~ the different factors which have influenced past conditions in the Little Belt, suggesting that its history may have been partly different from that of the Baltic Proper.

2 Regional setting~~settings~~ and methods

2.1 Regional setting

The Baltic Sea is connected to the North Sea by ~~, including the Gulfs of Bothnia, Riga and Finland, covers an area of 33,793 km^2 and spans a distance from~~ the ~~53° to 66°N latitude (Leppäranta and Myrberg, 2009; Fig. 1). The~~ Belt Seas~~Sea~~, including the Öresund, the Great Belt, and the Little Belt~~, connects the Baltic Sea to the North Sea,~~ through the Kattegat and Skagerrak. It~~The Baltic Sea~~ is one of the world's largest brackish water bodies, with a surface water salinity ranging from close to zero in the innermost parts of the Gulf of Finland, seven in the Baltic Proper and between 8 and 24 in the Belt Sea. A halocline, varying between 20 and 80 m water depth in the different subbasins, separates the upper water masses~~mass~~ from more saline bottom waters~~water~~. The mean water depth is 54 m, varying between 25 and 200 m with the deepest basin, the Landsort Deep (central Baltic Sea) having~~reaching~~ a maximum depth of 459 m (e.g. Leppäranta and Myrberg, 2009). The Baltic Sea basin is surrounded by two biomes, from temperate forest with mixed coniferous and broad-leaved trees in the south to boreal forest with taiga-like conditions in the north.

Currents ~~As one of the three straits connecting the Baltic Proper to the Kattegat, currents~~ in the Little Belt consist of either relatively low salinity (14-17) surface water flowing out of the Baltic Sea into the Kattegat or higher salinity (>24) currents flowing into the Baltic Sea. Depending on the volume and mixing rate the denser, inflowing water sinks after passing the main sills and can therefore be encountered at different water depths in the Baltic Proper. Because the Baltic Sea has a surplus of freshwater input, i.e. the input of water by precipitation and rivers exceeds evaporation, a positive barotropic pressure gradient exists between the Baltic Proper and the Kattegat, so that under 'normal'~~normal~~ conditions surface waters flow from the Baltic Proper into the Kattegat (HELCOM, 1986; Jakobsen and Ottavi, 1997). The contribution of water mass transport through the Little Belt is minor (<10%) in comparison to~~with~~ the Great Belt and the Öresund (HELCOM, 1986~~Jacobsen, 1980~~). Occasionally the surface flow reverses and more saline water enters over the sills into the straits (Matthäus and Schinke, 1999;

Mohrholz et al., 2015). The higher salinity causes the inflowing water to sink and continue as subsurface water into the Baltic Proper. Because~~This contrast in salinity results in a strongly stratified water column. However, because~~ the Little Belt is very narrow, with high current velocity and turbulence, a major marine inflow from the Kattegat can lead to mixing of the water column (Jakobsen and Ottavi, 1997).

Mean surface water salinity in the Little Belt was 15.9±0.4 for a 10-yr period (2004-2014), varying between 14.2±0.9 in spring and 17.6±1.5 in autumn, while mean bottom water salinity was 23.6±1.0 varying between 21.5±0.9 in winter and 25.2±1.1 in summer (ICES, 2017). During~~In~~ the same time period~~Little Belt region~~, the mean annual SST was~~ averaged over a time interval from 2004-2014 - is~~ 10.6±0.6 °C (ICES, 2017). The mean winter SST was~~is~~ 2.5±1.5 °C, while the mean summer SST was~~is~~ 17.6±0.7 °C with maximum water temperatures of 21-22 °C observed from late July to mid-August (ICES, 2017). Bottom water temperatures averaged~~average~~ 7.6±0.6 °C and varied~~vary~~ between 4.3±0.7 °C in winter and 9.3±1.3 °C in summer (ICES, 2017).

The Baltic Sea region has experienced several climate-driven hydrological changes during the Holocene. Its history is highly dynamic and governed by the regional isostatic rebound and global sea level changes resulting in alternating freshwater and brackish phases and complex shoreline development (e.g. Björck~~, 1995~~, 2008; Knudsen et al., 2011; Andrén et al., 2011). The time interval investigated in this study comprises the transition from freshwater ~~conditions~~ to the brackish-marine conditions of the Littorina Sea stage to the present brackish Baltic Sea~~.~~ In the Baltic Proper, the Baltic Ice Lake (~16,000 to ~11,700 cal. yr BP) was followed by the partly brackish Yoldia Sea stage (~11,700 to ~10,700 cal. yr BP), the lacustrine Ancylus Lake stage (~10,700 to 10,200 cal. yr BP), a transitional low salinity phase (~10,200 to ~7,400 cal. yr BP), and~~and finally~~ by the Littorina stage (~7,400 cal. yr BP; (e.g. ~~Andrén et al. 2000;~~ Sohlenius et al., 1996; Andrén et al., 2000; Björck, 2008; Andrén et al., 2011).

2.2 Material and methods

During IODP Expedition~~Exp.~~ 347, cores were recovered from five holes (A to E) at Site M0059 (Little Belt; Fig. 1), at ~37 m water depth (55°0.29′N, 10°6.49′E). The results of our multi-proxy analyses are based on sediments from Holes A, C, D, and E. For most proxies, ~35 samples have been analysed.

2.2.1 Sedimentology and age model

The sedimentology of Holes M0059A, D, and E was assessed in the framework of the expedition's~~IODP Exp. 347~~ onshore science party (Andrén et al., 2015a, b). The sedimentary sequence of IODP Site M0059 has been divided into seven lithostratigraphic units based on visual core descriptions and smear slide analyses (Andrén et al., 2015a), from which~~). Only~~ subunits Ia and Ib have been investigated in this~~the present~~ study. Subunit Ia (0-49.37 meters composite depth – mcd) is composed of mostly homogeneous black to greenish black clay, with some millimetre-scale laminations. It was deposited under brackish-marine conditions, as indicated by diatom assemblages (Andrén et al., 2015a; Fig. 2). Subunit Ib (49.37-53.57 mcd) is a ~~downhole~~ continuation of Subunit Ia. Its base consists of 10-15 cm of black laminated clays. The remainder of Unit Ib comprises greenish to gray, silty clay, intercalated by centimetre-scale pale green laminae. The~~Silt and the~~ presence of freshwater diatoms indicates~~indicate~~ lacustrine conditions (Andrén et al., 2015a, Fig. 2). Magnetic susceptibility data (supported by natural gamma ray and gamma ray attenuation density data) collected from Holes M0059A-E~~–M0059E~~ were used to correlate between each hole and to construct a composite splice section for IODP Site M0059 including a meters composite depth (mcd) scale (Andrén et al., 2015a), which was~~). This scale is~~ used in this study.

The age model for IODP Site M0059 is based on 16 radiocarbon dates derived~~taken~~ from bivalve fragments and intact bivalve specimens (*Abra alba*, *Macoma balthica*; Table 1; supplement Table S3).~~).~~ Age-depth modelling was performed with CLAM (version 2.2; Blaauw, 2010) with 2000 iterations using the Marine13 calibration dataset (Reimer et al., 2013) and with a deviation (ΔR) of -90 ± 53 from the Marine13 reservoir age. A detailed description of the age reconstruction is given by Van Helmond et al. (2017~~accepted~~). Below 48.64 mcd, the ages have been extrapolated linearly, assuming a constant sedimentation rate, because no material suited for dating purposes was recovered from the deeper sections of the sediment sequence.~~.~~ In order to confirm the precision of the ^{14}C-based age model, we have biostratigraphically compared the marine pollen record from IODP Site M0059 (Fig. 2; see below) with a pollen record from varved sediments in Lake Belau in northern Germany (Fig. 1; Dörfler et al., 2012).

Table 1: AMS radiocarbon dates from Expedition 347, Site M0059, for more detailed information compare Table S3 (supplement) and van Helmond et al. (2017).

Laboratory ID (LuSNo)	Mean composite depth (m)	Material dated	^{14}C Age (yr)	Error (yr)	Calibrated age (yr; median)
11289	2.84	*Abra alba*	700	35	405
11476	4.97	*Abra alba*	1265	35	899
11291	8.79	*Abra alba*	1585	35	1213
11292	14.24	*Macoma balthica*	2740	40	2556
11477	21.14	*Macoma balthica*	3780	35	3829
11295	23.49	*Macoma balthica*	4035	40	4187
11479	26.60	*Macoma balthica*	4395	40	4664
11297	27.03	*Macoma balthica*	4500	40	4785
11480	28.20	*Macoma balthica*	4540	40	4845
11300	29.51	*Macoma balthica*	4780	40	5147
11481	31.80	*Macoma balthica*	4890	40	5313
11482	34.05	*Abra alba*	5155	40	5603
11301	35.39	*Abra alba*	5415	40	5885
11483	38.04	*Abra alba*	5770	40	6289

11303	39.75	*Macoma balthica*	6130	40	6662
11304	48.64	bivalve fragments	6845	45	7437

2.2.2 Geochemistry

In order to measure the total organic carbon (TOC) content, sediment samples from Holes C and E were freeze-dried, powdered and homogenized using an agate mortar and pestle. About 0.3 g of powdered sediment per sample was decalcified using 1M HCl. Subsequently the samples were washed repeatedly with milliQ water after which they were dried for 72 h at 60 °C. Finally, the samples were powdered and homogenized again, after which they were measured using a Fisons Instruments NA 1500 NCS analyser at Utrecht University, the Netherlands. Results were normalized to international standards and TOC was calculated upon correction for weight loss by decalcification. The average analytical uncertainty of 0.07 wt.% was calculated based on duplicate analysis of sediment samples (Van Santvoort et al., 2002).~~.~~

2.2.3 Palynology and pollen-based quantitative climate reconstructions

For the analysis of terrestrial and marine palynomorph assemblages, 36 samples of ~1 cm thickness were taken from 0 to ~53 mcd. Per sample, 1 to 6 g of sediment was processed using standard palynological techniques (HCl and HF treatment and sieving with 7-µm mesh) for marine sediments (e.g. Kotthoff et al., 2008). *Lycopodium* marker spores were added to the samples in order to calculate palynomorph concentrations (Stockmarr 1971; Fig. 2, Fig. 3). When~~Whenever~~ possible, >200 terrestrial palynomorphs (excluding spores and bisaccate pollen grains) were determined and counted per sample under 400 to 1000x magnification. In addition, organic-walled dinoflagellate cysts (dinocysts; as indicators for marine conditions; e.g. de Vernal~~Zonneveld~~ and Marret, 2007~~Pospelova, 2015~~) and freshwater algae (as indicators for freshwater influence; e.g. Mudie et al., 2002) were determined and counted when occurring. We did not aim at counting a certain sum of dinocysts per samples, since their absolute amount varied greatly over the analysed interval. On average, 50 dinocysts were identified per sample. This relatively low value is explained by the general rarity of dinocysts~~the counted types~~ in some samples and relatively low dinocyst diversity in the Baltic Sea (e.g. Ning et al., 2016).

Quantitative climate data were calculated from pollen data using the Modern Analogue Technique (MAT; e.g. Guiot, 1990). For this technique numerical methods are used to identify recent analogues for fossil pollen assemblages (e.g. Guiot, 1990; Kotthoff et al., 2008; 2011). Climate conditions for the best modern analogues are considered to be most similar to the conditions during which the fossil pollen assemblage was deposited. The MAT reconstructions are based on a database with >3500 modern pollen spectra from Europe (Bordon et al., 2009) and the Mediterranean area (Dormoy et al., 2009). Here we used the ten modern assemblages with smallest chord distances for the reconstructions of the climate parameters. Bisaccate pollen was removed from the evaluated samples and the database due to its over-representation in marine pollen records (e.g. Kotthoff et al., 2008).

2.2.4 Diatoms

Sediment samples (n = 36; thickness: 1cm in total) for diatomthe analysis of diatoms were freeze-dried. Subsequently, a known mass of sediment, between 0.03 and 0.07 g dry weight, was subsampled from each sampleselected depths and treated according to Warnock and Scherer (2015). Briefly, sediments were cleaned with dilute HCl to remove carbonates and 10 % H_2O_2 to remove organic carbon. The resultant sediment slurry was disbursed in a 2 L square cross-section beaker containing distilled water and a small glass table with known area including a coverslip, allowing for ultimate abundance determination. Coverslips were dried and permanently mounted to glass slides with the mounting media Naphrax (refractive index = 1.65).

Each slide was counted to a minimum of 300 vegetative diatom valves. Absolute diatom abundance (ADA) can be calculated by counting the number of fields of view needed to reach 300 diatoms and scaling the number of diatoms counted in that known area relative to the total amount of surface area the sample settled onto and the original dry weight of the sediment sample (Warnock and Scherer, 2015). Diatoms were identified to the species level according to Snoeijs et al. (1993-1998), Krammer and Lange-Bertalot (1986-1991), and Patrick and Reimer (1966). The salinity preferences and life forms (benthic or pelagic) of diatoms were classified according to Snoeijs et al. (1993-1998, compare Tab. S5). All slides were analysed using differential interference contrast at 1000x magnification and oil immersion. *Chaetoceros* resting spores (CRS) were counted, but not identified to the species level and were not included in the absolute diatom abundance calculations for this study. Analysis of variance (ANOVA) was used to evaluate the differences between the means of these data, accompanied by a Tukey-Kramer test to evaluate pair-wise relationships (for all statistical tests $\alpha = 0.05$). Because data derived from sediment cores is inherently chronological the results of pairwise tests are only reported for adjacent environment zones (EZs). All statistical relationships were evaluated using PAST v. 3.10 (Hammer et al., 2001).

2.2.5 Benthic Foraminifera

Thirty-six samples of 2-cm sediment thickness (20 cm^3ml sediment) were prepared for foraminiferal analyses and wet-sieved through sieves with 63, 100 and 1000 µm mesh. Each fraction was subsequently dried at 40 °C and weighed. The 100-1000 µm fraction was used for the foraminiferal assemblage analysis. In samples with a high concentration of mineral grains, the 100-1000 µm fraction of the samples was subjected to heavy liquid treatment using the heavy liquid tetrachlorethylene (C_2Cl_4) with a specific gravity of 1.6 g/cm^3 to separate foraminiferal tests from mineral grains prior to analysis. The residual fraction after heavy liquid separation was checked for foraminifera; only very few specimens were found and thus only the 100-1000 µm light fraction was used for foraminiferal analyses. To ensure statistical validity of the assemblages, a minimum of 300 individual foraminifera were counted from each sample, when possible. Benthic foraminifera were counted and identified to species level to characterise the faunal assemblages. The benthic foraminiferal concentrations were calculated as number of specimens/cm^3 sediment.

2.2.6 Ostracods

Ostracods were~~Since ostracod material was not abundant enough at Site M0059 to produce reliable percentage data, we used the total abundance of ostracods per 30 cm³ sample. We~~ divided ~~the ostracods~~ into predominant ecological groups and ~~taxa and~~ used their ecological data to reconstruct paleosalinity. A total of 75 ~~30 cm³ sediment~~ samples (each comprising 30 cm^3) were processed for ostracod analysis. Since ostracod material was not abundant enough to produce reliable percentage data, we used the total abundance of ostracods per 30 cm^3. Samples were freeze-dried and washed over a 63-µm sieve and subsequently oven dried in paper filters at 40–50 °C. Ostracods were picked from the entire sample residues and their valves identified and counted.

Two ecological classes of ostracods in relation to salinity were distinguished based on ecological data and distribution of modern taxa in the Baltic Sea and adjacent areas (Frenzel et al., 2010): freshwater and brackish-marine. Among brackish-marine ostracods very shallow and deeper water species were distinguished based on ecological data (Frenzel et al., 2010). Predominance of a very shallow water group implies salinity above 6-10, and an environment such as a lagoon, estuary or very shallow water open sea. The deeper-living ecological group includes species that can be found in the open sea environments at both very shallow and deeper locations with salinity > 7-14.

2.2.7 Stable isotopes in foraminifera

Stable oxygen and carbon isotope ($\delta^{18}O$, $\delta^{13}C$) measurements for 36 samples were performed on 10-20 specimens (100-1000 µm fraction) of *Elphidium selseyense* and *Elphidium*~~*E.*~~ *incertum*. The analyses were performed on a Finnigan MAT 251 gas isotope ratio mass spectrometer equipped with a Kiel I automated carbonate preparation device at the MARUM, University of Bremen, Germany. The stable isotopic data were calibrated relative to the Vienna Peedee belemnite (VPDB) using the NBS19 standard. The standard deviation of the house standard (Solnhofen limestone) over the measurement period was 0.03 ‰ for $\delta^{13}C$ and 0.06 ‰ for $\delta^{18}O$.

2.2.8 Trace metal/calcium in foraminifera

Up to 40 specimens (>150 µm) of *E. selseyense* and 25 specimens of *E. incertum* (>150 µm) were selected for trace metal/calcium analysis. If the number of specimens was not sufficient, both species were combined. Due to poor preservation~~reservation~~, not enough specimens were present for the analysis of Mg/Ca ratios in depths <5 and >30 mcd. Trace metal/Ca in foraminifera from the Nordic/Baltic Seas has been shown to be occasionally affected by diagenetic coatings (Groeneveld and Filipsson, 2013; Ezat et al., 2016). Standard cleaning procedures for trace metal/Ca in foraminifera after clay removal either involve only an oxidation step to remove organic matter (Barker et al., 2003) or also include a reduction step before the oxidation (Martin and Lea, 2002) to remove (oxy)hydroxide coatings. Both methods, however, triggered a reaction on samples of Site M0059 which turned the foraminiferal fragments (dark) brownish. This suggests that an additional contaminating phase was present on the foraminiferal tests which was not removed by reduction but does respond to oxidation. A likely source for this are (Fe)-sulfides, which are easily formed in Baltic sediments including the Little Belt and adsorb cations (Raiswell and Canfield, 1998; Hardisty et al., 2016; Van Helmond et al., 2017~~accepted~~). Oxidation would then turn the (Fe)-sulfide into an (Fe)-hydroxide, which has a brownish color. To remove this phase from the foraminiferal tests the standard combination of reduction and oxidation was reversed. First, oxidation was performed to form the hydroxide, followed by a reduction step to remove this again. As reducing agent 0.1 M hydroxylamine-hypochlorid buffered in a 1 M Na-acetate solution was used (Shen et al., 2001; Steinke et al., 2010). 250 µl reducing agent was added to the samples; the samples were heated for 30 min. at 70° C, and rinsed three times with Seralpur water~~ three times~~. After cleaning, the samples were dissolved and centrifuged for 10 minutes (6000 rpm) to exclude any remaining insoluble particles from the analyses. The samples were diluted with Seralpur water before analysis with Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES; Agilent Technologies, 700 Series with autosampler ASX-520 Cetac and micro-nebulizer) at MARUM, University of Bremen, Germany. Instrumental precision was monitored after every five samples by analysis of an in-house standard solution with a Mg/Ca of 2.93 mmol/mol (standard deviation of 0.020 mmol/mol or 0.67 %). A limestone standard (ECRM752-1, reported Mg/Ca of 3.75 mmol/mol) was analysed to allow inter-laboratory comparison (Greaves et al., 2008; Groeneveld and Filipsson, 2013). The long-term average of the ECRM752-1 standard, which is routinely analysed twice after every 50 samples in every session, is 3.78 ±0.073 mmol/mol. Analytical precision for *Elphidium* spp. was 0.08 % for Mg/Ca. Reproducibility using replicates of the same samples but cleaned separately was +/- 0.17 mmol/mol (n = 18). Potential contamination was monitored using Al/Ca (clays), Mn/Ca, and Fe/Ca (both for diagenetic coatings) (see supplement for details).

Mg/Ca values reach numbers which are comparable to modern core top analyses of the same species (Groeneveld and Filipsson, unpublished data). Mg/Ca values before 4,000 cal. yr BP, however, are still relatively high, suggesting that the cleaning did not fully remove the contamination. Although FeS and FeS_2 are present in the studied sediments of Site M0059 (Van Helmond et al., 2017), it remains unclear what specific kind of sulfide would have been present on the foraminiferal fragments as Fe/Ca did not vary between the different methods (Fig. S1 in Supplement). Mean Mn/Ca was much lower for the samples in the oxidation-reduction series (10.09 vs 14.81 mmol/mol; Table S3 in Supplement; Fig. S1 in Supplement), but these are still values which are much higher than commonly accepted for uncontaminated foraminiferal calcite (Barker et al., 2003). It is possible that the high Mn/Ca values are truly part of the primary foraminiferal calcite and relate as such to redox conditions in the sediment. Groeneveld and Filipsson (2013) showed Mn/Ca values as high as 10.58 mmol/mol in living specimens of *Globobulimina turgida* from the hypoxic zone in the Gullmar Fjord. For future work it may be required to perform a second reduction step instead of just the one step performed here.

2.2.9 Clumped isotopes in molluscs

-The analyte for clumped isotope thermometry in the case of carbonate is CO_2 liberated by acid digestion, where Δ_{47} is the measure of the amount of mass-47 isotopologues of CO_2 (primarily $^{13}C^{18}O^{16}O$) relative to that predicted by a random arrangement of atoms (Dennis et al., 2011; Eiler, 2011~~2011a, b~~). A robust relationship between Δ_{47} and the formation temperature of marine molluscs has been determined (Henkes et al., 2013). We measured the clumped isotope composition of mollusc material from Holes M0059A and D and report Δ_{47} inferred temperatures for eleven samples. Mollusc material was separated from ~~the~~ sediment samples (~3 cm thickness) by wet sieving. A cold, ten-minute soak of dilute H_2O_2 was used for samples where organic matter was particularly difficult to remove. All samples were triple-rinsed in distilled water and hand cleansed with brushes under a microscope. After species identification, samples were ground in a mortar and pestle and analysed at Johns Hopkins University (USA) on a Thermo Scientific MAT-253 isotope ratio mass spectrometer coupled to an automated acid digestion and CO_2 purification system as described in Henkes et al. (2013). Samples were analysed (3-7 replicates, as material permitted) alongside carbonate standards of varying composition and CO_2 gases approaching equilibrium at 1000 °C and 30 °C, from January to March 2016 (see supplementary material). Measurements of the temperature-equilibrated CO_2 gas samples were used to create an absolute reference frame for normalization of Δ_{47} values (Dennis et al., 2011), with the calculations performed using a MATLAB® script that accounts for temporal drift in analytical conditions (Passey et al., 2010). Finally, we used the following empirically determined relationship between mollusc Δ_{47} and temperature (Henkes et al., 2013) to convert our measured Δ_{47} to paleotemperatures: $\Delta_{47} = 0.0327 \times 10^6/T^2 + 0.3286$~~-~~.

2.2.10 Biomarkers

A total of 40 sediment samples~~sediments~~ collected from Holes M0059A and D~~M0059D~~ was analysed for their lipid biomarker content. For this, ~1-5 gram of sediment (~0.5 cm thickness) was freeze-dried and extracted using a modified Bligh & Dyer technique (Rütters et al., 2002). An aliquot of each Bligh and Dyer extract (~5 mg) was separated into an apolar and polar fraction using column chromatography with activated Al_2O_3 as stationary phase and hexane:DCM (9:1, v:v) and DCM:MeOH (1:1) as respective eluents. The polar fractions were subsequently dried under a gentle stream of N_2 and separated into two aliquots for analyses of glycerol dialkyl glycerol tetraethers (GDGTs) and long chain diols, ~~(LCDs),~~ respectively. To analyse the GDGT content~~GDGTs~~, aliquots of the polar fractions were dissolved in hexane:2-propanol (99:1; v/v) and passed through a 0.4 µm polytetrafluoroethylene (PTFE) filter. Analysis of GDGTs was performed using an Alliance 2695 (Waters, UK) high performance liquid chromatograph (HPLC) coupled to a ZQ (Micromass, UK) single quadrupole mass spectrometer (MS) as detailed in Zink et al. (2016) following the analytical protocols of Hopmans et al. (2000) and Liu et al. (2012). Isoprenoid and branched GDGTs were detected using single ion recording of their protonated molecules $[M+H]^+$ as outlined in Schouten et al. (2013a). The TEX_{86} and TEX^L_{86} were~~was~~ calculated using the equations~~equation~~ given by Schouten et al. (2002) and Kim et al. (2010):

$$TEX_{86} = ([GDGT\text{-}2] + [GDGT\text{-}3] + [Cren']) / ([GDGT\text{-}1] + [GDGT\text{-}2] + [GDGT\text{-}3] + [Cren']) \quad [1]$$

$$TEX^{L}_{86} = [GDGT\text{-}2] / ([GDGT\text{-}1] + [GDGT\text{-}2] + [GDGT\text{-}3]) \quad [2~~1~~]$$

TEX^{L}_{86} values were transferred to absolute temperatures in the brackish-marine sediments of subunit Ia using the Baltic Sea surface sediment calibration (equation 3),~~,~~ which is best correlated with late summer SSTs (Kabel et al., 2012). In the freshwater interval of subunit Ib, we used the global lake calibration (equation 4) of Powers et al. (2010) to convert TEX_{86} values in water temperatures. We specifically apply and discuss the summer lake surface temperature (SLST) calibration here but also provide information on the annual and winter lake surface temperature variation in the supplementary material. ~~):~~

$$SST = 34.03 * TEX^{L}_{86} + 36.73 \quad [3~~2~~]$$

$$SLST = 46.6 * TEX_{86} – 5.6 \quad [4]$$

In order to assess whether the TEX^{L}_{86} is affected by the contribution of terrestrial-derived GDGTs~~can reliably be applied in our setting~~, we ~~also~~ calculated the branched isoprenoid tetraether ~~(BIT)~~ index (BIT) (Hopmans et al., 2004):

$$BIT = ([GDGT\text{-}1] + [GDGT\text{-}2] + [GDGT\text{-}3]) / ([Crenarchaeol] + [GDGT\text{-}1] + [GDGT\text{-}2] + [GDGT\text{-}3]) \quad [5~~3~~]$$

For the analysis of long chain diols, ~~LCDs, we dissolved~~ an aliquot of each polar fraction was dissolved in DCM at a concentration of 2 mg ml^{-1} and ~~silylated~~ the mixture was silylated by the addition of *N,O*-bis(trimethylsilyl)trifluoroacetamide (BSTFA) and pyridine and heating at 80 °C for 2 hours. Gas chromatography coupled to mass spectrometry (GC/MS) of long chain diols~~LCDs~~ was performed using an Agilent 7890A GC coupled to an Agilent 5975B MS following the method described in Rampen et al. (2012). Long chain diols~~LCDs~~ were quantified using selected ion monitoring ~~(SIM)~~ of the masses *m/z* 313 (C_{28} 1,13- and C_{30} 1,15-diols) and *m/z* 341 (C_{30} 1,13- and C_{32} 1,15-diols). The long chain diol index (LDI) was calculated and converted to SSTs for sediments deposited in subunit Ia using the equations provided by Rampen et al. (2012):

$$LDI = [C_{30}\ 1,15\text{-diol}]/([C_{28}\ 1,13\text{-diol}] + [C_{30}\ 1,13\text{-diol}] + [C_{30}\ 1,15\text{-diol}]) \quad [4]$$

$$LDI = 0.033 \times SST + 0.095 \quad [5]$$

To transfer relative abundances (RA) of long chain diols found in the freshwater interval of subunit Ib into surface water temperatures (SWT), the lake calibration of Rampen et al. (2014) has been applied:

$$SWT = 26.8 – 25.9 * RA\ C_{28}\ 1,13\ diol – 54.3 * RA\ C_{30}\ 1,13\ diol + 7.4 * RA\ C_{30}\ 1,15\ diol$$

The Diol Index (DI) was calculated according to Versteegh et al. (1997):

$$DI = 100 * [C_{30}\ 1{,}15\text{-diol}]/([C_{30}\ 1{,}15\text{-diol}] + [C_{32}\ 1{,}15\text{-diol}]) \quad [6]$$

3 Results

3.1 Comparison of ^{14}C age model with palynology-based chronology

The ^{14}C-based age model for Site M0059 is discussed in detail by Van Helmond et al. (2017~~accepted~~). The mean sedimentation rate was ~6.5 mm/yr and there are no obvious signs of hiatuses in Unit I. A comparison of the pollen record from Site M0059 with that of~~with~~ the varved high-resolution pollen record from Lake Belau in northern Germany (Dörfler et al., 2012; Figs. 1, 2), situated ~100 km south of our study site~~Site M0059~~, reveals a close congruency between the pollen signals in the lacustrine and marine records. Particularly clear signals occurring in both Lake Belau and M0059 pollen records are the arrival of *Fagus* (beech) in the catchment area ~6,000 cal. yr BP, a characteristic decline in *Ulmus* (elm) around ~5,600 cal. yr BP after preceding values between ~5 and ~10 %, maximum percentages of *Alnus* (alder) at ~5,200 cal. yr BP, and maximum percentages of *Fagus* between~~at~~ ~1,800~~500~~ and ~600 cal. yr BP (Fig. 2 and Dörfler et al., 2012). Grains of cultivated Poacea taxa, i.e. cereals (Fig. 2), particularly *Triticum* (wheat) and *Secale* (rye), are consistently present after ~1,100 cal. yr BP and increase significantly after ~800 cal. yr BP. This signal is also congruent with the Lake Belau record, although~~but~~ the cereal pollen signal at Lake Belau is stronger (Dörfler et al., 2012), probably due to higher agricultural activity close to the lake. The general palynomorph preservation is excellent over the analysed interval, and pollen concentration varies around 500,~~-~~000 grains per gram sediment for most of the analysed samples. This is in accordance with the high TOC values (>2 wt%) encountered for most samples ~~and between Holes~~ (Fig. 2). Only in the uppermost part (< 100 cal. yr BP),~~,~~ pollen concentration decreases to values around 200,~~-~~000 grains per gram.

3.2 Pollen-based climate reconstruction

The pollen-based climate reconstructions reveal a general increasing trend from ~7,800~~8,000~~ to ~2,000 cal. yr BP in both annual precipitation and annual temperature (TANN; Figs ~~Fig~~. 3, 4). The increase in the latter from ~5 to almost 9 °C is tied to an increase in coldest month temperatures (MTCO; ~-8 to almost 0 °C), while warmest month temperatures (MTWA) show a decreasing trend starting at ~7,000 cal. yr BP (~19 °C), which ends at ca. 2,000 cal. yr BP (~17 °C). Between ~2,000 and ~1,000 cal. yr BP, MTWA increase to >19 °C, and subsequently decrease again to <17 °C. The MTWA maximum around ~1,000 cal. yr BP is coeval with relatively low annual precipitation values (>640 mm compared to >800 mm earlier and subsequently).

3.3 Marine ecosystem changes

The Holocene record of Site M0059 was divided into four overall environmental zones (EZs; Table 2~~1~~) based on statistically assessed changes in diatom assemblages (section 3.3.1) and ~~coeval~~ congruent signals of other marine proxies (benthic foraminifera – section 3.3.2, ostracods – section 3.3.4, and aquatic palynomorphs – section 3.3.5). While EZ1 is characterized by freshwater conditions, EZs 2-4 indicate a brackish-marine depositional environment~~environments~~ that persisted in the Baltic Sea during the Littorina Sea stage. EZ1 corresponds with lithological subunit Ib (49.37-53.57 mcd), while EZs 2-4 correspond with subunit Ia.

Table 2~~1~~: Environmental zones of the Holocene record~~records~~ of Site M0059.

Zone	Depth (mcd)	Age (cal. yr BP)	Characteristics
EZ4~~EZ1~~	~6~~53~~ to top~~~49~~	~1,000~~7,800~~ to present~~~7,400~~	increase in brackish diatoms, *Gymnodinium* cysts, decrease in diatom abundance~~high absolute/relative values of freshwater proxies~~
EZ3~~EZ2~~	~22~~49~~ to ~6~~22~~	~~~7,400 to ~~~4,100 to ~1,000	increase in diatom and *Chaetoceros* spore~~increased~~ abundance, decreased~~ of~~ indicators of marine influence
EZ2~~EZ3~~	~49~~22~~ to ~22~~6~~	~7,400~~4,100~~ to ~4,100~~1,000~~	increased~~increase in diatom and *Chaetoceros* spore~~ abundance of~~,~~ ~~decreased~~ indicators of marine influence
EZ1~~EZ4~~	~53~~6~~ to ~49~~top~~	~7,800~~1,000~~ to ~7,400~~present~~	high absolute/relative values of freshwater proxies~~increase in brackish diatoms, *Gymnodinium* cysts, decrease in diatom abundance~~

3.3.1 Diatoms

Relative abundances of salinity-based diatom assemblages, as well as absolute diatom abundance (ADA) plotted as the number of valves per gram dry weight of sediment (v/dgw), absolute abundance of *Chaetoceros* resting spores (CRS; v/gdw), and the ratio of benthic to planktonic diatoms are presented on Figure 3. The division into four environmental zones (EZ) as described above was based on salinity preference, ADA, CRS abundance, and the ratio of benthic to planktonic diatoms (B:P). These are in general agreement with signals reflected by other proxies (see below).

EZ1 (~7,800 to ~7,400 cal. yr BP) is based on three diatom samples characterized by dominance of freshwater taxa, rare CRS abundance, (average $3.2 * 10^5$), low ADA (average $2.5 * 10^7$), and low B:P (0.48). EZ2 (~7,400 to ~4,100 cal. yr BP) is defined by a distinct increase in brackish and marine species at the expense of freshwater diatoms. In addition, there is a clear increase in the B:P ratio (average 4.17), ADA (average $4.65 * 10^7$) and CRS absolute abundance (average $1.0 * 10^7$). EZ2 contains both the highest B:P and the greatest range in values of B:P. EZ3 (~4,100 to ~1,000 cal. yr BP) shows an increase in marine, brackish-marine, and freshwater species at the expense of brackish species. The B:P ratio (average 2.65) declines some in EZ3, however ADA (average 5.1 *10^7) and CRS absolute abundance (average 2.2 * 10^7) are highest in this interval compared to the rest of the core. Marine and brackish-marine species increase in abundance from the base of this zone to ~1,100 cal. yr BP concurrent with a decrease in brackish species. Both diatom and CRS absolute abundance increase from the base of this zone to ~1,200 cal. yr BP. B:P increases from the base of the zone to ~1,000 cal. yr BP.

EZ4 (~1,000 cal. yr BP to present) begins with an increase in brackish species. The relative abundance of marine and brackish-marine taxa, as well as B:P ratio (average 2.07) decline rather gradually throughout this interval, whereas ADA (average 2.0 *10^7) and CRS abundance (average 5.3 * 10^6) decline rapidly at ~1,000 cal. yr BP and remain at low levels until the core-top. The significance of the differences between the four identified EZs were assessed in regards to the percent abundance of all five salinity affinities, as well as ADA, CRS abundance, and B:P. ANOVA reveals a significant difference between the means of all of these measures (Table S1 in Supplement). The Tukey-Kramer pairwise test was then used to evaluate the differences between individual EZs. Statistical differences between adjacent zones, representing change through time, are reported in Table S2 (Supplement). Pairwise statistical analysis reveals significant differences between EZ1 and EZ2 in terms of all ecological metrics with the exception of ADA. EZ2 and EZ3 can be distinguished statistically on the basis of the percent of diatoms with a brackish affinity, which decreases from EZ2 to EZ3, as well as CRS, which increases from EZ2 to EZ3. EZ3 can be significantly distinguished from EZ4 in terms of ADA and CRS abundance, both of which decrease. Finally, EZ3 does not have a significant change in salinity with respect to EZ4, however there is a shift in the species present between these zones.

3.3.2 Benthic foraminiferal assemblages

Benthic foraminifera are found in sediments covering the interval since ~7,400 cal. yr BP until today. The foraminiferal assemblages comprise very few species, with *Elphidium selseyense* (formerly named *E. excavatum* forma *selseyensis;* see Darling et al., 2016) being dominant. *Elphidium incertum* is also found throughout the entire core, while all other species occur only in specific intervals. In the lower part of EZ2, from ~7,400 to ~6,600 cal. yr BP, the foraminiferal assemblages are characterised by very high frequencies of *E. incertum* and, around ~6,900 cal. yr BP, relatively higher~~high~~ abundance of *Ammonia beccarii* (~15% compared to <1 % in samples above and below, Fig. 3).~~,~~ After ~6,600 cal. yr BP the relative abundance of *A. beccarri* is strongly reduced, while *E. incertum* continues to dominate and increases in abundance until ~5,700 cal. yr BP. During most of the interval since ~5,700 cal. yr BP (top zone EZ3 to zone EZ1), only *E. selseyense* and *E. incertum* are found consistently, with only minor, short-term occurrences of *Elphidium albiumbilicatum* and *Elphidium magellanicum* at ~5,900 cal. yr BP and ~4,850 cal. yr. BP, as well as a short-term peak~~occurrence~~ of *A. beccarii* at ~3,800 cal. yr BP. The samples representing the past ~460 cal. yr BP contain no or only very few foraminifera (*E. selseyense* and a few specimens of *E. incertum* and *E. albiumbilicatum*, Fig. 3).

3.3.3 Benthic foraminfer~~foraminifer~~ isotopes and trace metal/calcium

~~Mg/Ca values reach numbers which are comparable to modern core top analyses of the same species (Groeneveld and Filipsson, unpublished data). Mg/Ca values before 4,000 cal. yr BP, however, are still relatively high, suggesting that the cleaning did not fully remove the contamination. Although FeS and FeS_2 are present in the studied sediments of Site M0059 (Van Helmond et al., accepted), it remains unclear what specific kind of sulfide would have been present on the foraminiferal fragments as Fe/Ca did not vary between the different methods (Fig. S1 in Supplement). Mean Mn/Ca was much lower for the samples in the oxidation-reduction series (10.09 vs 14.81 mmol/mol; Table S3 in Supplement; Fig. S1 in Supplement), but these are still values which are much higher than commonly accepted for uncontaminated foraminiferal calcite (Barker et al., 2003). It is possible that the high Mn/Ca values are truly part of the primary foraminiferal calcite and relate as such to redox conditions in the sediment. Groeneveld and Filipsson (2013) showed Mn/Ca values as high as 10.58 mmol/mol in living specimens of *Globobulimina turgida* from the hypoxic zone in the Gullmar Fjord. For future work it may be required to perform a second reduction step instead of just the one step performed here.~~ The difference in average Mg/Ca between *E. selseyense* and *E. incertum* was not significant (1.52 vs 1.53 mmol/mol; Supplement Fig. 1S~~Supplements~~), so for the remainder only results of *E. selseyense* are included, as they are of higher resolution. Mg/Ca values decrease from 2.96 mmol/mol at ~4,000 cal. yr BP to values between 0.62 and 1.10 mmol/mol between ~2,200-800 cal. yr BP (Fig. 4). As a species-specific calibration is absent for *Elphidium* spp., we employed the Mg/Ca-temperature calibration for *Melonis barleaanum*, which has been shown to give reasonable temperatures for the Baltic Sea area (Kristjánsdóttir et al., 2007; Anjar et al., 2012). Calculated bottom water temperatures decrease from 10.9 °C at ~4,000 cal. yr BP to 0-4 °C between ~2,200 to ~800 cal. yr BP.

$\delta^{18}O$ values show an initial increase from -1.2 to 0.4 ‰ from ~7,400 to ~6,700 cal. yr BP. $\delta^{18}O$ average -0.2 ‰ for the interval ~7,400 to ~3,700 cal. yr BP and increase to an average of 0.4 ‰ afterwards, suggesting either a more gradual decrease in bottom water temperature, an increase in bottom water salinity, or both (Fig. 4, supplements Fig. S1).~~.~~ $\delta^{13}C$ values increase from -3.2 ‰ at ~7,000 cal. yr BP to -2 ‰ at ~5,000 to ~4,500 cal. yr BP (Fig. 3).~~.~~ Afterwards values oscillate around an average of -1.3 ‰, suggesting improved ventilation of the water column (supplements~~Supplements~~, Table S3).

3.3.4 Ostracods

Ostracod abundance was relatively low (~5 valves/30 cm^3, 23 samples barren), but preservation was good in most samples. EZ1 is entirely comprised of freshwater species. Abundant freshwater taxa *Candona* spp. and *Cytherissa lacustris* were identified in the interval between ~7,800 and ~7,400~~500~~ cal. yr BP. The rest of the record contains marine and brackish-water ostracod taxa. The ostracod assemblages imply a subdivision of EZ2 (Fig. 3). EZ2a (~7,400 to ~6,800 cal. yr BP) is mainly represented with two shallow water taxa, *Palmoconcha* spp. and *Hirschmania viridis*. The abundance peak of shallow water taxa of 6 valves/30 cm^3 is observed at ~7,000 cal. yr BP. EZ2b (~6,800 to ~3,600 cal. yr BP) contains both shallow water and deeper-living taxa, with deeper-living taxa being slightly more abundant and showing two abundance peaks in this interval. In the lower part (~5,600 to ~6,800 to ~5,600 cal. yr BP), a peak of 7 valves/30 cm^3 is observed for deeper-living taxa at ~6,500 cal. yr BP. A short interval (~5,600 to ~5,300 cal. yr BP) is barren of ostracods. The upper part of the interval, ~3,600 to ~5,300 to ~3,600 cal. yr BP, includes a deeper-living-taxa peak of 5 valves/30 cm^3 at ~5,000 cal. yr BP. *Sarsicytheridea bradii*, *Cytheropteron latissimum*, and *Elofsonella concinna*, *Robertsonites tuberculatus*, and *Paraciprideis* sp. are the dominant taxa in this interval. These are typical representatives of Arctic/Boreal shallow water shelf faunas (Stepanova et al., 2007). Open sea environment and salinity of 14-16 and higher is expected for this group of species (Frenzel et al., 2010). Shallower water species like *Palmoconcha* spp. and *Leptocythere* spp. are the most abundant among shallow water taxa.

EZ3 (~3,600 to ~1,000 cal. yr BP) is characterized by an overall increase in abundance and predominance of shallow water taxa (reaching a peak of 15 valves/30 cm^3 at ~3,500 cal. yr BP). The most abundant taxa here are the shallow water genera *Leptocythere* spp. and *Palmoconcha* spp. These taxa are present in the underlying EZ2, but become dominant here. These genera inhabit lagoons and open sea environments with salinity above 7-12. A short interval between ~2,600 and ~2,200 cal. yr BP is barren of ostracods.

Uppermost EZ1 (covering the past ~1,000 yr) is marked by a decrease in the taxonomic diversity; it is almost solely represented by *Sarsicytheridea bradii*, a taxon which. *S. bradii* can be found in open sea environments and at a salinity as low as 7 (Frenzel et al., 2010).

3.3.5 Aquatic palynomorphs

Percentages of dinocysts and freshwater algae (Fig. 3) are based on the total pollen sum (thus representing a dinocyst/pollen or a freshwater algae/pollen ratio, respectively). The freshwater algae *Pediastrum* and *Botryococcus* are present in the entire record, but values >3 % are only found at >7,700 cal. yr BP (Fig. 3). We have combined the dinocysts of phototrophic taxa belonging to gonyaulacoids into one group ("G-cysts"; predominately comprising *Protoceratium reticulatum*/*Operculodinium centrocarpum*, *Spiniferites* spp.,, and *Lingulodinium machaerophorum*), and microreticulate, gymnodinioid cysts of *Gymnodinium* in another. Cysts of heterotrophic taxa are rare and thus not depicted in Figure 3. While not all *Gymnodinium* cysts were identified to species level, most of the encountered *Gymnodinium* cysts probably belong to *GC. nolleri* (referred to as *Gymnodinium* cf. *nolleri* in. Cysts of heterotrophic taxa were generally rare within the following).samples. The G-cysts percentages are >3 % between ~7,800 and ~7,400 cal. yr BP (EZ1), but increase to > 5 % around ~7,400 cal. yr BP. Thereafter, values of this proxy stay rather constant at ~10 % until ~4,000 cal. yr BP (EZ 2). For the latest ~4,000 cal. yr BP, G-cysts percentages vary around 5 %, with particularly low values around 500 cal. yr BP (EZ 4). *Gymnodinium* cf. *nolleri* cysts are almost completely absent until ~7,000 cal. yr BP, increase rapidly at ~6,800 cal. yr BP, but in the following decline and are almost absent at ~4,000 cal. yr BP. A second interval of high *Gymnodinium* cf. *nolleri* abundances occurs between ~3,000 and ~300 cal. yr BP, with maximum values at ~1,000 and ~200 cal. yr BP.

3.3.6 Mollusc clumped isotopes

The analysedEleven mollusc shell fragments from Holes M0059A and D were assignedused to the speciesgenerate clumped-isotope bottom-water temperatures. The species analysed were identified as *Abra alba*, *Arctica islandica*, *Corbula gibba*, and *Macoma balthica* (see Table S4 in Supplement). The oldest analysed mollusc is from EZ2 (~6,800 cal. yr BP) and the youngest analysed shell fragment from EZ4 (~140 cal. yr BP). Clumped-isotope-inferred temperatures range from ~2 °C to ~12 °C (Fig. 4). In EZ2, temperatures vary between 5°C and 11.8°C, with a majority of. Average temperatures around ~8°C. The two temperatures obtained in EZ3from ~7,000 to ~4,000 cal. yr BP are 2.1~9 °C (with ~11.8 °C and 4.8~5 °C, respective maximum and the single temperature obtained in EZ4 is 7.minimum temperatures) while temperatures in the past ~4,000 yr increase from ~2.1 °C to ~7.7 °C (Fig. 4).

3.3.7 Biomarkers

The Diol Index (DI) shows consistently low values of 55.2±2.7 in EZ1 but rapidly increases to values of 90.5 with the establishment of brackish-marine conditions at the start of the Littorina Sea stage (Fig. 3). Thereafter, Diol IndexDI values gradually decline and show a minimum of 54.3 around ~4,000 cal. yr BP, after which values gradually increase again until ~3,000 cal. yr BP, where they peak at 80.1. In the following, the Diol IndexDI stays rather constant averaging 77±3.0 for the remainder of the record with an exception found around ~700 cal. yr BP, at which the Diol IndexDI decreases to values as low as 61.7.

TEX_{86} –based SLSTs generally evidence a warming trend throughout EZ1 with temperatures increasing from 12.9 to 14.8 °C except in the uppermost sample of this interval in which a drop in temperature to 12.5 °C is observed (Fig. 4). At the transition to the marine-brackish phase of EZ2,High TEX^{L}_{86}-inferred temperaturesbased SSTs of about 20 °C persist in EZ1 but they rapidly increasedecrease to 19.516 °C at the base of EZ2 and thereafter show a gradualslowly decline to yield minimum SSTs of ~14 °C at the topmost part of EZ2 (~514 °C until ~4,000 cal. yr BP (Fig. 4). In the following, TEX^{L}_{86}-SSTs gradually increase and cumulate in a peak SST of 26 °C around ~1,000 cal. yr BP, after which SSTs decline again and are at a minimum of 14 °C around ~300 cal. yr BP. The uppermost part of the record (<300 cal. yr BP) is characterized by increasing SSTs that maximize at 21.1 °C in the core top sample.

Branched isoprenoid tetraether index values are generally high At a value of 0.80, the BIT in the freshwater interval of EZ1 with an average of 0.93±0.04 is high (Fig. 4). With the establishment of brackish-marine conditions (base of EZ2), the branched isoprenoid tetraether indexBIT rapidly declines to values of 0.29±0.04, however, and shows only little variation (0.29±0.04) in the organic-rich deposits of the Littorina Sea stage.

Long chain diol distributionsThe LDI-inferred SSTs are with 15.3±1.4 °C comparatively low in EZ1 yield SWTs varying from 18.5 to 21.3 °C (average 19.7±1.3 °C). At the transition to EZ2, long-chain-diol-index-based SSTs but they rapidly increase toand show a maximum of 24.3°C. at the base of EZ2 (Fig. 4). Subsequently, reconstructedLDI-based SSTs gradually decline and show a minimum of 15.9 °C at the transition from EZ3 to EZ4 (~~~~1,000 cal. yr BP) that is followed by a short-lived warming event with peak temperatures of 20.8 °C around ~900 cal. yr BP. A second minimum in long-chain-diol-index~~LDI~~-based SSTs is observed between ~800 and ~400 cal. yr BP, after which temperatures again increase ~~again~~ to a value of 18.3 °C close to the core top.

4 Discussion

~~According to our results EZ2 to EZ4 represent the Littorina Sea stage, while EZ1 reflects an interval of freshwater conditions. This setting allows us to apply and test a wide array of sea water salinity proxies under widely variable conditions. Of the various proxies used, diatoms, dinocysts of phototrophic taxa, and the Diol index (DI) mainly reflect surface water conditions, while foraminifera and ostracods indicate changes in the bottom water.~~ The complex climatic development during the Holocene in the Baltic Sea region (Björck, ~~1995; Andrén et al.,~~ 2008; Zillén et al., 2008; Andrén et al. 2011) enables us to compare and validate several temperature reconstruction methods, with pollen reflecting terrestrial conditions, long chain diol index~~LDI~~ and TEX_{86}/TEX^{L}_{86} indicating changes in the surface water, and mollusc clumped isotopes and foraminiferal Mg/Ca and $\delta^{18}O$ allowing the reconstruction of bottom water conditions. Of the various salinity proxies used in this study, diatoms, cysts of phototrophic dinoflagellates, and the Diol Index mainly reflect surface water conditions, while foraminifera and ostracods indicate changes in the bottom water.

4.1 Salinity and productivity changes

All biogenic~~biological~~ proxies indicate a phase of low salinity during **EZ1** (before ~7,400 cal. yr BP)~~; during EZ1;~~ diatom and ostracod data suggest freshwater conditions, and diatom data additionally indicate ~~and~~ low productivity in the lowermost part of EZ1 (Fig. 3), though this is not fully consistent with relatively high TOC values in the lowermost part of EZ1 (Fig. 2) and results of Van Helmond et al. (2017).~~3).~~ Among the aquatic palynomorphs, remains of the green algae *Pediastrum* sp. and *Botryococcus* sp., together with low occurrences of marine dinoflagellate cysts compared to pollen grains, also indicate a significant freshwater influence. ~~These factors indicate that EZ1 represents a low productivity freshwater environment. Low diatom abundance and a freshwater flora, taken together with sedimentological data including laminated silty clay (Andrén et al., 2015a), imply a lacustrine environment in the area around Site M0059 during this interval.~~ Likewise, the Diol Index~~DI~~ shows lowest values in this interval that are in~~of~~ the same order of magnitude reported from other lacustrine environments (Versteegh et al., 1997). Comparison with the varved pollen record from Lake Belau (Fig. 2; Dörfler et al., 2012) suggests~~indicates~~ that EZ1 is probably not older than ~9,000 cal. yr BP, as e.g. indicated by the presence of *Alnus* and *Ulmus* (~5 % each) in the lowermost samples. ~~with ~5 %. This is corroborated by the constant temperature values indicated by both pollen- and TEX^{L}_{86}-based SST encountered at the transition from EZ1 to EZ2.~~ Our findings are thus congruent~~in congruence~~

with those of Bennike and Jensen (2011) and Van Helmond et al. (2017~~accepted~~) who suggested~~stated~~ that during the early Holocene, a large lake developed in the southern part of the Little Belt region.

Fully marine conditions in the southern Kattegat were already established by ~9,300 cal. yr BP (Bendixen et al., 2016), but not sooner than ~8,500 to~~before~~ ~7,500~~300~~ cal. yr BP in the central Baltic Proper (Björck, 2008). This implies that during EZ1 the Little Belt may have been connected to the Baltic Proper, but not to the Kattegat. Bennike and Jensen (2011) suggested that the transition to brackish conditions may have started at ~8,500 cal. yr BP in the Little Belt, although~~however~~ the oldest dated marine shell from the Little Belt is dated to ~7,700 cal. yr BP (Bennike and Jensen, 2011), ~~which is~~ consistent with our findings.

The change to ~~the~~ more marine conditions in **EZ2** (~7,400 to ~4,100 cal. yr BP) occurred quickly, as already implied by Andrén et al. (2015b), since most~~several~~ proxies show a rapid decrease or disappearance of freshwater indicators (e.g. diatoms, green algae, ostracods). At the same time, the applied salinity proxies indicate a shift to more saline conditions, e.g. increasing ~~salinity, e.g. by growing~~ CRS abundance, as most *Chaetoceros* requires brackish to marine conditions (Snoeijs et al., 1993-1998) and a significant rise in the Diol Index values.~~).~~ Maximum abundances of dinocysts of phototrophic taxa occurred in EZ2, which are coeval with abundance maxima at the southern and southeastern coast of Sweden found by Ning et al. (2015) or~~and~~ Yu and Berglund (2007), and in the Gotland and the Fårö Basins (Brenner, 2005;~~,~~ Willumsen et al., 2013).

We suggest that maxima~~Maxima~~ in *Gymnodinium* cf. *nolleri* cysts between ~6,800 and ~5,200~~4,300~~ cal. yr BP ~~(~42 to ~25 mcd)~~ may ~~also~~ indicate more saline conditions, though they may also be related to increased~~a~~ temperature ~~increase~~ (e.g. Thorsen et al., 1995;~~,~~ Thorsen and Dale, 1997; see below) and evidenced here by high TEX^{L}_{86}- and long-chain-diol-index-SST in this interval.~~).~~ The *Gymnodinium* peak at ~6,800 cal. yr BP has~~is~~ to our knowledge not yet been described from the Baltic Sea and does~~seems~~ not seem to have occurred in the Baltic Proper~~farther eastwards~~ (Brenner, 2005; Yu and Berglund, 2007; Ning et al., 2015). Thorsen et al. (1995) and Harland and Nordberg (2011) describe later *Gymnodinium* mass occurrences from the Skagerrak and the Kattegat, but sediments of equivalent~~the appropriate~~ age containing our *Gymnodinium* ~~to find the~~ peak at ~6,800 cal. yr BP ~~in our record~~ were not recovered~~reached~~ in the framework of those~~their~~ studies.

Increasing content of foraminifera per gram sediment within a short interval also point to a salinity increase, as well as the near disappearance of the foraminiferal species~~foraminifera~~ *A. beccarii* (<1 %) at ~6,600 cal. yr BP and the relatively high frequencies of *E. incertum* until ~5,700 cal. yr BP. *Ammonia beccarii* is a euryhaline species (Murray, 2006), but it increases in frequency in lower-salinity environments in the Kattegat-Baltic Sea region (e.g. Lutze, 1974; Seidenkrantz, 1993). *Elphidium incertum* is a shallow infaunal species that favours sandy substrate, in brackish, inner shelf areas (salinity >25), where it is particularly frequent just below the halocline in stratified waters (Lutze, 1974; Darling et al., 2016). Foraminiferal-$\delta^{18}O$ values are also in line with~~point to~~ increasing salinity, increasing from -1.2 to 0.4 ‰ (Fig. 3).~~.~~ The following drop in *E. incertum* abundance and consequent increase in *E. selseyense* in the upper part of ~~this zone (~~EZ2~~)~~ may potentially be ascribed to somewhat reduced bottom-water salinities, as *E. selseyense* is an opportunistic species that is widespread in tidal to shelf areas with relatively large variations in temperature and salinity (Murray, 2006; Darling et al., 2016). As stable $\delta^{18}O$ values do not suggest a strong change in salinity between ~6,600 and ~3,700 cal. yr BP, the shift in benthic foraminiferal fauna may also be linked to a reduction in bottom-water oxygenation, as *E. incertum* is also reported to require relatively high oxygen concentrations (Lutze, 1974; Murray, 2006). This, however, is not corroborated by ~~However, the~~ results of Van Helmond et al. (2017), who observed~~(accepted) indicate~~ a significant reduction in bottom-water oxygenation only at the onset of this interval.

In~~Bottom water salinity change was not as abrupt but gradual, thus in~~ terms of ostracod fauna, EZ2 can be subdivided into two sub-zones, with the lower interval ~7,400 to ~6,800 cal. yr BP representing a transitional early marine stage environment with salinity above 10-14 and the second interval ~6,800 to ~3,900 cal. yr BP~~PB~~ with salinity above 14-16. Both ostracod intervals within EZ2 reflect the onset of the Littorina Sea and the salinity increase pattern as evidenced by the highest concentration of euhaline taxa. At the same time, the transition from lower to higher salinities must have been gradual, with the lower part of EZ2 containing higher numbers of shallower water meso- and polyhaline taxa decreasing upwards. This implies that bottom water salinity change was not abrupt but occurred more gradual. There was only little change in diatom-based primary productivity compared to EZ1 and~~. There is~~ likely a deepening of the photic zone or shallowing of the water column as indicated by the sharp increase in B:P. A decreasing Diol Index and possibly also decreasing *Gymnodinium* percentages during the second half of EZ2 imply slightly decreasing surface water salinity between ~5,500 and ~4,100 cal. yr BP. This is also corroborated by a decrease of the marine and brackish-marine diatom assemblages,~~yr BP.~~ The interval represented by EZ2 (~7,400 to ~4,100 cal. yr BP) is thus characterized by brackish to marine conditions with higher salinity at the onset of the Littorina Sea stage and slowly decreasing surface water salinity afterwards, while salinity slightly increased~~particularly~~ in the bottom~~surface~~ water. Gustafsson and Westman (2002) regard the interval between ~6,500 and ~5,000 cal. yr BP~~this~~ as the most marine period in the Baltic Sea in general and suggest that low precipitation could be the main cause for the particularly high salinity during this interval compared to the rest of the record. While our data points to an earlier maximum in salinity (Fig.3), a connection between low precipitation and high salinity ~~increased salinity, which~~ is in accordance with the generally low precipitation values reconstructed via the MAT (<600 mm/yr excluding one sample until 4,000 cal. yr BP) for EZ2~~,~~ compared to values from the late 20th century which are generally >600 mm/yr and often reach ~800 mm/yr (~~, e.g.~~ Omstedt et al., 1997). In EZ3 (~4,100 to ~1,000 cal. yr BP), however, high salinity seems not to be coupled with low precipitation (Fig. 3, see below).

At the transition between EZ2 and **EZ3** (~4,100 to ~1,000 cal. yr BP),~~,~~ salinity was probably lower for a short interval, as indicated by the low values of the Diol Index~~DI~~ and a short increase in the abundance of *A. beccarii*, which appears to be a relevant signal even though it is only reflected in one sample.~~.~~ In EZ3~~, (~4,100 to ~1,000 cal. yr BP),~~ the Diol Index~~DI~~, diatom and benthic foraminiferal assemblages, benthic $\delta^{18}O$, and to some degree, ostracod occurrences (with particularly high values at ~3,500 cal. yr BP and the complete disappearance of the very shallow water ostracod taxa~~yr BP~~) indicate another increase in both surface and bottom water salinities ~~salinity~~ between ~4,100 and ~3,000 cal. yr BP. The composition of the diatom assemblages implies ~~(with ostracod-based results suggesting salinities around 14-16), and diatoms imply~~ that EZ3 includes another particularly marine phase of the Little Belt region.~~, recorded at Site M0059.~~ Peak marine conditions, as indicated by diatom species' salinity affinities, occur from ~1,200 to ~1,000 cal. yr BP, at the transition to EZ4. This is evident~~can be seen~~ in a~~the~~ statistically significant decrease in brackish diatom species, while the proportions of marine and brackish-marine diatom species both increase throughout this interval. The Diol Index also shows ~~particularly~~ high values at the transition between EZ3 and EZ4 compared to most of the record, though relatively high values were already established since ~3,000 cal. yr BP. In this case, there is no clear coupling between increased salinity and decreased precipitation, but several temperature proxies indicate high temperatures around ~1000 cal. yr BP, pointing to higher evaporation.

Environmental Zone 3 shows diatom B:P ratios which are statistically similar to EZ2, implying a deep photic zone or shallow water column (supported by a peak in shallow water ostracod taxa in EZ3) and high productivity at the seafloor. In addition, this zone is characterized by particularly high ~~The highest recorded~~ primary productivity, as indicated by ADA, CRS, and somewhat increased ~~probably~~ benthic foraminifera and ostracod abundances. Also ~~occurs within EZ3 as well (~1,700 cal. yr BP), during an interval of particularly high~~ precipitation was~~(and thus presumably~~ increased, likely causing increased freshwater runoff indicated by the~~; Fig. 3,~~ pollen assemblages (Fig. 3). ~~based reconstructions), while the peak salinity conditions at the transition to EZ4 are coupled with a significant decrease in annual precipitation. While there is no significant difference in ADA between EZ2 and EZ3, there is a significant difference between EZ1 and EZ3, showing the longer term increase in diatom-based primary productivity.~~

Following the peak marine interval, **EZ4** (since~~past~~ ~1,000 cal. yr BP) begins with increases in brackish diatom taxa and decreases in marine and brackish-marine diatom species to the core-top. These ~~These species shifts are not statistically significant, however, implying that~~ changes between EZ3 and EZ4 imply that species shifts are more likely~~are~~ related to variations in primary productivity and nutrient conditions ~~more~~ than salinity. Yet, however, ~~shifts. But~~ the Diol Index and *Gymnodinium* percentages also decrease during this interval.~~at the same time.~~ In case of *Gymnodinium*, the decrease could be tied to temperature changes (according to Thorsen and Dale, 1997; see below). This might also be the case for the Diol Index as a slight correlation between this proxy and water temperature has been reported previously (Rampen et al., 2012).~~, see below).~~ Productivity decline from EZ3 to EZ4 is demonstrated by statistically significant decreases in ADA and CRS abundance. The uppermost diatom sample in this interval has the lowest recorded ADA as well as the lowest B:P of any brackish water interval in this study.~~.~~ This sample (of almost recent age) likely represents modern human influence to the Baltic Sea, i.e. eutrophication. Eutrophication would cause a decline in overall diatom abundance, as diatoms are often replaced by cyanobacteria (O'Neil et al., 2012; Michalak et al., 2013) and dinoflagellates (Wasmund and Uhlig, 2003) in cases of high levels of nutrient loading. In turn, this~~eutrophication. This~~ would lead to a shallowing of the photic zone resulting from sunlight being rapidly absorbed by cyanobacteria and dinoflagellates in the upper water column, as seen in the low B:P ratio. The relative and absolute amount of dinocysts is decreasing though in the uppermost palynology sample, thus denser sampling will be needed to determine~~highlight~~ the anthropogenic impact~~human influence~~ to the Baltic Sea ecosystems in future studies. Human influence is, however, indicated by the significant increase of pollen of cultivated Poacea taxa (Fig. 2), starting at

~1,000 cal. yr BP, with persistentconsistent occurrences since ~700 cal. yr BP. The coeval decrease of pollen of tree taxa like *Alnus* and *Fagus* may be an anthropogenic deforestation signal due to increased agricultural activity (Fig. 2).

The *Gymnodinium* maxima encountered in EZ3 and EZ4 are probably temporally related to two mass occurrences of *Gymnodinium* in the eastern Kattegat as described by Harland and Nordberg (2011) for ~300 and ~2,000 and ~300 cal. yr BP. The occurrence of *Gymnodinium* cysts in the sediments from the Skagerrak/Kattegat isare tied to warm water conditions according to Thorsen and Dale (1997). This connection), and this would be congruent with our findings that the maximum at the transition from EZ3 to EZ4 is coeval with the Medieval Warm Period (MWP, also called the Medieval Climate Anomaly) and withand high/increasing temperatures. indicated by most proxies, but not by the LDI-based temperature. However, while Thorsen and Dale (1997) assign the cysts to *G. catenatum*, Harland and Nordberg (2011) claim that the *Gymnodinium* cysts found in Holocene sediments from the Skagerrak and Kattegat rather belong to *G. nolleri* (in accordance with our results) and that the known mass occurrences may not be tied to high temperatures. Considering our findings, *Gymnodinium* mass occurrences may as well be tied to particularly high salinity as implied by the good correlation with other salinity proxies, e.g. the Diol Indexindex (which varies around values of ~80, Fig. 3), but higher resolution studies beyond the scope of this study would be needed to be able to prove such a connection statistically. 3).

EZ4 is characterized by a taxonomic diversity decrease in ostracods; this assemblage is almost solely represented by one species, *S. bradii*. This change, together with a decrease in juvenile percentage, it may imply an unfavourable habitat for ostracods probably related to shallowing of the site andenvironment, salinity increase, low oxygen conditions and dissolution and/or not in situ burial.

Taken together, the different salinity proxies providegive a consistent picture of how salinity in the water column changed in the Little Belt during the last ~8,000 cal. yr BP, with freshwater conditions preceding ~7,400 cal. yr BP, a rapid increase in salinity afterwards, a decrease until the transition to EZ3 (until ~4,000 yr), a subsequent increase until ~3,000 yr BP and more saline conditions thereafter.a decrease in EZ4. Precipitation (reconstructed via pollen assemblages) may have been one of the factors influencing salinity, particularly between ~8,000 and ~4,000 cal. yr BP. Slight discrepancies between the salinity proxies are likelycan be explained by a) differences between surface and bottom waters and b) otheradditional factors influencing microfossil assemblages such as productivity and temperature. While qualitative estimates are congruent for most proxies, quantitative salinity estimates could only rarely be made in the framework of our study.

4.2 Temperature reconstructions

Inorganic- (e.g. Mg/Ca and $\delta^{18}O$ of benthic foraminifera, clumped isotopes) and organic-based temperature proxies (e.g. TEX_{86}, long chain diol indexLDI) have become indispensable tools in paleoenvironmental research as they provide quantitative information of past climate variations. Yet, proxy-based temperature estimates may vary significantly and/or show different trends even within the same sample set. This apparent mismatch between proxies severely complicates their application in paleoenvironmental and -–climate research. Ideally, multiple proxies should therefore be used simultaneously to provide independent paleotemperature records (e.g. Krossa et al., 2017)..

Pollen-based reconstruction of seasonal and mean annual air temperaturestemperature as well as estimates on surface water temperature variations using lipid paleothermometersthe TEX$^{L}_{86}$ and LDI are were obtainedfeasible for the entire sequencerecord of Site M0059, but clumped isotope and Mg/Ca data are missing in particular from the freshwater interval reflected in **EZ1** and in the lowermost section of **EZ2** due to the lack of sufficient carbonaceous micro- and macrofossils. Despite the low resolution of some proxies, there is a certain degree of similarity in temperature trends observed across the different proxies used in this study. The pollen-based temperatures reconstructed for the two uppermost samples from the interval between 100 cal. yr BP and(comprising the presentpast ~100 years) show an average value of ~0.1 °C for MTCO and of ~16.4 °C for MTWA, which is close tofits well with mean temperatures observed in Denmark during January (~1.5 °C) and August (~17.2 °C; Danish Meteorological Institute, 2017). The most complete temperature records arerecord is provided by the sedimentary distribution of GDGTs (TEX$_{86}$ and its derivatives) and long chain diols (in form of the long chain diol index). Although absolute temperature estimates differ between the two proxies, trends are overall very similar in EZ1 showingLDI, which indicates a rather constant SWT of 13.5±1.0 °C (TEX$^{L}_{86}$) and 19.7±1.3 °C (long chain diols),summer SST of ~14.6 °C in the lowermost part of EZ1 that is followed by a rapid temperature increase in both lipid paleothermometers to maximum values of 19.5 °C (TEX$^{L}_{86}$) and 24.5 °C (long chain diol index)°C at the transition from EZ1 to EZ2 at ~7,400 cal. yr BP (Fig. 4). An interval of generally higher mean annual air and water temperatures has previously been described from other records of the Baltic Sea region such as Lake Flarken, Sweden (Seppä et al., 2005) or the Skagerrak (Butruille et al., 2017; Krossa et al., 2017) and is consistent with the Holocene Climate Optimum (HCOThermal Maximum (HTM), a time period of warm summers in higher latitudes. The pollen-based temperature reconstructions imply that in the terrestrial realm, high summer temperatures were already established before ~7,400 cal. yr BP, but that temperatures were very low during winter. In EZ2, the MTWALDI and long chain diol indexMTWA indicate a gradual and slow cooling trend by ~1 to 4 °C towards the top of EZ2. A similar cooling trend is also observed inOn the contrary, the TEX$^{L}_{86}$ record that despite generally high surface waterindicate a rapid cooling and rather constant temperatures shows a decline in temperature by ~6 of ~15°C duringthroughout EZ2 with a trend similar to the clumped isotope record. The general order of magnitude of the pollen-based temperatures for EZ2 (~-8 to ~1.5°C MTCO and ~1917.5 to ~17.519°C MTWA) is in accordance with pollen-based climate reconstructions from, e.g. central Germany (Kühl and Moschen, 2012). Furthermore,), and the overallgeneral trends in all temperature reconstructions are congruent with trends reported by Davis et al. (2003) and Mauri et al. (2015) for western central/northern Europe. However, findings of pollen of thermophilous species in Danish records from the Boreal and Atlantic periods (~9,000 to 5,000 cal. yr BP) imply that winters should have been mild enough for these taxa (e.g. Iversen, 1944).

In **EZ3**, the long-chain-diol-index-based-SST, pollen-inferredLDI SST, MTWA and Mg/Ca ratios suggest a continuation of the cooling that agrees with trends observed in other records (Seppä et al., 2005), while MTCO, TANN and the TEX$^{L}_{86}$ indicate a gradual warming that cumulates in maximum air and surface water temperatures SSTs at the transition to EZ4 at ~1,000 cal.

yr BP and therewith in a time interval equivalent to the Medieval Warm Period (MWP). A congruent short-lived warming that interrupts the general cooling trend is also observed in the long chain diol record.~~.~~ In **EZ4**, the long-chain-diol-index~~LDI-~~ and TEX$^{L}_{86}$-based SSTs show~~are characterized by~~ a rapid cooling with minimum temperatures of 14°C (TEX$^{L}_{86}$) and 17°C (long chain diol index~~LDI~~) observed at ~400 cal. yr BP~~, corresponding to the Little Ice Age~~. Such a cooling trend is also evident in all pollen-based temperature reconstructions and likely corresponds to the Little Ice Age (LIA).~~.~~ In contrast to the pollen record, however, the long chain diol index~~LDI~~ and TEX$^{L}_{86}$ both show a warming trend in the uppermost part of the studied sequence~~topmost samples~~ with SSTs exceeding~~increasing above~~ 20 °C in the sample closest to the core top. Surface~~, which is of the same order of magnitude as modern~~ water temperatures of similar magnitude are presently observed during late July to mid-August in the Little Belt (ICES, 2017) and imply that both lipid paleothermometers reflect a late summer signal in our setting. For the TEX$^{L}_{86}$, this finding is in agreement with previous observation made by Kabel et al. (2010) in the Baltic Proper. Likewise, the long chain diol index has been reported to reflect summer surface water temperatures in a variety of oceanographic regions (Lopes dos Santos et al., 2013; Jonas et al., 2017), although it has recently been advocated to reflect an annual water temperature signal in the Ångermanälven River estuary (Warnock et al., 2017).~~).~~

Reconstructed absolute temperatures vary significantly between the different inorganic-based and organic-based proxies (Fig. 4). This is - to some extent - explained by the different realms the proxies reflect but even between the long chain diol index~~LDI~~ and TEX$^{L}_{86}$ lipid paleothermometers, which are both considered to reflect summer SSTs in the Baltic Sea, significant deviations are observed. Such discrepancies have ~~been~~ previously been reported for both proxies from subpolar (Rodrigo-Gámiz et al., 2015) to tropical regions (Jonas et al., 2017~~in review~~) and were explained by differences in either the habitat depth and/or seasonality of the biological sources of both proxies. Long chain diols used to calculate the long chain diol index~~LDI~~ are synthesized by eustigmatophyte algae (Volkman et al., 1992) that are oxygenic photoautotrophs, and therefore the long chain diol index~~LDI~~ should exclusively record SWTs~~SST~~. Indeed, the long-chain-diol-index~~LDI~~-based SWT~~SST~~ in the sample closest to the core top is 18.3°C and therewith closely matches the summer SST of 17.6±0.7°C observed in the Little Belt region (ICES, 2017). This finding is in accordance with the observation that the long chain diol index~~LDI~~ reflects SST during the late summer-autumn season based on a comparison of long chain diol~~LCD~~ distribution patterns in globally distributed marine surface sediments and monthly satellite SST data (Rampen et al., 2012). In addition to the marine realm, long chain diols~~LCDs~~ have also been observed in freshwater environments (Rampen et al., 2014). These authors noted a moderate linear correlation between summer temperatures and the long chain diol index~~LDI~~ in a set of globally distributed lake sediments. Yet, the slope of long chain diol index~~LDI~~ regression lines found in lacustrine and marine settings differs significantly, suggesting that the reconstruction of long-chain-diol-index~~LDI~~-based SWT~~SST~~ may be flawed in settings of high riverine input of organic matter. Indeed, substantial offsets between long-chain-diol-index~~LDI~~-based SSTs and satellite derived SSTs have been observed in front of the Tagus and Sado river mouths (Iberian Atlantic margin) with the long chain diol index~~LDI~~ yielding SST that are up to 8 °C lower than measured average or summer SSTs (de Bar et al., 2016). Yet, the branched isoprenoid tetraether index is characterized by consistently low values that speak against an increased freshwater discharge that may have confounded the use of the long chain diol index in our setting.~~The comparatively low summer SST values of on average 14.6±0.4°C that are observed in the freshwater interval of EZ1 and the subsequent rapid increase in SST towards the base of EZ2 may, therefore, be a result of the significant changes from a freshwater to brackish-marine environment of the Little Belt rather than a true climate signal. This is corroborated by high relative proportions of 1,15-C_{32} diol that indicates substantial contributions of LCDs from freshwater eustigmatophytes (Volkman et al., 1999; Rampen et al., 2014) and the lack of major changes in absolute temperatures based on the TEX^L_{86} lipid paleothermometer and pollen patterns across the EZ1/EZ2 boundary (Fig. 4).~~

Temperatures reconstructed using the sedimentary distribution of isoprenoid GDGTs (i.e, TEX_{86}/TEX^L_{86}) ~~TEX^L_{86}-based SSTs~~ vary from ~12 to ~26 °C (average of 17.0~~1~~±3.5 °C) with three distinct maxima observed at the base of~~transition from EZ1 to~~ EZ2 (~7,500 to ~7,300 cal. yr~~.~~ BP; 19.6±0.1 °C) as well as in~~at~~ the lowermost part~~base~~ (~900 cal. yr BP; 25.9 °C) and close to the top of EZ4 (16 cal. yr BP~~present-day~~; 21.1°C). The latter~~This~~ present-day TEX^L_{86}–based water temperature is ~~with 21.1 °C~~ close to SSTs observed in the Little Belt region during late July to mid-August (ICES, 2017). This suggests that the TEX^L_{86} reflects summer surface water temperatures in the Baltic Sea as previously also argued by Kabel et al. (2012), who observed the best correlation for GDGT distribution patterns in surface sediments of the central Baltic~~ Sea~~ with average water temperatures from July to October. The TEX^H_{86} has also been shown to correlate with surface water temperatures in the Baltic Sea (Kabel et al. 2012). The calculation of this proxy, however, requires the robust identification of crenarchaeol that in the marine environment is ubiquitously distributed (Schouten et al., 2002). In brackish and freshwater environments this component is generally less abundant (e.g. Schouten et al., 2013b) and in the Little Belt region could not be detected in all the samples and generally with less confidence in the remaining samples questioning the use of the TEX^H_{86} in reconstructing SWTs in the Baltic Sea.~~In terms of absolute temperature and overall trends, the TEX^L_{86} record is to some degree similar to the clumped isotope record but differs significantly from the LDI as well as other temperature-based profiles (i.e. pollen and Mg/Ca ratios of benthic foraminifera).~~ A factor potentially complicating the reconstruction of GDGT~~TEX^L_{86}~~-based SWTs~~SSTs~~ is the input of large quantities of soil-derived isoprenoid GDGTs (Weijers et al., 2006; Schouten et al., 2013b). A quantitative mean to determine the input of terrestrial organic matter to aquatic environments is the branched isoprenoid tetraether index~~BIT~~ with low values of this proxy (<0.1) indicating open marine conditions and high values being representative for terrestrial settings (<0.9; Hopmans et al., 2004). Empirical studies suggest that the TEX_{86} and its derivatives do not allow a reliable reconstruction of SSTs if branched isoprenoid tetraether index~~BIT~~ values exceed a threshold of ~0.3 (Weijers et al., 2006; Zhu et al., 2011). Branched isoprenoid tetraether index~~BIT~~ values in the Little Belt have an average of 0.29±0.04 in EZ2-4, close to but still below this threshold. The TEX^L_{86} does, therefore, not seem to be biased by an allochthonous contribution of isoprenoid GDGTs. This is also supported by an absence of correlation between branched isoprenoid tetraether index~~BIT~~ and TEX^L_{86} values (r^2 = 0.04; p >0.001), which is only to be expected if the terrestrial influence on the TEX^L_{86} is negligible (Schouten et al., 2013a). In fact, a ~~very similar~~ TEX^L_{86} temperature record with similar trends, covering only the last 1,000 cal. yr BP with temperature maxima during the MWP and Modern Hypoxic Period~~, (MHP),~~ has been reported from the Gotland Basin in the central Baltic Proper (Kabel et al., 2012), suggesting that the TEX^L_{86} indeed traces climate-driven variations in

SWTSST in the brackish-marine Littorina Sea stage. However, in EZ1 high BIT values of 0.87 indicate a higher contribution of terrestrial-derived GDGTs that may potentially confound the application of the TEX^L_{86} in the freshwater interval of the Little Belt. Yet, TEX^L_{86}-SSTs in EZ1 and the immediately overlying marine-brackish sediments of EZ2 are largely similar and are in agreement with the reported warming in the Baltic Sea region during the HTM (Seppä et al., 2005; Krossa et al., 2017).
Temperatures inferred from carbonate-clumped isotopes and Mg/Ca ratios of benthic foraminifera are largely similar to those observed during late summer in the Little Belt. Indeed, in temperate climate settings molluscs and benthic foraminifera precipitate carbonate only if environmental conditions permit, so shell geochemical proxies (such as carbonate clumped isotopes and Mg/Ca) tend to be skewed towards the seasons when growth is favourable (Filipsson et al., 2004; Austin et al., 2006; Schöne, 2008; Skirbekk et al., 2016). Despite temperatures which are within range of present day variability, the cleaning experiments on the foraminiferal calcite show that the 8°C decrease in bottom water temperaturesBWT may not be realistic after all. It cannot be excluded that the foraminiferal tests were still contaminated by the presence of authigenic carbonates like for example rhodochrosite, which can also contain Mg, and which cannot be removed by the current cleaning methodologies. The occurrence of such authigenic carbonate deposits in the Baltic Sea is common (Huckriede and Meischner, 1996; Andrén et al., 2015b; Hardisty et al., 2016; Van Helmond et al., 2017accepted) and likely also affects foraminiferal tests (Groeneveld and Filipsson, 2013). Remaining contamination is also suggested by the significant correlation coefficient between Mg/Ca and Mn/Ca ($r^2 = 0.72$) after the oxidation-reduction cleaning. This suggests that especially the older part of the Mg/Ca record is contaminated.
The presence of benthic foraminifera in EZ2-4 and their absence in EZ1 is related to salinity, i.e. foraminifera do not occur in the freshwater setting of EZ1. The absence of foraminifera in the upper meters of the record (<5 mcd), however, is more likely due to poor preservation of the foraminiferal calcite. Similarly, the foraminiferal abundance decreases in EZ2, such that enough specimens were still present to perform stable isotopes analyses, but there were too few to perform reliable Mg/Ca analyses. Poor preservation may have been caused by the degradation of organic matter in the sediment, which led to lower pH values of the pore water such that dissolution of the foraminiferal tests took place.

5 Conclusions

In this study, we have investigated and compared how inorganic- and organic-based temperature as well as salinity proxies perform in the coastal setting of the Little Belt with highly variable environmental conditions. Sediments deposited since ~7,8008,000 cal. yr BP at IODP Site M0059 were analysed to capture the transition from freshwater to marine conditions and thus to study the effect of facies change on proxy applications.
Our study demonstrates that a multi-proxy approach allows deciphering the various factors which have influenced past oceanographic conditions in the Little Belt. Between ~7,800 and 7,400 cal. yr BP, a direct connection of the Little Belt to the Baltic Proper may have existed as salinity-specific proxies indicate lacustrine conditions, while a connection to the Kattegat can be excluded. Salinities Water temperatures and probably also water temperaturessalinities increased within 200 yr after

the onset of the Littorina Sea stage at ~7,400 cal. yr BP. An interval of particularly saline conditions and high summer water and air temperatures followed, although both salinity and water temperatures declined with increasing precipitation until ~4,000 cal. yr BP. After ~4,000 cal. yr BP, the Little Belt witnessed decreasing temperatures during the warm season both in the marine and terrestrial realm, while salinity increased.

In addition, our study highlights the importance and value of a multi-proxy approach to reconstruct past oceanographic conditions. The different salinity proxies used here show generally similar trends in relative changes in salinity, but do not allow quantitative estimates of salinity (except for marine ostracods). In contrast, the reconstruction of temperatures is associated with particularly~~particular~~ large uncertainties and variations in absolute values by up to 8 °C for bottom waters and even up to 16 °C for summer surface waters. For example, different cleaning techniques for Mg/Ca in the foraminifera show different results which partly correlate with indicators for contamination especially in the deeper intervals studied. This suggests that the Mg/Ca of those samples is likely over-estimated, so that the decreasing trend in Mg/Ca and thus calculated bottom water temperatures~~BWT~~ may not be as large. The differences in results based on the lipid proxies (long chain diol index~~LDI~~ and TEX^{L}_{86}) can partly be explained with the application of modern-day proxy calibrations in areas which experienced significant changes in depositional settings (e.g. change from freshwater to marine conditions). Our study shows that particular caution has to be taken when applying and interpreting proxies in coastal environments, where water mass conditions can experience more rapid and larger changes than in open-ocean settings. Approaches using a multitude of independent proxies may thus allow more robust paleoenvironmental assessment.

6 Data availability

Data not enclosed in the supplements~~supplementary~~ will be uploaded to the PANGEA database (LINK). Already available~~uploaded~~ are ostracod data (~~PDI-14486~~https://doi.pangaea.de/10.1594/PANGAEA.873270).

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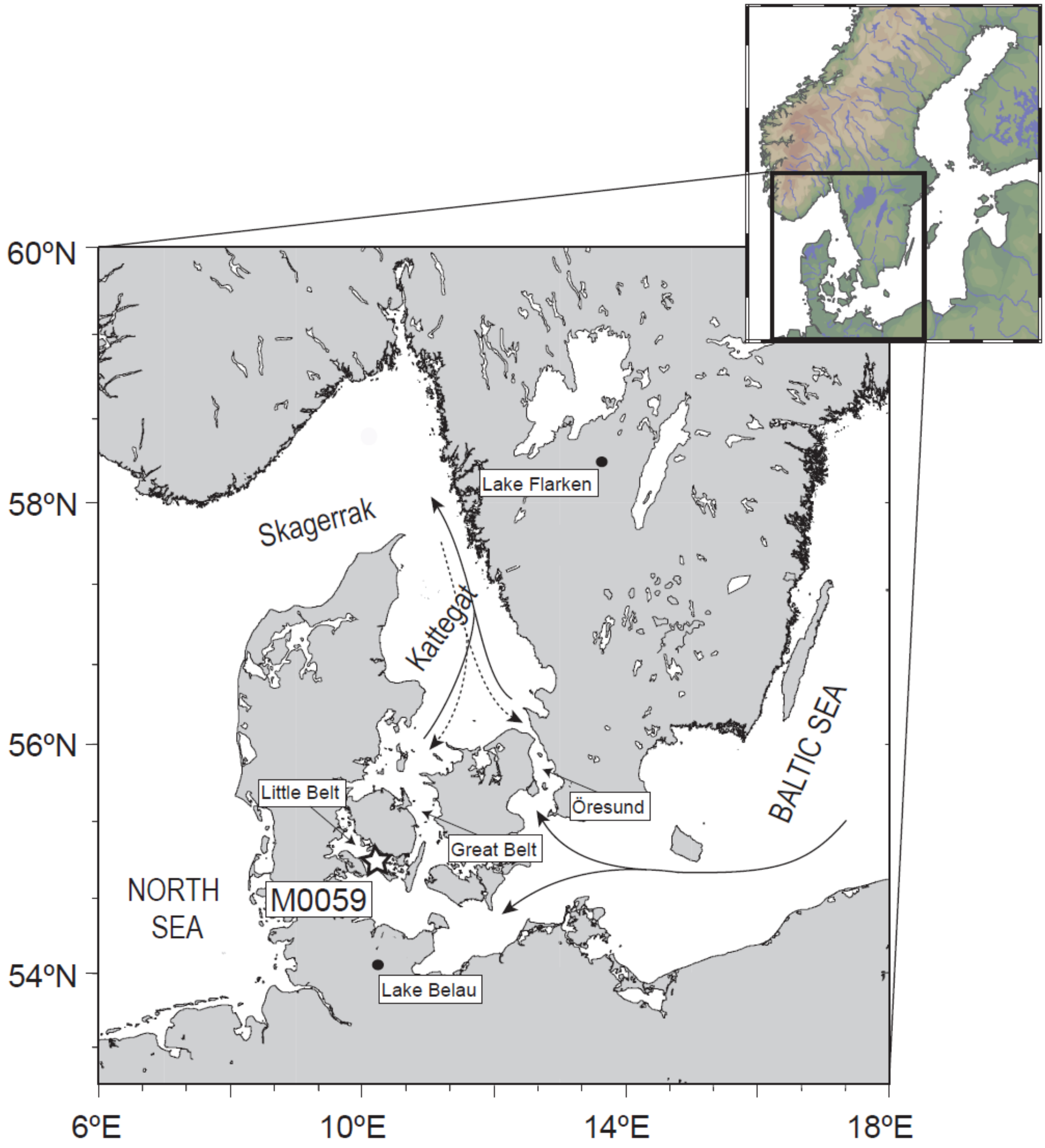


60ºN
58ºN
56ºN
54ºN
6ºE
10ºE
14ºE
18ºE
Skagerrak
Kattegat
Lake Flarken
BALTIC SEA
Little Belt
Öresund
Great Belt
NORTH SEA
M0059
Lake Belau

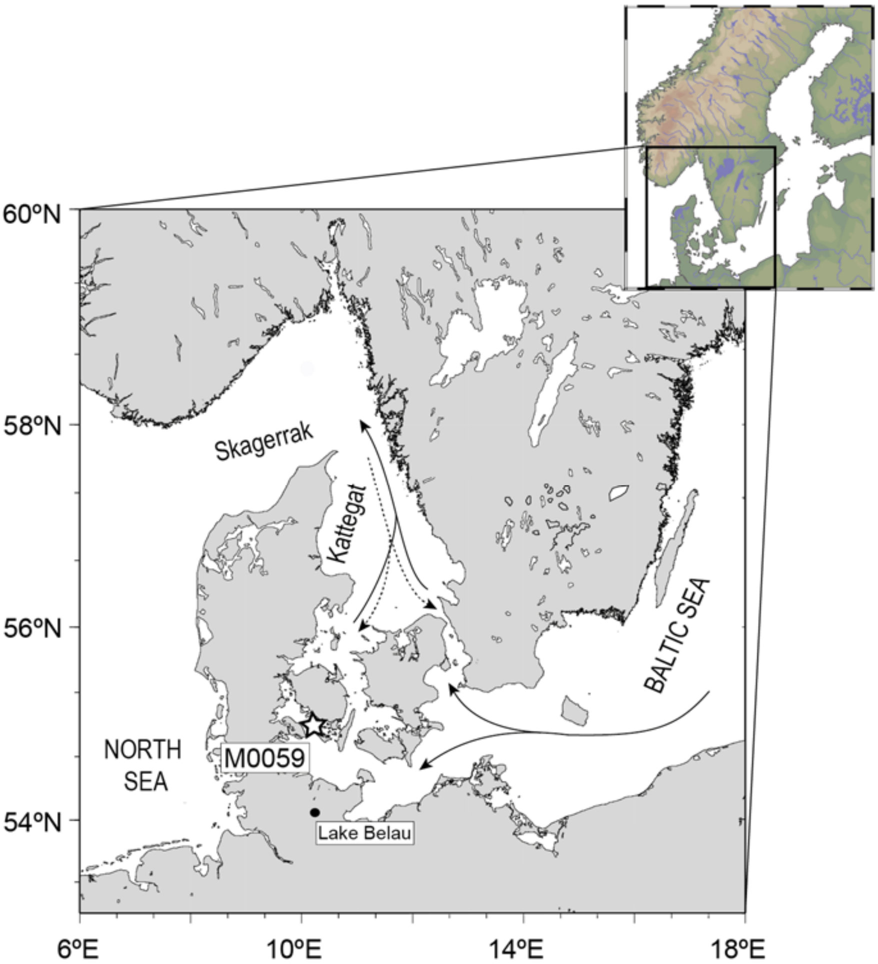
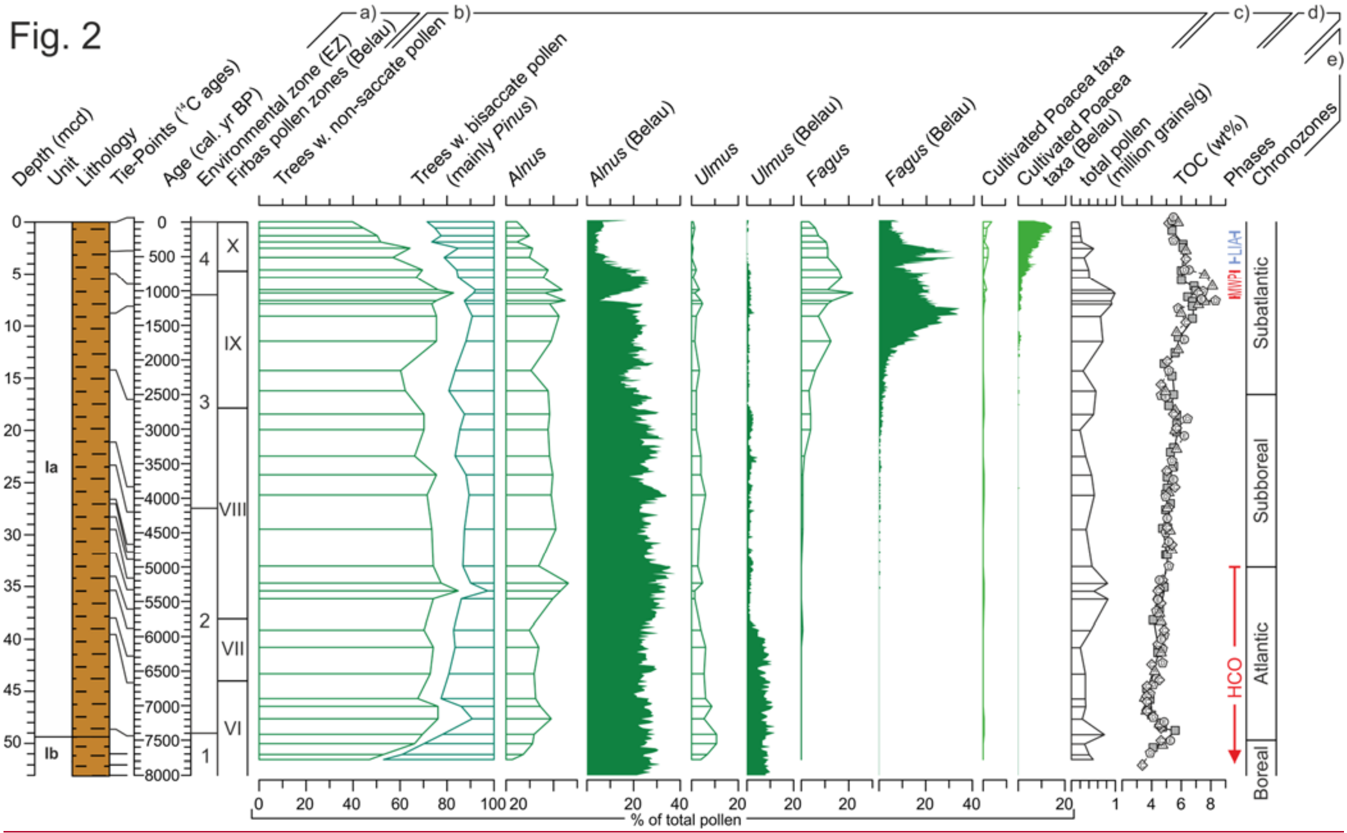


Figure 1: Map of the southern Baltic Sea (redrawn from Groeneveld and Filipsson, 2013). The positions of IODP~~Integrated Ocean Drilling Program~~ Site M0059 (white star; 55°0.29′N29'N, 10°6.49′E49'E; Andrén et al., 2015a),~~) and of~~ Lake Belau ~~(in northern Germany (black point;~~ Dörfler et al., 2012), and Lake Flarken (Seppä et al., 2005) are indicated. Continuous (surface) and dashed (bottom) lines indicate dominant current directions.

Fig. 2

1285 

a)
b)
c)
d)
e)
Depth (mcd)
Unit
Lithology
Tie-Points (14C ages)
Age (cal. yr BP)
Environmental zone (EZ)
Firbas pollen zones (Belau)
Trees w. non-saccate pollen
Trees w. bisaccate pollen (mainly Pinus)
Alnus
Alnus (Belau)
Ulmus
Ulmus (Belau)
Fagus
Fagus (Belau)
Cultivated Poacea taxa
Cultivated Poacea taxa (Belau)
total pollen (million grains/g)
TOC (wt%)
Phases
Chronozones
Ia
Ib
X
IX
VIII
VII
VI
1
2
3
4
HCO
MWP
LIA
Subatlantic
Subboreal
Atlantic
Boreal
% of total pollen

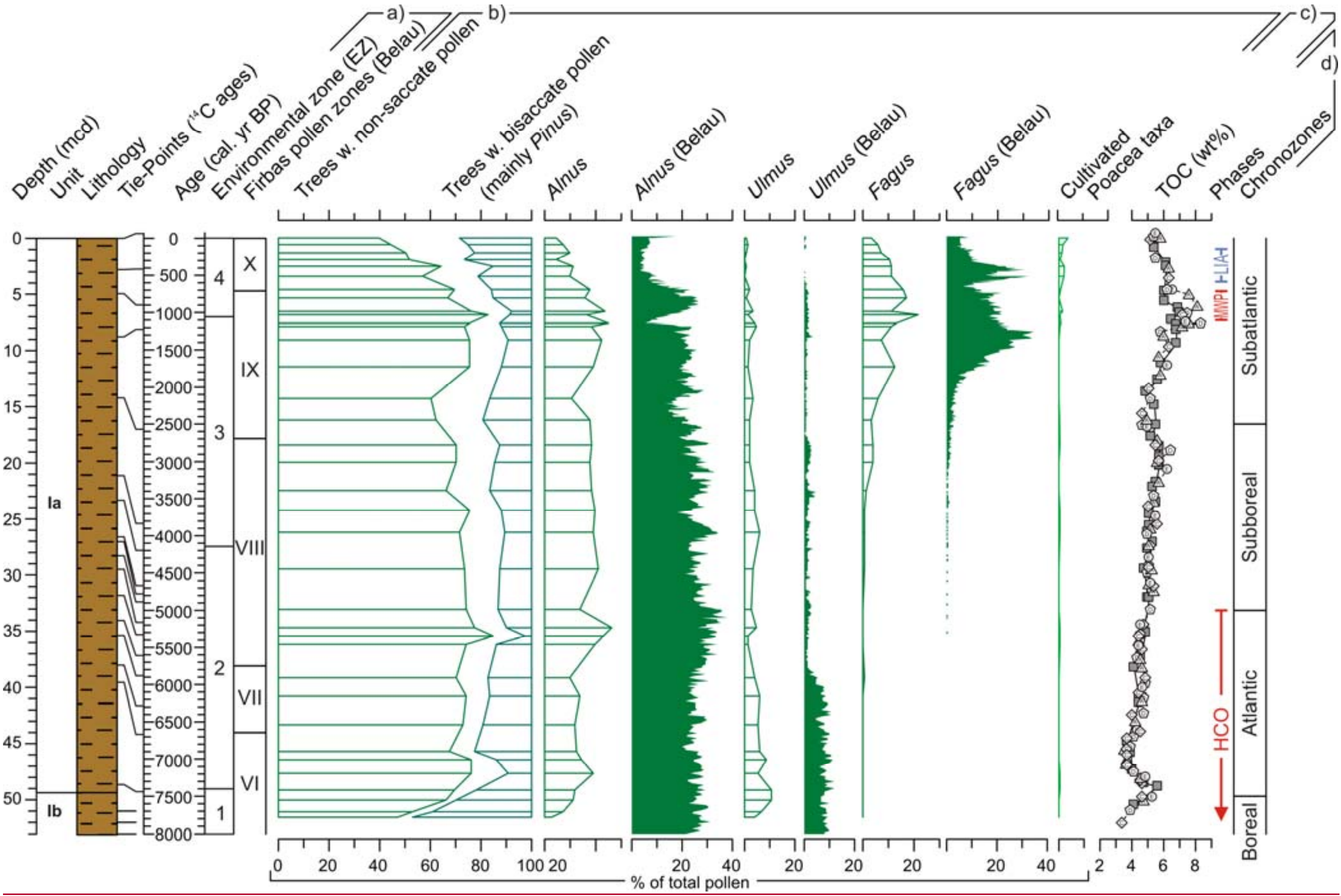


Figure 2: Comparison of the pollen record from IODP Site M0059 with the varved pollen record of Lake Belau (northern Germany, Dörfler et al.,~~.~~ 2012). Sedimentological units, lithology (Andrén et al., 2015a), position of ^{14}C ages (Van Helmond et al., 2017~~accepted~~) plotted vs. depth; plotted vs. age (extrapolated below ~48.64 mcd): a) environmental zones (EZ; IODP Site M0059), Firbas pollen zones (Lake Belau), b) selected pollen taxa (w. horizontal bars: IODP Site M0059, filled: Lake Belau), c) total organic carbon (TOC; white: shipboard data – triangles: Hole A, rhombi: Hole C, pentagons: Hole D, circles: Hole E; grey squares: onshore data) for IODP Site M0059, d) climate phases and chronozones.

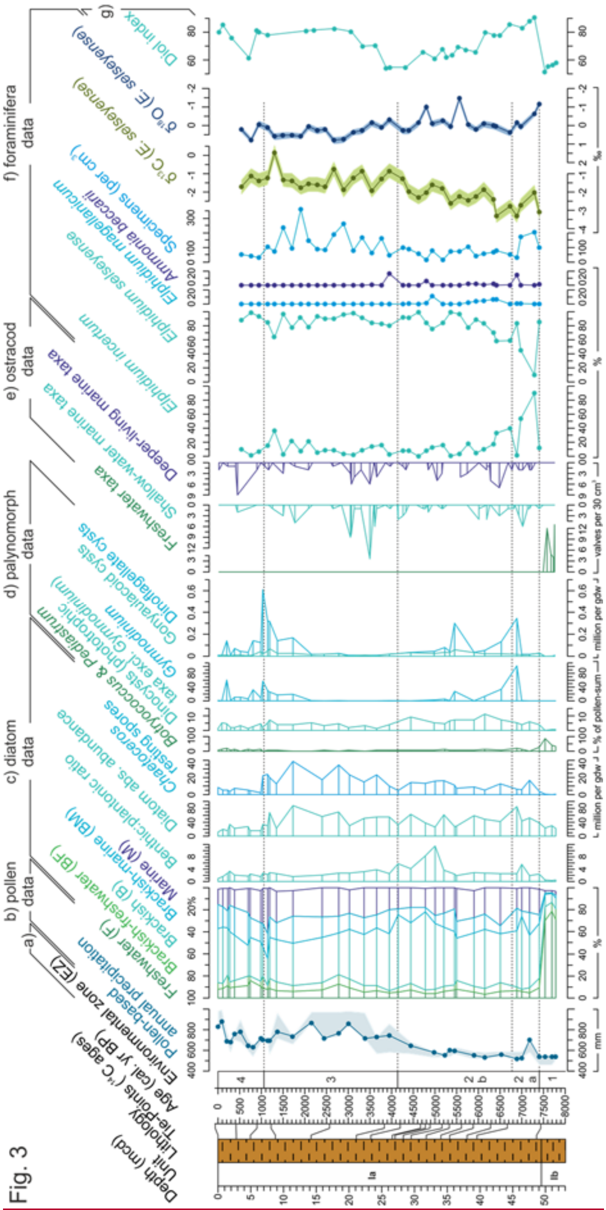
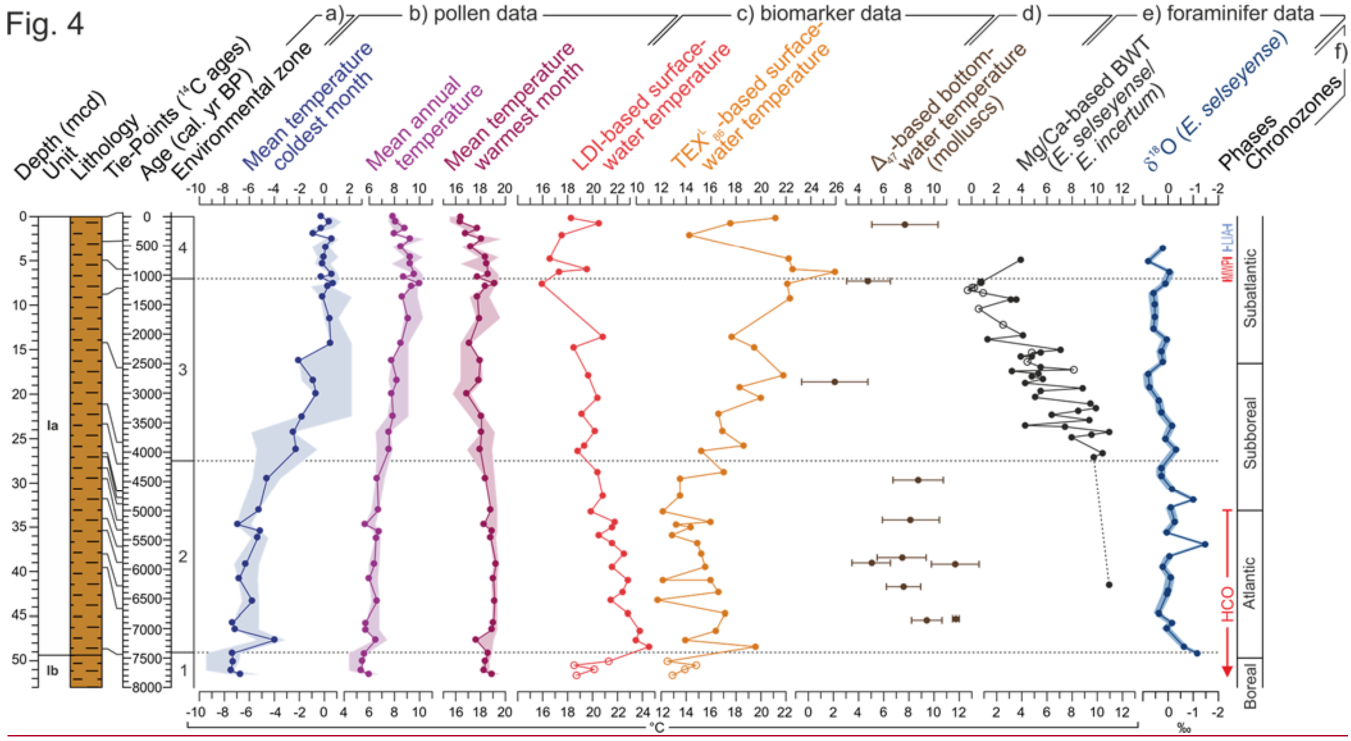


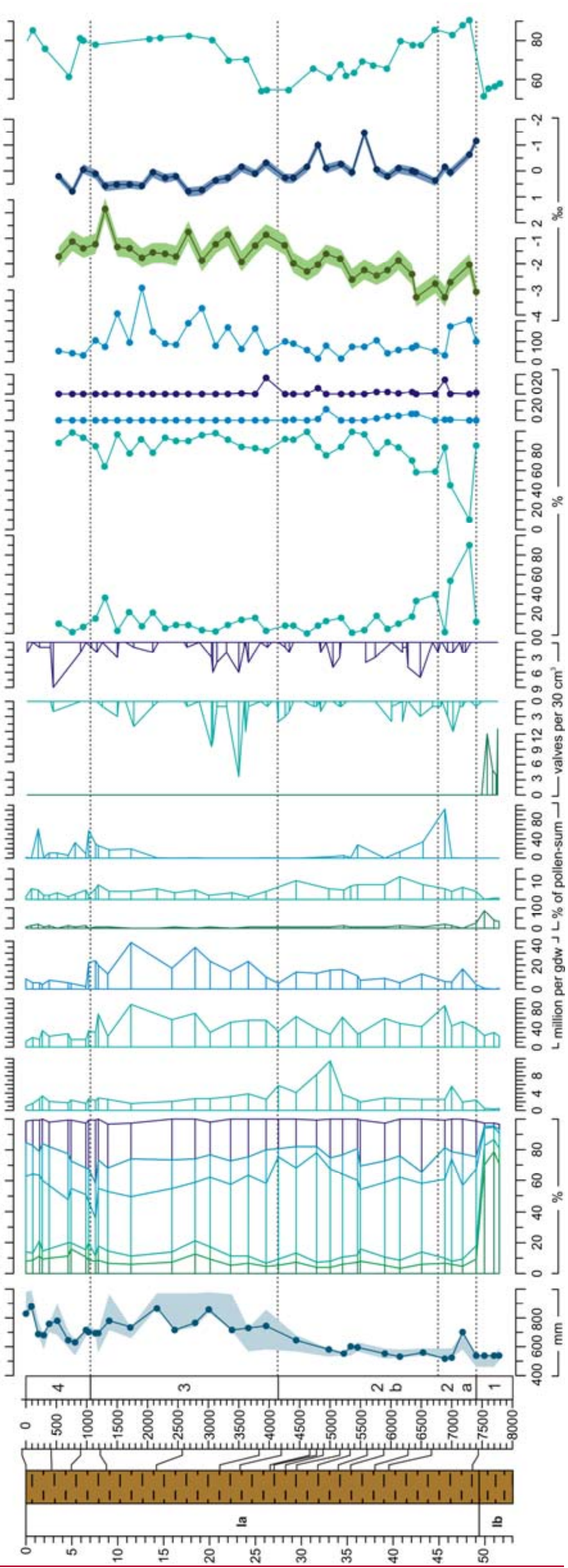
Figure 3~~:~~ (next page): Sedimentological units, lithology (Andrén et al., 2015a), position of ^{14}C ages (Van Helmond et al., 2017~~accepted~~) vs. depth; IODP Site M0059 precipitation and salinity proxies plotted vs.~~versus~~ age (extrapolated below ~48.64 mcd): a) environmental zones (EZs) based on diatom data; b) pollen-based precipitation reconstructions based on the modern analogues technique; c) diatom salinity-based affinities and life forms (benthic vs. pelagic) following Snoeijs et al. (1993-1998) with species assignments provided table S5 in the supplement;~~);~~ d) palynomorphs/pollen ratios based on total amount of terrestrial pollen, freshwater algae comprising *Botryococcus*~~*Bottryococcus*~~ and *Pediastrum* species, dinocysts predominately comprising cysts of *Protoceratium reticulatum* (*Operculodinium* cysts), *Lingulodinium,* and *Spiniferites* species (*Gymnodinium* excluded); e) Ostracod shallow water/deeper living marine taxa plotted from right to left; f) total abundance of benthic foraminifera per cm^3 of dried

sediment with the relative abundance of the most common species; benthic foraminiferal taxa *(Elphidium incertum*, *E. selseyense*, *E. magellanicum,* and *Ammonia beccarii*) shown as % of total benthic foraminiferal fauna; total abundance of benthic foraminifera shown as specimens per cm³ of dried sediment; stable carbon and oxygen isotope data analysed on *E. selseyense*; g~~f~~) Diol Index ~~(DI)~~ indicating relative changes in surface water salinity.

Fig. 4



a)
b) pollen data
c) biomarker data
d)
e) foraminifer data
f)
Depth (mcd)
Unit
Lithology
Tie-Points (14C ages)
Age (cal. yr BP)
Environmental zone
Mean temperature coldest month
Mean annual temperature
Mean temperature warmest month
LDI-based surface-water temperature
TEX86L-based surface-water temperature
Δ47-based bottom-water temperature (molluscs)
Mg/Ca-based BWT (E. selseyense/ E. incertum)
δ18O (E. selseyense)
Phases
Chronozones
Subatlantic
Subboreal
Atlantic
Boreal
HCO
MWP
LIA
Ia
Ib
°C
‰



Depth (mcd)
Unit
Lithology
Tie-Points (14C ages)
Age (cal. yr BP)
Environmental zone (EZ)
Pollen-based annual precipitation
a)
b) pollen data
Freshwater (F)
Brackish-freshwater (BF)
Brackish (B)
Brackish-marine (BM)
Marine (M)
c) diatom data
Benthic:planktonic ratio
Diatom abs. abundance
Chaetoceros resting spores
d) palynomorph data
Botryococcus & Pediastrum
Dinocysts (non-heterotrophic taxa excl. Gymnodinium)
Gymnodinium
Freshwater taxa
e) ostracod data
Shallow-water taxa
Deeper-living marine taxa
f) foraminifera data
Elphidium incertum
Elphidium selseyense
Elphidium magellanicum
Ammonia beccarii
Specimens (per cm3)
δ13C (E. selseyense)
δ18O (E. selseyense)
g) Diol index
mm
%
million per gdw
% of pollen-sum
valves per 30 cm3
‰

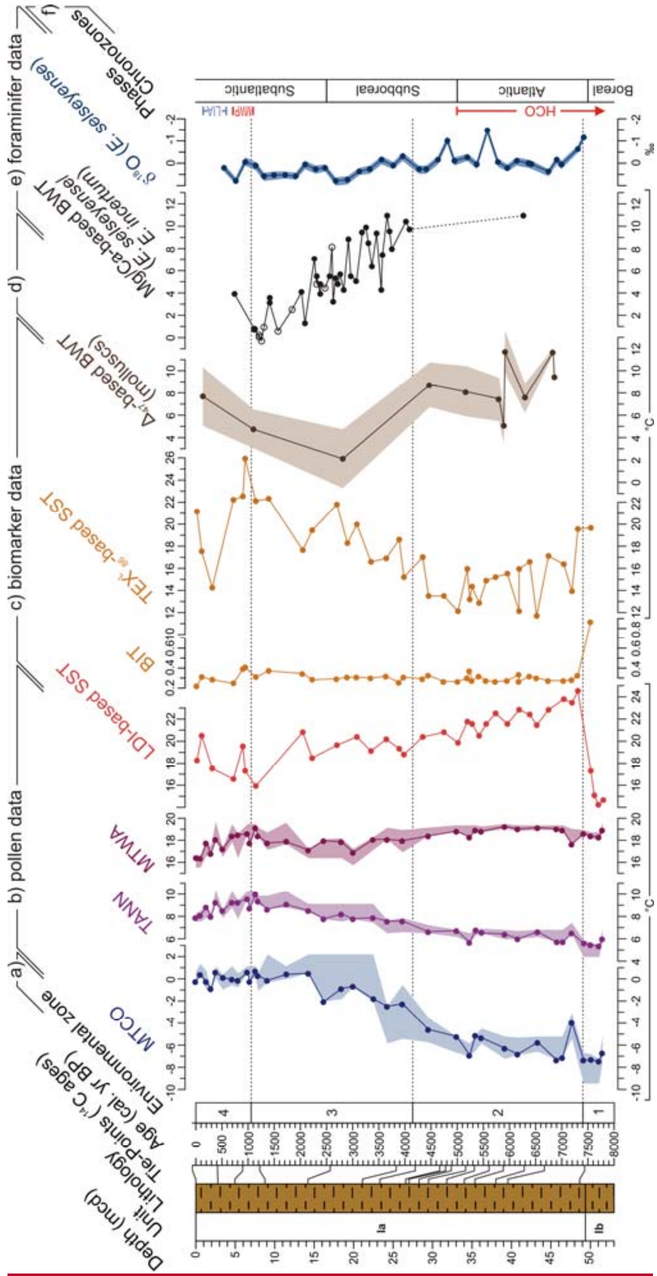


Figure 4: Sedimentological units, lithology (Andrén et al., 2015a), position of ^{14}C ages (Van Helmond et al., 2017in review) vs. depth; IODP Site M0059 temperature proxies plotted vs.versus age (extrapolated below ~48.64 mcd): a) environmental zones (EZs) based on diatom data; b) pollen-inferredbased climate reconstructions based on the modern analogues technique, shaded area reflects the range of the best 10 analogues; c) Long-chain-diol-index (LDI)- and TEX$^{L}_{86}$-reconstructed SSTs both reflecting a summer signalSSTs; BIT shown as quantitative measure for the amount of terrestrial organic matter transported to marine realm; d) Δ$_{47}$-inferred temperatures based on clumped isotope composition of mollusc shellsmaterial; e) Mg/Ca-based bottom water temperature (BWT) reconstructed using the benthic foraminifera *E. selseyense* and *E. incertum*; stable oxygen isotopes based on the benthic foraminifer *E. selseyense*; f) climate phases and chronozones.

~~**MTCO = mean temperature coldest month, TANN = annual temperature, MTWA = mean temperature warmest month, SST = surface water temperature, BWT = bottom water temperature.**~~