

**Interactive comment on “Coastal primary productivity changes over the last millennium: a case study from the Skagerrak (North Sea)” by Anna Binczewska et al.  
Anonymous Referee #1**

Response: We appreciate constructive comments and suggestions from anonymous referee 1. Responses to the review are below.

Reviewer 1: The paper presents a new data set from two high-resolution cores in the Skagerrak, spanning the last 1.1 thousand years, with the purpose of investigating historical changes in productivity. The data itself is a nice contribution to our understanding of recent changes in the ecosystem and forms a good follow-up to previous work from the same group and is very relevant to the topics covered by Biogeosciences. However, I have some concerns about the overall discussion and interpretation of the data. Additional data is not needed, but the existing data should be more carefully reconsidered.

In particular, the main conclusions about changes in productivity appear to rely closely on only one part of the data set i.e. the benthic foraminifera records. The authors identify three periods of different productivity based on some good analyses of the changes in benthic assemblages, but then appear to try to match each of the other records (TOC,  $\delta^{13}\text{C}$ , Mg/Ca,  $\delta^{18}\text{O}$ , Mn/Ca) to these three periods, which in many cases does not seem appropriate based on the figures provided. For example, in description of the Mg/Ca results, the authors highlight high temperatures between 900 and 1200 AD, I suppose because 1200 AD is where they have identified a benthic change. However, in my opinion, for the core EMB046/10-4GC this period does not stand out, and for the core EMB046/20-3GC the temperatures seen in the earlier period continue until perhaps 1400. More careful analysis and description of this and the other records should be provided.

Response: We have clarified this point by changing the subdivision of the record into two intervals and adding a sentence to the discussion as follow:

‘The above described changes in oxygen isotopes and BWT, seem to not correspond to variability seen in foraminiferal assemblages and the  $\delta^{13}\text{C}$  records’.

The subdivision of the record into intervals was done based on foraminiferal data, TOC and  $\delta^{13}\text{C}$ . At the same time isotope and Mg/Ca data seem to not follow those subdivision and instead show most pronounced changes, similar for both cores, between ~ CE 1700 – 1850.

We have revised the result and discussion sections in order to emphasise all data sources.

Major comments:

Reviewer 1: In addition, some of the speculation regarding sources of water/nutrients to the area (particularly the Atlantic Water) needs some more thought, and could be improved by trying some additional calculations based on the existing data.

Response: We have calculated  $\delta^{18}\text{O}_{\text{smow}}$  and have included the results in the modified fig. 4 and 5. We will describe the obtained data in the results part and use them in the discussion accordingly. Also we have added more information to the introduction about nutrients origin, see response to the comments below: ‘Reviewer 1: Pg 3 Line 20’; ‘Reviewer 1: Pg 3 Line 6’. In addition, we have modified the study area part of the paper by giving more details about the different water masses (please see answer to the review 2) and their origin, and we have made it clear at which levels in the water column these water masses are found. We hope that presented now the water masses description is more clear hence we have followed this description while improving the discussion part.

Reviewer 1: Uncertainties in the data need to be better characterised in the text and figures.

Response: We have added information about uncertainties of TOC and Mg/Ca to the text. Uncertainties in the data have been plotted, accordingly. Please see attached Figures.

Reviewer 1: Also, I think the authors could use the introduction to better highlight the importance of their work for a reader not familiar with the Skagerrak.

Response: We have made this point clear by adding information to the introduction as follows:

Pg 3, line 21: ‘The North Sea and the Skagerrak absorb large quantities of atmospheric CO<sub>2</sub> via biological pump (1.38 mol C m<sup>-2</sup> yr<sup>-1</sup> and 1.2 mol C m<sup>-2</sup> yr<sup>-1</sup>, respectively), thus both play an important role in the carbon cycle (Thomas et al. 2005; Hjalmarsen et al., 2010). The Skagerrak acts as a main depositional basin for about half of the refractory carbon produced in the North Sea and for a high amount of labile organic matter imported with waters of the near-bottom current from the Danish coast or caused by intense algal blooms (Boon et al., 1999). Input of nutrients largely regulates food webs, which makes nutrients of great economic importance for the coastal areas worldwide (Micheli, 1999; FAO, 2016) and in the Skagerrak nutrients are particularly important for the Nordic fisheries (Hop et al., 1992; Iversen et al., 2002; Olsen et al., 2004; Skogen et al., 2007). Fisheries and aquaculture sectors of the Skagerrak commercially valuable for the Scandinavian nation also make a relevant contribution to meeting growing global demand for food, which will largely rely on coastal regions to host a major part of food production in the future (e.g. FAO, 2013).’

Pg 3, line 29: ‘Thus, to better understand the ongoing and possible future productivity changes and associated environmental effects, more historical studies are needed.’

### **Specific Substantial Comments**

#### **Motivation**

Reviewer 1: As a reader unfamiliar with the Skagerrak, I felt that more was needed in the introduction to explain why the work is important and to highlight the interest of the work to a wider audience. There are references to changes in the ecosystem, but it would help the reader a lot to know more specifically why changes in production are important to the region (e.g. fisheries etc). Perhaps put this motivation up front before the more technical introduction.

Response: For the changes in the text please see response above.

#### **Uncertainty**

Reviewer 1: The uncertainties on each record need to be better characterised throughout the paper. In particular, uncertainties should be quoted for all methodologies, and the level of confidence indicated. At present it is unclear whether the errors that are quoted are at 1 or 2 sigma, and this makes a huge difference. It would be helpful to have a bar showing the uncertainty beside each record in the figures as well.

Response: The errors are quoted at 1 sigma. More information has been added regarding uncertainties. See responses to specific comments underneath.

Pg 5 Line 20: What is the TOC uncertainty? Even though it is published elsewhere it wouldn't take much space to include it here. Just a sentence to say uncertainty is 0.01 % (confidence).

Response: Description of the TOC analysis has been modified as follows:

‘The TOC content was determined using ‘Rapid CS cube –Elementar’ analyser (Department of Geology and Paleogeography, University of Szczecin, Poland) with a measurement accuracy of 0.01% (95% confidence level (CL) at 99.5% detection limit (DL)).’

Reviewer 1: Pg 6 Line 3: What is the level of confidence for these uncertainties? And are they long term precision or just the precision for the runs?

Response: We have modified the sentence according to the comments as follows:

‘The long-term analytical uncertainty is ±0.08‰ and ±0.03‰ (95% CL) for oxygen and carbon isotopes, respectively’.

Reviewer 1: Pg 6 Lines 19-27: Discussion of errors needs to be clearer in this section.

Response: We have modified the sentences according to the comments. We have changed the section method for the trace element analysis by characterizing the uncertainties through the section.

(modified version): ‘Shells of *M. barleeanus* were also cleaned and analysed for trace elements at the Trace Element Lab (TELab) at Uni Research Climate, Bergen (Norway). For each analysis, approximately 15-20 specimens were gently crushed between two glass plates under a microscope to allow the contaminants to be removed. The samples were cleaned following the procedure described by Barker et al. (2003). The cleaning method includes clay removal steps, oxidation of the organic matter and surface leaching. Samples containing enough material were mixed and split into two subsamples to allow duplicate analysis. All samples were dissolved

in trace metal pure 0.1M HNO<sub>3</sub> (prepared from HNO<sub>3</sub> TraceSELECT®) and diluted to a final concentration of 40 ppm of calcium (Ca).

The trace elements were measured on an Agilent 720 inductively coupled plasma optical emission spectrometer (ICP-OES). Six standards have been prepared at TELab and have a composition similar to foraminiferal carbonate (0.50 – 7.66 mmol mol<sup>-1</sup>). Further, Fe/Ca and Al/Ca values have been checked and showed no significant correlation with the measured Mg/Ca values. The correlation coefficients (R<sup>2</sup>) between Mg/Ca and, Fe/Ca and Al/Ca ratios are respectively, for the core EMB046/20-3GC, 0.012 and 0.095, and for the core EMB046/10-4GC, 0.020 and 0.067, indicating no systematic contamination due to insufficient cleaning. The Mn/Ca values in our samples are higher than the recommended maximum (<105 μmol mol<sup>-1</sup>) (Boyle, 1983), indicating that diagenetic coatings might also affect our results. The Mn/Ca values, however, show no significant correlation with the measured Mg/Ca values (R<sup>2</sup> = 0 for EMB046/20-3GC and R<sup>2</sup> = 0.021 for EMB046/10-4GC). Standard solution with Mg/Ca of 5.076 mmol mol<sup>-1</sup> is analysed after every eight samples to correct for instrumental biases and analytical drift of the instrument. The long-term Mg/Ca analytical precision, based on the standard solution, is ±0.016 mmol mol<sup>-1</sup> (1σ Standard Deviation) or 3.11% (relative SD). Average reproducibility of duplicate measurements (pooled SD, dof = 41) is equivalent to an overall average precision of 4.09%. The average Mg/Ca of long-term international limestone standard (ECRM752-1) measurements was 3.76 mmol mol<sup>-1</sup> (1σ = 0.07 mmol mol<sup>-1</sup>) with the average published value of 3.75 mmol mol<sup>-1</sup> (Greaves et al., 2008). The published *Melonis* spp. Mg/Ca - Bottom Water Temperature (BWT) is calculated from the measured Mg/Ca using the new *Melonis* spp. calibration (Mg/Ca = 0.113(±0.005)\*BWT + 0.792(±0.036)), based on core top data covering a Mg/Ca range of 0.68 – 3.66 mmol mol<sup>-1</sup> for a temperature range of -0.89 – 15.58°C (Hasenfratz et al., 2017). According to the calibration uncertainty, an 1σ temperature error (95% CL) of ±0.9°C to ±1.7°C has to be taken into consideration for the temperature range (4.1 – 9°C) covered by EMB046/20-3GC. For EMB046/10-4GC the 1σ temperature error (95% CL) is similar and ranges between ±1°C to ±1.6°C for the temperatures 5°C – 8.5°C. Further discussion on Mg/Ca-derived BWT within this article will use the Hasenfratz's calibration (Hasenfratz et al., 2017).<sup>7</sup>

Reviewer 1: Line 19: what is the 0.016 long term precision measured on (I assume a standard material) and what is its Mg/Ca value? What is the confidence level?

Response: The 0.016 mmol mol<sup>-1</sup> long-term precision refers to the long-term standard deviation based on the analysis of an in-house standard solution with Mg/Ca of 5.076 mmol mol<sup>-1</sup> after every eight samples. We have changed the sentence according to the points listed by the reviewer, please see above.

Reviewer 1: Line 20: Join these two sentences together (e.g. 'show a good reproducibility, with the pooled...').

Response: We have combined the two sentences together, please see above. The new sentence reports the reproducibility and indicates the pooled standard deviation.

Reviewer 1: Line 22: This is ok but the authors still need the confidence level.

Response: The error has been quoted to 1 sigma, please see above.

Reviewer 1: Lines 25-27: I would like to see an estimate of the typical temperature uncertainty obtained when propagating Mg/Ca ratios through the calibration equation here. According to the Hasenfratz paper, the ± 2 uncertainty ranges from ± 0.6 to 2 °C depending on the temperature. I guess we might be looking at ±1.5 °C, and most of the wiggles in Figure 3 might fit within these uncertainty bounds.

Response: We have added the temperature uncertainties obtained for the range of temperature we have for the two different cores. We have also modified all figures where the Mg/Ca-Temperature records are shown and include the uncertainties so that the temperature uncertainties linked to the used calibration is shown.

Reviewer 1: The authors really need to make sure that the moving average record is real and not just random scatter.

Response: The now added uncertainties to the plots show that the smoother record can be considered representative for the real long term signal. We have took that into account when revising the manuscript. In the new version the

uncertainty bands are shown together with the smoothed records, showing more clearly the relationship between the raw datasets and the smoothed records.

Reviewer: Pg 6 Line 28: I am less concerned that errors on counts would be a big problem for the results, especially for those with the biggest signals. However, it would still be nice to have an estimate of the counting uncertainty for each species. I.e. Replicate a sample several times how close can you repeat the counts? There are also some more formal ways to estimate counting uncertainty. See e.g. (Heslop et al. 2011, Diagnosing the uncertainty of taxa relative abundances derived from count data, *Marine Micropaleontology* 79, pp 114-120).

Response: We thank the reviewer for an advice on the study by Heslop et al. (2011). However, given the high number of samples (161 samples), which had to be analysed and at least 300 ind. counted per sample, the replicate analysis was outside of the scope of this study due to a lack of time and resources. Also, for foraminifera analysis we used the wet-counting method, which means that foraminifera were counted straight after washing. After that samples were dried and stored for further analyses (isotopes and Mg/Ca), which also resulted in a limited amount of material available for foraminiferal replicate analysis. The wet counting method allowed us to reduce loss of fragile agglutinated tests, thin-shelled taxa (e.g. *Alabominella weddelensis*, *Epistomiella* spp., *Nonionella iridea*) or inner organic linings (IOL) (Duffield and Alve, 2014; Brodniewicz, 1965) and in consequence provides more accurate record of foraminifera assemblages. Because of the chosen wet-counting method a repeat of counts could be done only on dried material what may cause differences between the replicates due to loss of fragile agglutinated and thin-shelled forms. Therefore, uncertainty for each species cannot be delivered from the replicate counting. Also since the extreme numbers we find for some species (e.g. *B. skagerrakensis* incl its juvenile forms) are clearly discernible in both cores presented herein (plus another core off western Norway – not shown) we believe that they are not the artefact of a chosen counting method but are rather true numbers.

Reviewer: Pg 7 Line 10: It would be useful to know what the typical age uncertainty for a given depth might be for both cores. The period after 1900 looks well-constrained by Hg, but radiocarbon can be difficult to use to match two cores exactly. However, I don't think the age model should affect your results too much. My main concern would be in saying things like 'between 1550 and 1650 one core shows this while the other core shows that.' Can the cores really be associated to that level of accuracy?

Response: We agree with the reviewer that there are limits to the certainties that can be set for radiocarbon dated chronologies' that influences the interpretation of changes at short time scale (e.g. multidecadal). We have modified the text accordingly to the comments.

Furthermore, since submitting, we have realized that there might have been some reason for concern regarding some of the dates used to set the chronology and have therefore re-dated several levels and created new age models, to improve the confidence that can be put on the age model, important when investigating such short time scales. We have also changed the  $\Delta R$  value used for calibrating the dates from  $0 \pm 50$  to  $200 \pm 50$ , since this improves the relationship between the historical tie points and radio carbon dates. When establishing the original age model, the two cores were set at a common depth scale. We keep this correlation after updating the absolute ages. Hence, the relationship between the two cores has not changed, but potential changes in the relationship comparing to other records will be re-evaluated. The new age model is presented in full in the revised manuscript.

### **Describing the records in terms of the three periods**

Reviewer 1: This was my main area of concern when reading through the paper. Firstly, I note that the three time periods loosely correspond to different sampling resolutions (i.e. relatively high resolution for the early and late periods and relatively low resolution for the middle period). Could this be affecting where lines were drawn? I don't think it is a big problem but it could be worth some investigation or a note in the text.

Response: We double-checked sampling resolution. The core EMB046/20-3GC was analysed for foraminifera every 1 – 3 cm with an exception of 7 cm interval between 89 – 96 cm (~ CE 1055 – 1030 years). The core EMB046/10-4GC was counted every 1 – 2 cm. The timing of the periods as set did not correspond to times when the sedimentation rate changed according to the age model. Thus, the different distribution of foraminifera data versus age scale is caused not by resolution differences (those are relatively steady). Originally, there was indicated a strong increase in sedimentation rates for the oldest part of the record. Using the improved age model, this is no longer the case. The new age model shows more realistic changes relative to what is common in this area during this time. As mentioned above, the full new chronological framework is presented in the revised manuscript.

The method part has been modified as follows:

(previous version): “The two Skagerrak records over the targeted time interval covering the last 1100 years were counted at 1 – 5 cm and 1 – 2 cm resolution for EMB046/20-3GC and EMB046/10-4GC, respectively”

(modified version): “The two Skagerrak records over the targeted time interval covering the last 1100 years were counted at 1 – 3 cm resolution with an exception of 7 cm interval between 89 cm and 96 cm (~ CE 1030 – 1055) for EMB046/20-3GC, and at 1 – 2 cm resolution for the entire 1100 years of the EMB046/10-4GC record”.

Neither is the timing of the periods influenced by changes in sedimentation rates, as these changes within the periods are not at the transition.

Reviewer 1: Secondly, as I noted above, the most convincing case for separating the record into three periods seems to be the faunal data. If I were to ignore those data and to try to describe the temperature, TOC,  $\delta^{13}\text{C}$  and Mn/Ca I would not find the patterns described in the text. The description of the temperature signal does not seem very objective. I gave one example above, and I note again how the record for EMB046/10- 4GC doesn't seem to have any period that is very different, especially once you include the temperature uncertainty. I can see a period of low temperature for the other core between maybe 1450 and 1650-1700, but I do not see why we would distinguish the first 200 years from the next 500. The temperature and oxygen isotope records need a more thorough and objective analysis of whether they do actually match the faunal data, especially as the authors use such a match to argue for changes in water mass driving the faunal changes.

Response: We believe that foraminifera are good indicators for productivity changes, however we agree that other data presented in our study should be discussed in more detail and even though they do not necessarily follow the foraminiferal pattern they should be examined in terms of different forcing factors, which might influence changes of productivity e.g. changes in water masses, nutrients sources, temperature variability. Therefore, we have revised the discussion part in a way where all data series are paid equal attention.

Reviewer 1: On Pg 12, Line 20 the authors describe the TOC as low, during the period of low productivity. However, it is higher than in the first period (argued to be moderately productive) and where the authors have also argued for lower oxygen concentration based on Mn/Ca. I find it hard to see how you could have less production, more bottom water oxygen and yet higher TOC if TOC is being considered as a productivity proxy.

Response: We agree with the reviewer that TOC records do not show any major changes in the interval between ~ CE 900 – 1700. The most visible change in the TOC records appears after ~ CE 1700 (according to the new age model). We have modified the result and discussion part accordingly.

We also decided to not include the Mn/Ca data into the manuscript, since the Mn/Ca presented on new age model does not show any significant changes.

Reviewer 1: How about the possibility that the sediment TOC gets less down the core simply because it is decaying over time?

Response: We agree that the decrease in TOCs with depth at both sites is probably in part caused by decaying organic matter. That is why we try to not address TOC changes in details for the part of the record older than CE 1700. However, the pronounced increase in TOCs after ~ CE 1700 towards cores tops coincides with changes in foraminiferal assemblages as higher abundance in palaeoproductivity fauna and increases in *B. skagerraknesis* factor suggesting higher productivity at that time. Higher productivity may thus have led to increase of organic matter in the sediments and most likely also contributed to changes in TOC profile.

### **Influence of different water masses**

Reviewer 1: Given the issues I have outlined above, the inferences that different water masses are influencing the sites at different time (e.g. Atlantic Water contributing to moderate productivity during the early period), are not well-supported. For example, the authors argue that warmer conditions (from Mg/Ca and  $\delta^{18}\text{O}$ ) during the 900-1200 period can be explained by increased Atlantic Water. Firstly, I suggest that the authors need to robustly test their trends with appropriate errors as outlined above.

Response: We have modified Figs. 4, 5 by adding error bands to the BWT-derived Mg/Ca and  $\delta^{18}\text{O}$ .

Reviewer 1: Secondly, the arguments based on temperature (especially in this section, Pg 11) are split by a section on carbon isotopes, which confuses the flow of the paper. There seem to be two arguments for temperature change: increased Atlantic Water influence and generally high temperature during the MWP. I think the authors do combine

these arguments by reference to NAO changes, but the link is not made very clear. In addition, the authors should at least address why the temperature in core EMB046/20-3GC remains high well into their second time period, when the productivity has already decreased, which they overall argue is a partly a response to less AW.

Response: We have made this point clear by restructuring discussion part following already modified study area part. We also believe that modified figure 5 where we compared our data to the NAO records reported by Trouet et al. (2009), Olsen et al. (2012), Faust et al. (2016) will help to clarify connection between water masses changes, NAO, temperature and climate. We have revised the section such that the discussion about carbon isotopes no longer disturbs the flow.

Reviewer 1: There is some discussion of complicating factors that might affect the temperature/productivity link, but it is not very clear and should be restructured. To solidify the link to increased AW I would suggest using the Mg/Ca and  $\delta^{18}\text{O}$  to reconstruct the  $\delta^{18}\text{O}$  of the deep water (e.g. salinity), because the  $\delta^{18}\text{O}$  of the shells also has a temperature signal. Knowing the water  $\delta^{18}\text{O}$  might provide a more useful indicator of water provenance and is standard practice in most paleoceanographic work, although the uncertainty might again be very high in this case. The references used to support the conclusions here seem appropriate, and they may be the simplest and best way to argue that the changes seen are do in part to water masses.

Response: We thank reviewer for the suggestion. We have calculated  $\delta^{18}\text{O}_{\text{snow}}$  and have included the results in the fig. 4 and 5. We have described the obtained data in the results part and use them in the discussion accordingly.

### **$\delta^{13}\text{C}$ records**

Reviewer 1: The authors attempt to put the  $\delta^{13}\text{C}$  records into the context of their productivity results, and they note correctly that the late increase in  $\delta^{13}\text{C}$  is due to the Suess effect. However, given that changes in water masses are invoked to explain changes in productivity, I would expect to see some analysis regarding whether their  $\delta^{13}\text{C}$  changes could be explained this way, rather than by changing productivity at the sites. I think the authors correctly conclude that the  $\delta^{13}\text{C}$  records do not correspond to the productivity records. Therefore, I would recommend removing much of the  $\delta^{13}\text{C}$  discussion, simplifying it to a sentence or two saying that not much coherence is seen. I also think the Suess effect is well known enough that such a long paragraph from Pg 16 line 10 is not really warranted. Cutting out the  $\delta^{13}\text{C}$  discussion would also help streamline the paper.

Response: We have modified this paragraph according to the comments.

### **Specific Minor Comments**

Reviewer 1: Pg 3 Line 6: Note that in general, not all organic matter makes it to the seafloor (in fact most doesn't), and much of it is remineralised in the water column. If this situation is different in the Skagerrak the authors should say so and why.

Response: The Skagerrak forms the deepest part of the Norwegian Trench and therefore acts as a sink for organic matter produced in the North Sea. Boon et al. (1999) presented an interesting study on distribution, metabolism of organic matter and variation in the supply of fresh phytodetritus to the sea floor in the Skagerrak and neighbouring area. They reported that the Skagerrak is a decomposition area for about half of the refractory carbon produced in the North Sea but also for a high amount of labile organic matter. The high amount of fresh organic matter found in the sediments is likely caused by intense algal blooms or advection of labile organic matter from the shallower coastal waters of northern Denmark transported via near-bottom currents to the Skagerrak (Boon et al. 1999). Because the deeper Skagerrak basin is dominated by fine-grained silty-clay sediments it is possible that mineralisation of labile organic matter slows down due to sorption to mineral surfaces of sediment particles (Keil et al. 1994).

We have added more information about organic matter in the Skagerrak accordingly to the comments and the response given above as follows:

Pg 3 line 21: The Skagerrak acts as a main depositional basin for about half of the refractory carbon produced in the North Sea and for a high amount of labile organic matter either imported with waters of the near-bottom current from the Danish coast or produced by intense algal blooms (Boon et al., 1999).

Reviewer 1: Pg 3 Line 9: Sentence reads a little strangely. Consider rephrasing to something like 'Via photosynthesis, primary producers can help to remove CO<sub>2</sub> from the atmosphere as part of the biological pump'.

Response: Changed accordingly.

Reviewer 1: Pg 3 Line 11: Change to 'likely negatively impact'. Response: Changed

Reviewer 1: Pg 3 Line 13: Sentence needs rephrasing. Need to specify 'export of organic matter' rather than 'production'. Response: Changed

Reviewer 1: Pg 3 Line 18: Include Figure 1 reference here to guide readers who don't know anything about the Skagerrak. Response: Added

Reviewer 1: Pg 3 Line 20: How does increased air-sea gas exchange lead to increased nutrients? Perhaps expand a little.

Response: We have added 'atmospheric CO<sub>2</sub> uptake' to the sentence Pg 3 line 16: 'Coastal zones are among the most productive marine regions characterised by high: atmospheric CO<sub>2</sub> uptake, organic matter accumulation and decomposition (e.g. Hjalmarrsson et al., 2010)'. We have also added the following sentence: 'The North Sea and the Skagerrak absorb large quantities of atmospheric CO<sub>2</sub> via biological pump (1.38 mol C m<sup>-2</sup> yr<sup>-1</sup> and 1.2 mol C m<sup>-2</sup> yr<sup>-1</sup>, respectively), thus both play an important role in the carbon cycle (Thomas et al. 2005; Hjalmarrsson et al., 2010)'. We believe that these changes and also first paragraph with more technical introduction sufficiently address the air-sea gas exchange topic.

Reviewer 1: Pg 3 Line 23: 'positive impacts on growth'. Growth rate? Growth magnitude? Be more careful about saying 'positive impacts'. Do you mean positive in the sense of being 'good', or simply 'more'?

Response: 'positive impacts on growth' changed to 'positive impacts on growth rate'

Reviewer 1: Pg 3 Line 24: Similar to above, what is a negative change in trophic levels? Fewer trophic levels? This needs to be more specific.

Response: 'negative' changed to 'disruptive'

Reviewer 1: Pg 4 Line 7: At the first introduction of the Kattegat, provide reference to Figure 1.

Response: Added

Reviewer 1: Pg 4 Line 9: It might be better to say that 'in the past the NAO has represented one of the leading modes of natural climate variability over the North Atlantic'. Or remove the word 'natural' altogether. I think it may now be difficult to say whether the NAO is wholly 'natural' anymore.

Response: We removed 'natural' - pg 4 line 7 and 'naturally' - pg 4 line 1.

Reviewer 1: Pg 4 Line 12: Specify what you mean by BCE.

Response: We added 'Before the Common Era (BCE)'.

Reviewer 1: Pg 4 Line 26: 'governed by' could be more specific. How does the sill control the AW?

Response: We have modified study area part. Please see comment above.

Reviewer 1: Pg 5 Line 2: 'internal' might not be the best word here. Internal to what? Perhaps say 'In addition to the mean circulation, processes such as : : ' Also as a general point, it helps the reader if all the references can be at the ends of sentences where possible. It is possible in this instance.

Response: We have modified study area part. Please see comment above. We have tried to keep all the references at the ends of sentences where possible.

Reviewer 1: Pg 5 Line 16: There are two sentences here that are almost the same. Consider rephrasing to avoid repetition.

Response: We have modified these sentences as follow:

(modified version): 'This study based on results from the upper 170.5 and 164.5 cm, in cores EMB046/20-3GC and EMB046/10-4GC respectively, what correspond to the last 1100 years. Here we present new stable isotope ( $\delta^{13}\text{C}$ ,  $\delta^{18}\text{O}$ ), and trace element ratio (Mg/Ca) data covering the last 1100 years, in combination with foraminiferal assemblage data and multivariate statistics.'

Reviewer 1: Pg 5 Line 25: Avoid the use of 'proved' (or proven). I think it is fine to just say 'potential'. Response: We changed this through the manuscript.

Reviewer 1: Pg 6 Line 1: What grade of methanol was used?

Response: The grade of methanol is  $\geq 98.8\%$ . We have added this information to the text.

Reviewer 1: Pg 6 Line 1: 'For each measurement 2-4 specimens were used.' How many measurements were done for each depth? Are 2-4 specimens enough to get a robust average isotope signal?

Response: The isotope measurements were run in high resolution (1 cm intervals) and no replicates were conducted. For each measurement 50–100  $\mu\text{g}$  was needed which is equal to ca. 2–4 *M. barleeanus* specimens. Such an amount of tests is sufficient for a sensitive mass spectrometer (Finnigan MAT 253) at Bergen University and has been previously used by many others (e.g. Milzer et al. 2013), thus we believe that by following the known procedure for isotope analyses, we were able to obtain robust isotope signal. Based on experience from the area we think that we get a robust isotope signal even though few specimens are used in each analysis. We do however focus on the trends, not the results of individual measurements as we agree that relying on individual measurements might overestimate the accuracy of the information we can extract.

Reviewer 1: Pg 6 Line 10: I think the authors could be more specific about the grade of HNO<sub>3</sub> used. What Ca concentration were the final solutions? Were these matched to the standard concentrations?

Response: We have rewritten the sentences according to these comments. Please see above the modified 'trace elements' paragraph.

Reviewer 1: Pg 6 Line 14: These results do not indicate 'no contamination', only 'no systematic contamination'. The authors are correct in the following sentence where they indicate that because of their high Mn/Ca values, contamination may be an issue. No need for the sentence on Line 16, as it repeats what was already said.

Response: According to points listed, we have modified the sentences. Please see above the modified 'trace elements' paragraph. The sentence on Line 16 has been deleted.

Reviewer 1: Pg 6 Line 18: 'After every 8 samples'? 'For' might not be specific enough.

Response: We have changed the sentence according to this comment. Please see above the modified 'trace elements' paragraph.

Reviewer 1: Pg 6 Line 18: Which standard solutions were used?

Response: We have added a sentence presenting the Mg/Ca concentration range used for the standard solutions. Please see above the modified 'trace elements' paragraph.

Reviewer 1: Pg 6 Line 28: 'The foraminiferal faunal analysis' Response: Added

Reviewer 1: Pg 7 Line 14: Include 'IntCal' in the wording somewhere here. Response: Added

Reviewer 1: Pg 7 Line 21: What is the detection limit for the TOC measurements? I think the results look fine but might be worth checking.

Response: The detection limit for the TOC measurements is larger than 99.5 %. We have added this information to the text.

Reviewer 1: Pg 7 Line 26: Here is an instance where knowing what the relative age uncertainty when comparing the different cores could be important. 1550-1650 is not a very long time period in terms of typical radiocarbon uncertainties.

Response: The age uncertainty of the carbon dates in our records vary between 30 and 60 years. Thus, we agree with the reviewer that interpretation of changes in short time periods (e.g. multidecadal) cannot be well verified. We have modified the text accordingly to these comments.

Reviewer 1: Pg 7 Line 28: To me 'long-term trends' implies a gradual change to different conditions over the whole record. Instead these records are quite flat until the Suess effect kicks in. I might say 'long-term variations'.

Response: Changed to 'long-term variations'.

Reviewer 1: Pg 8 Line 6: Same comment as above but now for oxygen isotopes.

Response: Changed to 'long-term variations'.

Reviewer 1: Pg 8 Line 26: I know that identifying planktonic forams is very difficult at the tiny sizes looked at here. I agree with the author's decision to discuss only the total number rather than species. Do the benthic ID's suffer from the same difficulty. I have less benthic experience to offer a full comment here.

Response: There are not similar issues regarding benthic foraminifera since most of their juveniles are easily discernible at the species level. We observed a wide range of sizes in benthic taxa, from very small e.g. *Alabaminella weddellensis*, *Epistominella* sp. (*E. exigua*, *E. vitrea*), *Nonionella iridea* or *Cassidulina* sp. (*C. laevigata*, *C. neoteretis*) to bigger e.g. *Melonis barleeanus*, *Pullenia bulloides*, *Hyalinea balthica*. The advantage for the identification of the foraminiferal assemblage from the Skagerrak region is that many research studies performed before have targeted this topic and as a result there is a lot published information about benthic foraminiferal taxonomy from the region.

Reviewer 1: Pg 9 Line 7: What is meant by 'less fluctuating'? Apart from one very large peak in 20-3GC the records look quite similar. Are the standard deviations very different?

Response: We have modified this sentence accordingly to the comment.

(modified version): 'The benthic foraminiferal record from the core EMB046/10-4GC is characterised by consistently high absolute abundances (123 – 455 ind. g<sup>-1</sup> wet sed.) in contrast to overall lower values in the core EMB046/20-3GC (43 – 527 ind. g<sup>-1</sup> wet sed., where the highest value represents an individual peak above 361 ind. g<sup>-1</sup> wet sed. significantly standing out from the rest of the record).' Unfortunately, we cannot give standard deviations (please see comment above concerning the uncertainty in foraminiferal records).

We have calculated standard deviations (SD) for entire records (total benthic forams g<sup>-1</sup>) for each core. For EMB046/20-3GC the SD is 79.92 and for EMB046/10-4GC the SD is 75.82.

Reviewer 1: Pg 9 Line 9: How does changes in mass accumulation affect the results? When looking at forams per gram, two things can change the magnitude: 1) number of forams and 2) grams of sediment. Can the authors rule out changes in mass accumulation rate with their age model?

Response: Unfortunately, we do not have sediment volume data to calculate mass accumulation.

Reviewer 1: Pg 9 Line 18: This statement seems quite broad. Several of the low abundance benthics do not seem to show any trends (perhaps because of the counting uncertainty?). Some of them show different trends. I think *B. skagerrakensis* can be highlight more here, because it is really the main record that shows any large and consistent changes.

Response: We modified this sentence according to the comment.



(previous version): 'In general for both cores, the relative and the absolute abundance of the benthic foraminifera follow similar trends, showing a distinct variability of species *B. skagerrakensis* (Fig. 3).

(modified version): 'Among benthic foraminiferal species *Brizalina skagerrakensis* shows the most prominent and consistent changes when comparing both records (Fig. 3).'

Reviewer 1: Pg 10 Line 6: This first sentence needs rephrasing. What is meant by 'quality'? Again avoid 'proven'. Is it the individual species or the 'factors' that have an association with organic matter? I don't think the wording makes it clear.

Response: We have modified this sentence accordingly to the comments. The individual species have an association with organic matter thus factors related to food preferences of species are included in each factor.

(previous version): 'All dominant species in our benthic foraminiferal assemblages, grouped into factors, have proven association with quality and availability of organic matter at the sea floor (...).'

(modified version): 'All dominant species in our benthic foraminiferal assemblages, grouped into factors, have documented association with quality (e.g. fresh or decaying) and availability of organic matter at the sea floor (...).'

Reviewer 1: Pg 10 Line 15: The following 3 sections should be rewritten taking into account the substantial comments above, taking more care over the uncertainties in each record, and appreciating more that e.g. temperature and oxygen isotopes don't necessarily match the benthic productivity records. Abstract and conclusion: Can be looked at again after more careful consideration of the data.

Response: The discussion section will be revised according to the comments. We believe that added now uncertainties to the data will help with clarifying the discussion of the results. Also we will take into account the other data presented in the manuscript (Mg/Ca, isotopes, now added  $\delta^{18}\text{O}_{\text{smow}}$ ) and discuss them properly.

Reviewer 1: Figure 2:  $n\text{ g}^{-1}$  I assume to mean number per gram. It could be misunderstood as 'per nanogram' so perhaps change to 'Number  $\text{g}^{-1}$ '.

Response: ' $n\text{ g}^{-1}$ ' has been changed to 'ind.  $\text{g}^{-1}$ ' in all figures and through the text.

Reviewer 1: Figure 4: For the uninitiated like me, 'Factor loading' doesn't mean very much as an axis title. Perhaps explain a bit more in the text.

Response: We have clarified this point by adding sentences to the results section (Pg 9, line 31), as follow:

'The weight (importance) of each factor found in the sample is expressed by each factor loading (Fig. 4). Factors with loadings above 0.5 are considered most significant.'

### Technical Corrections

Reviewer 1: There are a large number of instances where the language could be tightened up in the paper that would help make it easier to read. I would suggest having the paper thoroughly proof read again. Previous papers from some of the same authors read well. I have put a very few points below.

Response: The manuscript will be tweaked, the language tightened up and references double checked.

Reviewer 1: Pg 5 Line 29: Change 'since' to 'because'. I have had it pointed out to me before that 'since' can be a confusing word in a paper dealing with the past. Response: Changed

Reviewer 1: Pg 6 Line 12: Rephrase sentence to 'Fe/Ca and Mn/Ca ratios show no correlation with measured Mg/Ca values.' Response: Changed

Reviewer 1: Pg 6 Line 26: Hasenfratz miss-spelled. Response: Corrected

Reviewer 1: Pg 9 Line 8: Change 'sticking out' to something sounding more scientific.

Response: Changed to 'standing out'

Reviewer 1: Figure 3 caption: '5-point' not '5-points'. Response: Changed

**Interactive comment on “Coastal primary productivity changes over the last millennium: a case study from the Skagerrak (North Sea)” by Anna Binczewska et al.  
Anonymous Referee #2**

Response: We appreciate constructive comments and suggestions from anonymous referee 2. Responses to the review are below.

Reviewer 2: The paper presents two records of benthic foraminiferal assemblages and geochemical analyses from the northern deep Skagerrak region. The records are excellent, presenting high-resolution data for the last millennium. The strength of the paper is especially the fact that data from two neighboring cores are presented, as provides evidence of a general pattern. The paper is overall well-written and clearly presented and I believe that it fits well within the scope of the journal.

However, the ms has a tendency to focus too much on local conditions and comparison to relatively few previous studies. It would therefore benefit from including information from a broader range of study sites as well as from other types of records, including terrestrial and lacustrine records. Also more direct comparisons between records as well as an improved precision of the discussion of water masses is needed. Finally, not all data (e.g. Mg/Ca) are actually used to any significant extend in the discussions:

Response: The concerns about the discussion and interpretation of the data are addressed. We have added broader information and more details to the discussion about water masses and Mg/Ca (also see further information below).

Reviewer 2: A key element of the paper is the link between the record and the North Atlantic Oscillation (NAO). A number of studies have suggested a more positive phase of the NAO during the MCA and a negative phase during the LIA. However, the here the authors only refer to one study without taking into account that other, earlier, studies have also made this suggestion (e.g. from off Portugal, in the Labrador sea/West+East Greenland etc.).

Response: The sentence: “In contrast, the North Atlantic Oscillation (NAO) reconstruction by Trouet et al. (2009) suggests a tendency for prevailing positive NAO conditions during the MCA and hence, south-westerlies dominating the hydrographic and meteorological regimes during winter.” have been changed to:

“In contrast, the North Atlantic Oscillation (NAO) reconstructions by Trouet et al. (2009), Olsen et al. (2012), Faust et al. (2016), among others, all suggest a tendency for prevailing positive NAO conditions during the MCA and hence, south-westerlies dominating the hydrographic and meteorological regimes during winter.”

We have added more references concerning the NAO through the text, accordingly.

Reviewer 2: Also, since the present manuscript provides a high-resolution records, these data should in fact be plotted vs. the high-resolution NAO reconstructions (Trouet et al, as well as vs. other high-resolution records such as those by Olsen et al 2012 and Faust et al 2016).

Response: We would like to thank the reviewer for the advice on papers by Olsen et al. (2012); Faust et al. 2016) and Nejse et al. 2000. We have included information and data from these studies in the revised manuscript, presenting direct comparison between those records and ours. We have also included reference to other relevant studies Bakke et al. (2008).

We have plotted three suggested NAO reconstructions vs. our data. Please find enclosed Fig. 5.

Reviewer 2: It would be very interesting to see, if the overall quite well-known trend of positive NAO during the MCA and negative NAO during the LIA is also seen at shorter, decadal/multidecadal time scales. Whether such a correlation between productivity and NAO cannot be verified, it would be valuable information. Olsen, J., Anderson, N.J, Knudsen, M.F, 2012: Variability of the North Atlantic Oscillation over the past 5,200 years. *Nature Geoscience* 5, 808–812, doi:10.1038/ngeo1589 Faust, J.C., Fabian, K., Milzer, G., Giraudeau, J., Knies, J., 2016: Norwegian fjord sediments reveal NAO related winter temperature and precipitation changes of the past 2800 years. *Earth and Planetary Science Letters* 435, 84-93.

Response: While the long trend of positive NAO during the MCA and more negative NAO during the LIA correlated well with the productivity periods defined in this ms, the correlation at the shorter time scale is harder to address. This is due to the dating uncertainties of the different records e.g. the uncertainty of the <sup>14</sup>C dates in our records vary between 30 and 60 years, in records by Olsen et al (2012) from ±5 to ±35. Also, the relation

between NAO and productivity at the decadal/multidecadal time scale could be better justified by looking at the high resolution data from the short cores (MUCs) as well as instrumental records covering last ~120 years and comparing them to decadal trends in the NAO reported by e.g. Hurrell (1995). We intend to show the NAO-productivity correlation at the decadal time scale in the next manuscript which is currently being prepared by Binczewska et al.

Reviewer 2: The study region is influenced by several different water masses, including local outflow of low-salinity water from riverine outflow, saline Atlantic water and more intermediate salinity water as a mixture of North Sea and riverine waters (e.g. the Jutland Current). However, in the presentation of the water masses, it is not always clear at which levels in the water column these water masses are found, nor whether they also influence the actual study sites. This problem continues throughout the discussion and the one gets the impression that either there is increased Atlantic water or increased low-salinity water. However, stratification could allow both. Thus, the discussion needs to be much more precise.

Response: We have modified the 'study area' as follows:

'The Skagerrak basin is located in the northeastern part of the North Sea, connected to the Baltic Sea through the Kattegat (Fig. 1). The basin has a mean water depth of 210 m and a sill depth of 270 m. With a maximum depth of 700 m the Skagerrak represents the deepest part of the Norwegian Trench (Rodhe, 1996). The area is characterised by an anticlockwise circulation and complex hydrography. The surface circulation (<30 m) is to a large extent dominated by a surface current consisting of inflowing saline water from southern North Sea and the North Atlantic and outflowing less saline water from the Baltic Sea (Danielssen et al., 1997). The inflowing nutrient-rich surface water flows along the Danish coast driven by the Southern Jutland Current (SJC) and the Northern Jutland Current (NJC) while the outflowing Baltic Sea water (BW ~20 – 30 psu) flows as the Baltic Current (BC) along the Swedish west coast towards the northeast Skagerrak where it merges with the NJC and turns to the northwest as low saline Norwegian Coastal Current (NCC) (Rodhe, 1996; Rydberg et al., 1996). The water flowing from the Skagerrak towards the Norwegian Sea (NCC) partly recirculates to the western Skagerrak (Rodhe, 1996). The surface water has a high nutrient concentration mostly due to the freshwater input via rivers draining from the Norwegian south coast, German and Danish east coasts, and the Baltic catchment area but also the upwelling of the underlying nutrient-rich Atlantic water is considered to be an additional nutrient supply (Gustafsson and Stigebrandt, 1996; Rodhe, 1996). As a consequence of the mixing of different water types and the high freshwater input enhanced by precipitation, the upper layer of the surface water has low salinity (25 – 32 psu) and is determined as the Skagerrak Coastal Water (4.5 – 10 °C). The intermediate water layer (30 – 270 m) is referred to as Skagerrak Water (32 – 35 psu, 4.5 – 10 °C) and is driven by the subsurface circulation (Andersson, 1996). The deep water layer below sill depth (>270 m) is dominated by Atlantic Water and is recognised as the Skagerrak Basin Water (>35 psu, 5.5 – 6.5 °C) (Aure and Dahl, 1994).

The subsurface circulation (below 30 m water depth), consists of nutrient-rich Atlantic deep water (AW >35 psu, 5.5 – 8.5 °C) flowing through the northern North Sea, and the water from the central and southern North Sea (NSW ~31 – 35 psu) (Rodhe, 1996). The inflowing water follows the southern side of the Norwegian Trench to enter the Skagerrak in its central part, where this water can be mixed with fresh surface-water and flows out as the NCC (Winther and Johannessen, 2006).

Large-scale atmospheric systems and regional meteorological factors (e.g. precipitation and storms) influence the flow regime creating a high-dynamic system in the upper layer of the water column where water mixing is largely caused by the southwesterly winds (Gustafsson and Stigebrandt, 1996). At the same time, calmer hydrographic conditions are typical for the intermediate layer and the deep water down to ~ 400 m with a maximum water residence time of 3 months (Andersson, 1996). This is in contrast to the renewal of the deepest water mass below ~ 400 m, which is replenished every 1 to 3 years depending on the strength of the Atlantic water inflows (Aure and Dahl, 1994; Rodhe 1996), closely correlating with the NAO index (Brückner and Mackensen, 2006).

We hope that the water masses description presented above is more clear hence we have followed this description while improving the discussion section.

Reviewer 2: In this context, I do agree that the increased flux of planktic foraminifera indicated increased inflow of Atlantic water. However, how sure are the authors that the planktic foraminifera are in fact locally produced and not brought in from the Atlantic via the currents? The planktic foraminifera may not be autochthonous and even if they are, they would likely not represent direct surface waters. Thus, this inflow may not have occurred right at the surface, but rather as a subsurface current, thus still allowing an increased surface-outflow of lower-salinity waters.

Response 2: In the foraminiferal assemblage we found mostly large test sizes of *G. bulloides* and *N. pachyderma* and small tests of *G. glutinata* and *G. uvula*. This wide range of size (adults and juveniles) suggests that the

planktonic foraminifera found in the Skagerrak cores were living in nearby water masses (Murray; 1976). Because waters with suspended sediment are not favourable for the planktonic foraminifera (which is also seen from their relatively low absolute abundance), it is possible that planktonic foraminifera were floating below the surface water level. Moreover, the depth habitats in the water column of planktonic species found in our record was reported by e.g. Jonkers et al. (2010) and Schiebel et al. (2017). According to those studies *N. pachyderma* dwells at 50–100 m of the water column and has the maximum calcification at 100–200 m, while *G. bulloides* dominates waters above thermocline at < 60 m, *G. uvula* occurs in highest amount in the surface waters and *G. glutinata* prefers the upper 50 m of the water column.

Murray, J. W. 1976: A method of determining proximity of marginal seas to an ocean. *Marine Geology*, 22: 103-119.

Jonkers et al. 2010: Seasonal stratification, shell flux, and oxygen isotope dynamics of left-coiling *N. pachyderma* and *T. quinqueloba* in the western subpolar North Atlantic, *Paleoceanography*, 25, PA2204, doi:10.1002/palo.20018, 2

Schiebel et al. 2017: Modern planktic foraminifers in the high-latitude ocean, *Marine Micropaleontology* 136, 1–13

Reviewer 2: In the discussions on whether the changes in productivity are primarily linked to the influx of Atlantic water or if it could be linked to wind mixing during episodes of stronger winds and/or linked to changes in runoff from land linked to precipitation, it would be relevant to also compare with precipitation data. Here, e.g., studies of mass balance in Norwegian glaciers (e.g. Nesje et al 2000) as well as lake studies would be relevant. Nesje, A., Lie, Ø. And Dahl, S.O. 2000: Is the North Atlantic Oscillation reflected in Scandinavian glacier mass balance records? *Journal of Quaternary Science* 15, 587-601.

Response: We thank the reviewer for an advice on study by Nesje et al. (2000). We have plotted productivity data versus winter precipitation (Nesje et al; 2000), however the resolution of those data is too low over the last 1100 years to add significantly to the discussion. However, we have instead done a comparison to winter precipitation data from Bakke et al. 2008, where it looks like the precipitation has an overall decreasing trend throughout the last 1100 years.

We have expanded the discussion with precipitation information presented in Fig. 5, accordingly.

Reviewer 2: Another point to raise is the actual use of the data. The dataset includes benthic foraminiferal assemblage studies, including factor analyses, planktic foraminiferal concentrations (no details on species distribution, so I assume that this was not analysed?), Mg/Ca, Mn/Ca, and stable carbon and oxygen isotopes.

Response: We found the same planktonic species at both studied locations. We did identify planktonic foraminifera to species level in each analysed sample. However due to their overall low abundance we prefer to present assemblage as total number of planktonic individuals. In line with both reviewer 1 and 2 comments we have used more of the data more actively in the revised discussion.

Reviewer 2: However, the geochemical data is only used for calculating bottom-water temperatures, and these temperatures are more or less accepted without any further discussions. The reliability and uncertainty of the data needs to be taken into account. Thus, the discussions on the palaeoproductivity is almost solely based on the benthic foraminiferal assemblages. The benthic foraminifera are good indicators, but since so much more data exist and are presented, they should also be used properly in the discussions.

Response: The discussion section has been revised according to the comments. In line with suggestions from Reviewer 1 we have added the uncertainties to the data and information on uncertainties, and thereby we will consider to what degree we can be confident in how we interpret the data. In the revised version we have also used the other records presented (Mg/Ca, isotopes, now calculated and added  $\delta^{18}\text{O}_{\text{smow}}$ ) more actively in the discussion.

Reviewer 2: Finally, despite an introduction trying to build a link between this study and the understanding of the consequences of greenhouse gas emissions, it the actual significance of the study region is not clear: Why is Skagerrak relevant? Because it represents an intermediate area between the open ocean and coastal regions?

Response: We have made this point clear by adding information to the introduction and modifying the paragraph on Pg 3, line 16 – 29, as follows:

‘Coastal zones are among the most productive marine regions characterised by high: atmospheric CO<sub>2</sub> uptake, organic matter accumulation and decomposition (e.g. Hjalmarsson et al., 2010). The Skagerrak, located between the North Sea and the Baltic Sea and in the close proximity to land, has many potential nutrient sources, such as the North Atlantic, Baltic Sea, North Sea, as well as continental discharge and river runoff (Aure and Dahl, 1994; Andersson, 1996; Gustafsson and Stigebrandt, 1996). Upwelling and precipitation further increase the nutrient supply to the surface waters, additionally stimulating productivity in this region (Pingree et al., 1982; Aure and Dahl, 1994; Fonselius, 1996). The North Sea and the Skagerrak absorb large quantities of atmospheric CO<sub>2</sub> via the biological pump (1.38 mol C m<sup>-2</sup> yr<sup>-1</sup> and 1.2 mol C m<sup>-2</sup> yr<sup>-1</sup>, respectively), thus playing an important role in the carbon cycle (Thomas et al. 2005; Hjalmarsson et al., 2010). The Skagerrak acts as a main depositional basin for about half of the refractory carbon produced in the North Sea and for a high amount of labile organic matter either imported with waters of the near-bottom current from the Danish coast or caused by intense algal blooms (Boon et al., 1999). Input of nutrients largely regulate food webs, which makes nutrients of great economic importance for the coastal areas worldwide (Micheli, 1999; FAO, 2016) and in the Skagerrak nutrients are particularly important for the Nordic fisheries (Hop et al., 1992; Iversen et al., 2002; Olsen et al., 2004; Skogen et al., 2007). Fisheries and aquaculture sectors of the Skagerrak, commercially valuable for the Scandinavian nations, also make a relevant contribution to a growing global demand for food, which will largely rely on coastal regions to host a major part of food production in the future (e.g. FAO, 2013). Effects of increased primary production range from positive impacts on growth rate, size and reproduction of fish and shellfish populations to disruptive alterations in the food webs, thus yielding or reducing the profit rates of fisheries (Hop et al., 1992; Micheli, 1999; Iversen et al., 2002; Olsen et al., 2004, 2005; Breitburg et al., 2009; FAO, 2016). Negative changes in trophic levels of the Skagerrak ecosystem have been attributed to overfishing (Cardinale and Svedäng, 2004), however, ongoing studies alert about adverse impact of increased nutrient inputs driving heavy phytoplankton blooms and eutrophication in the region (e.g. Baden et al., 1990; Aure et al., 1996; Breitburg et al., 2009). Eutrophication causes high demand and depletion of oxygen in the bottom waters, which affect species diversity, morphology and population growth, and forces organisms to migrate (Rosenberg et al., 1990; Conley, 2009). Thus, to better understand the ongoing and possible future productivity changes and associated environmental effects, more historical studies are needed.’

Reviewer 2: Also the actual relevance of the outcome of the study to the problems raised in the introduction is not clear and should be made clear in the conclusions. It is an interesting and relevant study, but please make it clear to the reader, too.

Response: After revising discussion part we have modified the conclusions which now addresses the research questions raised in the introduction.

Minor comments:

Reviewer 2: Latin grammar rules means that the name of the species should be ”*Melonis barleeanus*”, not “*Melonis barleeenum*”.

Response: We have changed everywhere to *Melonis barleeanus*.

Reviewer 2: Are you sure that *Cassidulina neoteretis* is present in the material? If yes, this could indicate an high influx of deep Atlantic or even Nordic Sea water. "

Response: We sincerely thank the reviewer for underlining this feature. The identification of *C. laevigata* vs *C. neoteretis* in the Skagerrak material was done based on studies by Mackensen and Hald (1988) and Seidenkrantz (1995). *C. neoteretis* was also found there by other studies e.g. Erbs-Hansen et al (2011). Since relative abundance of *C. neoteretis* exceeds 5% only in two samples in each of the cores we considered it as a rather rare species. However, we have now had a closer look at the changes in the *C. neoteretis* records. We observed a peak of high relative abundance of *C. neoteretis* between ~ 1750 – 1800 years which correlates well with a drop in BWT and δ<sup>18</sup>O at the same time, indicating colder bottom water temperature. Therefore, it is possible that this is an indication of a higher influx of deep Atlantic Water or even Nordic Sea waters (Mackensen and Hald 1988, Seidenkrantz 1995). We will add this information in the revised manuscript.

Reviewer 2: Page 4, lüne 25-30: It is not quite clear from the description of the water masses, which ones are surface waters, intermediate waters and bottom waters. One for one water mass is the depth in the water column provided. As the depth of outflowing/inflowing waters is very important, this must be made clear. It also needs to be specified very clearly, which water mass sweep the actual study sites in the deep Norwegian Trench.

Response: See the comment above regarding water mass clarification.

Reviewer 2: Page 5, line 12-15: It should be pointed out specifically that both cores are taken from the deep Norwegian Trench.

Response: We have added a sentence to the material and method section as follows:  
“Both cores are taken below sill depth within the deep waters of the Norwegian Trench.”

Reviewer 2: Material: please provide a short, overall description of the sediment in the two cores.  
We have added a following sentence:

“Both cores consist of mostly soft organic-rich clay and show no significant changes in grain size and lithology throughout the records.”

Reviewer 2: Factor loadings are provided and used in the discussions and presented well in the final figure of proxy comparison. However, in order to evaluate the results of factor analyses, the authors should consider actually plotting them vs age in a diagram comparing them to the faunal data.

Response: We have modified the figure with foraminiferal fauna according to the comment.

# Coastal primary productivity changes over the last millennium: a case study from the Skagerrak (North Sea).

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**Abstract.** A comprehensive multi-proxy study on two sediment cores from western and central Skagerrak was performed in order to detect the variability and causes of marine primary productivity changes in the investigated region over the last 1100 years. The cores were dated by Hg pollution records and AMS  $^{14}\text{C}$  dating and analysed for palaeoproductivity proxies such as total organic carbon,  $\delta^{13}\text{C}$ , total planktonic foraminifera, benthic foraminifera (total assemblages as well as abundance of *Brizalina skagerrakensis* and other palaeoproductivity taxa) and palaeothermometers such as Mg/Ca and  $\delta^{18}\text{O}$ . Our results reveal two periods with changes in productivity in the Skagerrak region: i) a moderate productivity at ~ CE 900 – 1700 and ii) a high productivity at ~ CE 1700 – present. During ~ CE 900 – 1700, moderate productivity was likely driven by the nutrients transported with the warm Atlantic water inflow associated with a tendency for a persistent positive NAO phase during the warm climate of the Medieval Climate Anomaly, which continues in to the LIA until ~ CE 1450. The following more lower and variable temperature period at ~ CE 1450 – 1700 was likely caused by a lower contribution of warm Atlantic water but stronger deep-water renewal due to a generally more negative NAO phase and a shift to the more variable and generally cooler climate conditions of the Little Ice Age. The productivity and the fluxes of organic matter to the seafloor seem to not correspond to the temperature and salinity changes recorded in the benthic *Melonis barleeanus* shells. Since ~ CE 1700 towards present day our data point to an increased nutrient content in the Skagerrak waters. This increased nutrient content was likely caused by enhanced inflow of warm Atlantic water, increased Baltic outflow, intensified river runoff and enhanced human impact through agriculture expansion and industrial development. Intensified human impact likely increased nutrient transport to the Skagerrak and caused changes in the oceanic carbon isotope budget, known as the Suess effect, which is clearly visible in our records as a negative shift in  $\delta^{13}\text{C}$  values from ~ CE 1800. In addition, a high appearance of *S. fusiformis* during the last 70 years at both studied locations suggests increased decaying organic matter at the sea floor after episodes of enhanced primary production.

## 1 Introduction

Growth of marine microalgae is stimulated by enhanced concentrations of major nutrients like nitrogen and phosphorus in the photic zone (e.g. Sigman and Hain, 2012). Microalgae in the oceans are primary producers, which provide food for consumers at higher trophic levels and oxygen for respiration (e.g. Micheli, 1999). Through photosynthesis and the biological pump, marine primary producers also extract  $\text{CO}_2$  from the atmosphere. Carbon, nutrients and trace elements, which are fixed by primary producers are further ingested by higher organisms or sink to the ocean floor where they are stored in the form of organic matter. The organic matter will eventually be remineralised, releasing the carbon, nutrients and trace elements to the bottom water (e.g. Sigman and Hain, 2012). Supply of carbon to the oceanic ecosystems is an important part of the biogeochemical cycles, which presently are being disturbed by the human impact. Via photosynthesis, primary producers can help to remove  $\text{CO}_2$  from the atmosphere through the biological pump. However, increasing levels of dissolved  $\text{CO}_2$  in the oceans associated with so-called “ocean acidification” may negatively impact ocean’s carbonate producers (e.g. Doney et al., 2009; Haynert et al., 2012) by influencing their survival and fitness (e.g. Thomsen et al., 2017). Excessive export of organic



matter furthermore changes the oxygen condition at the sea floor due to decay of organic matter, which lowers the dissolved oxygen content, in turn, negatively influencing life regime (e.g. Kristiansen and Aas, 2015 and references therein).

Coastal zones are among the most productive marine regions characterised by high: atmospheric CO<sub>2</sub> uptake, organic matter accumulation and decomposition (e.g. Hjalmarrsson et al., 2010). The Skagerrak, located between the North Sea and the Baltic Sea and in the close proximity to land, has many potential nutrient sources, such as the North Atlantic, Baltic Sea, North Sea, as well as continental discharge and river runoff (Aure and Dahl, 1994; Andersson, 1996; Gustafsson and Stigebrandt, 1996). Upwelling and precipitation further increase the nutrient supply to the surface waters, additionally stimulating productivity in this region (Pingree et al., 1982; Aure and Dahl, 1994; Fonselius, 1996). The North Sea and the Skagerrak absorb large quantities of atmospheric CO<sub>2</sub> via the biological pump (1.38 mol C m<sup>-2</sup> yr<sup>-1</sup> and 1.2 mol C m<sup>-2</sup> yr<sup>-1</sup>, respectively) and thus play an important role in the carbon cycle (Thomas et al., 2005; Hjalmarrsson et al., 2010). The Skagerrak acts as a main depositional basin for about half of the refractory carbon produced in the North Sea and for a high amount of labile organic matter either imported with waters of the near-bottom current from the Danish coast or produced by intense algal blooms (Boon et al., 1999). Input of nutrients largely regulate food webs, which makes nutrients of great economic importance for the coastal areas worldwide (Micheli, 1999; FAO, 2016) and in the Skagerrak nutrients are particularly important for the Nordic fisheries (Hop et al., 1992; Iversen et al., 2002; Olsen et al., 2004; Skogen et al., 2007). Fisheries and aquaculture sectors of the Skagerrak, commercially valuable for the Scandinavian nations, also make a relevant contribution to a growing global demand for food, which will largely rely on coastal regions to host a major part of food production in the future (e.g. FAO, 2013). Effects of increased primary production range from positive impacts on growth rate, size and reproduction of fish and shellfish populations to disruptive alterations in the food webs, thus yielding or reducing the profit rates of fisheries (Hop et al., 1992; Micheli, 1999; Iversen et al., 2002; Olsen et al., 2004, 2005; Breitburg et al., 2009; FAO, 2016). Disruptive changes in trophic levels of the Skagerrak ecosystem have been attributed to overfishing (Cardinale and Svedäng, 2004) but ongoing studies alert about adverse impact of increased nutrient inputs driving heavy phytoplankton blooms and eutrophication in the region (e.g. Baden et al., 1990; Aure et al., 1996; Breitburg et al., 2009). Eutrophication causes high demand and depletion of oxygen in the bottom waters, which affect species diversity, morphology and population growth, and forces organisms to migrate (Rosenberg et al., 1990; Conley, 2009). Thus, to better understand the ongoing and possible future productivity changes and associated environmental effects, more historical studies are needed.

Although the Skagerrak is a well-investigated area, retrospective studies from this region have focused on climate change instead of productivity, and hence, past primary productivity changes are not well known (Polovodova Asteman et al., 2018). Previous studies suggested that among the processes driving primary productivity changes in the Skagerrak are 1) the North Atlantic Oscillation (NAO), 2) an input of anthropogenic nutrients from the Skagerrak catchment area and 3) nutrients transported from the Baltic Sea. Thus, while the NAO influences the inflow of the nutrient-rich Atlantic water mass into the Skagerrak (Gil et al., 2005; Brückner and Mackensen 2008), anthropogenic activities in the Skagerrak catchment area such as e.g. land-use changes also cause an increased nutrient input and high organic matter flux to the basin (e.g. Filipsson and Nordberg, 2010). In addition, eutrophication of the Baltic Sea and resulting transport of nutrient-rich water with the Baltic

Current through surface water exchange processes represents potentially an additional nutrient source (Andersson, 1996; Hjalmarsson et al., 2010; Filipsson et al., 2017; Krossa et al., 2015; Polovodova Asteman et al., 2018). In its turn, a nutrient-overloaded ecosystem in the Skagerrak may further supply dissolved inorganic nitrogen (DIN) to the Kattegat bottom waters (Carstensen et al., 2006) and increase the nutrient level in the coastal waters of Norway (Rosenberg et al., 1987; Rydberg et al., 2006) (Fig. 1). The last two processes involve human induced influences on the ecosystem, while the NAO relates to effects following variability in the climate system. Over the last 1100 years the interaction between these processes has changed, as human influence have increased. In perspective of the last 4500 years, it is seen that productivity and its variability has increased from 50 years Before the Common Era (BCE) towards present day (Polovodova Asteman et al., 2018). The increased productivity occurred as a response to enhanced local runoff coinciding with high winter rainfall and general cooling in Scandinavia, as well as intensified Baltic outflow, which may have significantly contributed to the nutrient supply in the Skagerrak in the past (Polovodova Asteman et al., 2018).

Our study aims to detect the variability and causes of marine primary productivity changes in the Skagerrak over the last 1100 years. We address this aim through a comprehensive multi-proxy study of two sediment cores from the central and the western Skagerrak, integrating records of the total organic carbon (TOC), foraminiferal assemblage data, stable carbon and oxygen isotopes ( $\delta^{13}\text{C}$ ,  $\delta^{18}\text{O}$ ) and trace element ratio (Mg/Ca). In addition we evaluate our results in context of the long-term productivity changes described previously in Polovodova Asteman et al. (2018).

## 2 Study area

The Skagerrak basin is located in the northeastern part of the North Sea, connected to the Baltic Sea through the Kattegat (Fig. 1). The basin has a mean water depth of 210 m and a sill depth of 270 m. With a maximum depth of 700 m the Skagerrak represents the deepest part of the Norwegian Trench (Rodhe, 1996). The area is characterised by an anticlockwise circulation and complex hydrography. The surface circulation (<30 m) is to a large extend dominated by a surface current consisting of inflowing saline water from southern North Sea and the North Atlantic and outflowing less saline water from the Baltic Sea (Danielssen et al., 1997). The inflowing nutrient-rich surface water flows along the Danish coast driven by the Southern Jutland Current (SJC) and the Northern Jutland Current (NJC) while the outflowing Baltic Sea water (BW ~20 – 30 psu) flows as the Baltic Current (BC) along the Swedish west coast towards the northeast Skagerrak where it merges with the NJC and turns to the northwest as low saline Norwegian Coastal Current (NCC) (Rodhe, 1996; Rydberg et al., 1996). The water flowing from the Skagerrak towards the Norwegian Sea (NCC) partly recirculates to the western Skagerrak (Rodhe, 1996). The surface water has a high nutrient concentration mostly due to the freshwater input via rivers draining from the Norwegian south coast, German and Danish east coasts, and the Baltic catchment area but also the upwelling of the underlying nutrient-rich Atlantic water is considered to be an additional nutrient supply (Gustafsson and Stigebrandt, 1996; Rodhe, 1996). As a consequence of the mixing of different water types and the high freshwater input enhanced by precipitation, the upper layer of the surface water has low salinity (25 – 32 psu) and is determined as the Skagerrak Coastal Water (4.5 – 10 °C). The intermediate water layer (30 – 270 m) is referred to as Skagerrak Water (32 – 35 psu, 4.5 – 10 °C) and is driven by the subsurface circulation

(Andersson, 1996). The deep water layer below sill depth (>270 m) is dominated by Atlantic Water and is recognised as the Skagerrak Basin Water (>35 psu, 5.5 – 6.5 °C) (Aure and Dahl, 1994).

The subsurface circulation (below 30 m water depth), consists of nutrient-rich Atlantic deep water (AW >35 psu, 5.5 – 8.5 °C) flowing through the northern North Sea, and the water from the central and southern North Sea (NSW ~31 – 35 psu) (Rodhe, 1996). The inflowing water follows the southern side of the Norwegian Trench to enter the Skagerrak in its central part, where this water can be mixed with fresh surface-water and flows out as the NCC (Winther and Johannessen, 2006).

Large-scale atmospheric systems and regional meteorological factors (e.g. precipitation and storms) influence the flow regime creating a high-dynamic system in the upper layer of the water column where water mixing is largely caused by the southwesterly winds (Gustafsson and Stigebrandt, 1996). At the same time, calmer hydrographic conditions are typical for the intermediate layer and the deep water down to ~ 400 m with a maximum water residence time of 3 months (Andersson, 1996). This is in contrast to the renewal of the deepest water mass below ~ 400 m, which is replenished every 1 to 3 years depending on the strength of the Atlantic water inflows (Aure and Dahl, 1994; Rodhe 1996), closely correlating with the NAO index (Brückner and Mackensen, 2006).

### 3 Material and methods

Two gravity cores (GC) were retrieved from the Skagerrak during a R/V Elisabeth Mann-Borgese cruise in May 2013. Core EMB046/20-3GC (4.8 m long) was taken from the central Skagerrak (SE Norwegian Trench; 58°31.75'N, 09°29.13'E; 533 m water depth), while core EMB046/10-4GC (4.62 m) comes from the western Skagerrak (SW Norwegian Trench; 57°49.73'N, 07°17.62'E; 457 m water depth) (Fig. 1). Both cores were taken below sill depth within the deep waters of the Norwegian Trench. The cores were cut in 1-m sections on board before being split and subsampled every 1 cm ashore. This study based on results from the upper 170.5 and 164.5 cm sections, in cores EMB046/20-3GC and EMB046/10-4GC respectively, what corresponds to the last 1100 years. A part of the foraminiferal dataset and the TOC data were previously published in Polovodova Asteman et al. (2018). Here we present new stable isotope ( $\delta^{13}\text{C}$ ,  $\delta^{18}\text{O}$ ), and trace element ratio (Mg/Ca) data covering the last 1100 years, in combination with foraminiferal assemblage data and multivariate statistics. Both cores consist of mostly soft organic-rich clay and show no significant changes in grain size and lithology throughout the records. The TOC content was determined using 'Rapid CS cube –Elementar' analyser (Department of Geology and Paleogeography, University of Szczecin, Poland) with a measurement accuracy of 0.01% (95% confidence level (CL) at 99.5% detection limit (DL)). For detailed methodology of geochemistry measurements (TOC) see Polovodova Asteman et al. (2018).

For the stable carbon and oxygen isotopes ( $\delta^{13}\text{C}$ ,  $\delta^{18}\text{O}$ ) and trace elements analyses, well-preserved tests of benthic foraminifera *Melonis barleeanus* were picked from the dried sediment (fraction >150  $\mu\text{m}$ ). *Melonis barleeanus* was selected for the analyses due to its relatively high abundance in the whole study record at both sites and its well-known potential for geochemical palaeoreconstructions (Mackensen et al., 2000; Kristjánssdóttir et al., 2007; Brückner and Mackensen, 2008; Butruille et al., 2017). Stable isotopes measurements were performed at 1 cm intervals and the trace elements analyses were

done at 1 – 2 cm intervals from both gravity cores down to 170 cm (EMB046/20-3GC) and 164.5 cm (EMB046/10-4GC). No stable isotope or trace element analyses were done between 4.5 cm and 7.5 cm in EMB046/10-4GC, due to lack of material, because most of foraminifera from that interval were used for <sup>14</sup>C AMS dates.

Stable isotope analyses were run on a Finnigan MAT 253 mass spectrometer equipped with an automatic Kiel device at the FARLAB of the University of Bergen. Prior to measurement the tests of *M. barleeanus* were lightly crushed, cleaned with methanol ( $\geq 98.8\%$ ) using an ultrasonic bath and dried at 60 °C. For each measurement 2 – 4 specimens were used. All results are reported in ‰ versus Vienna Pee Dee Belemnite standard (V-PDB), using the National Bureau of Standards (NBS) 19 and 18, in combination with the internal lab standard CM12. The long-term analytical uncertainty is  $\pm 0.08\%$  and  $\pm 0.03\%$  (95% CL) for oxygen and carbon isotopes, respectively.

Shells of *M. barleeanus* were also cleaned and analysed for trace elements at the Trace Element Lab (TELab) at Uni Research Climate, Bergen (Norway). For each analysis, approximately 15-20 specimens were gently crushed between two glass plates under a microscope to allow the contaminants to be removed. The samples were cleaned following the procedure described by Barker et al. (2003). The cleaning method includes clay removal steps, oxidation of the organic matter and surface leaching. Samples containing enough material were mixed and split into two subsamples to allow duplicate analysis. All samples were dissolved in trace metal pure 0.1M HNO<sub>3</sub> (prepared from HNO<sub>3</sub> TraceSELECT®) and diluted to a final concentration of 40 ppm of calcium (Ca).

The trace elements were measured on an Agilent 720 inductively coupled plasma optical emission spectrometer (ICP-OES). Six standards have been prepared at TELab and have a composition similar to foraminiferal carbonate (0.50 – 7.66 mmol mol<sup>-1</sup>). Further, Fe/Ca and Al/Ca values have been checked and showed no significant correlation with the measured Mg/Ca values. The correlation coefficients (R<sup>2</sup>) between Mg/Ca and, Fe/Ca and Al/Ca ratios are respectively, for the core EMB046/20-3GC, 0.012 and 0.095, and for the core EMB046/10-4GC, 0.020 and 0.067, indicating no systematic contamination due to insufficient cleaning. The Mn/Ca values in our samples are higher than the recommended maximum (<105 μmol mol<sup>-1</sup>) (Boyle, 1983), indicating that diagenetic coatings might also affect our results. The Mn/Ca values, however, show no significant correlation with the measured Mg/Ca values (R<sup>2</sup> = 0 for EMB046/20-3GC and R<sup>2</sup> = 0.021 for EMB046/10-4GC). Standard solution with Mg/Ca of 5.076 mmol mol<sup>-1</sup> is analysed after every eight samples to correct for instrumental biases and analytical drift of the instrument. The long-term Mg/Ca analytical precision, based on the standard solution, is  $\pm 0.016$  mmol mol<sup>-1</sup> (1σ Standard Deviation) or 3.11% (relative SD). Average reproducibility of duplicate measurements (pooled SD, dof = 41) is equivalent to an overall average precision of 4.09%. The average Mg/Ca of long-term international limestone standard (ECRM752-1) measurements was 3.76 mmol mol<sup>-1</sup> (1σ = 0.07 mmol mol<sup>-1</sup>) with the average published value of 3.75 mmol mol<sup>-1</sup> (Greaves et al., 2008). The published *Melonis* spp. Mg/Ca - Bottom Water Temperature (BWT) is calculated from the measured Mg/Ca using the new *Melonis* spp. calibration (Mg/Ca = 0.113(±0.005)\*BWT + 0.792(±0.036)), based on core top data covering a Mg/Ca range of 0.68 – 3.66 mmol mol<sup>-1</sup> for a temperature range of -0.89 – 15.58°C (Hasenfratz et al., 2017). According to the calibration uncertainty, an 1σ temperature error (95% CL) of  $\pm 0.9^\circ\text{C}$  to  $\pm 1.7^\circ\text{C}$  has to be taken into consideration for the temperature range (4.1 – 9°C) covered by EMB046/20-3GC. For EMB046/10-4GC the

1σ temperature error (95% CL) is similar and ranges between ±1°C to ±1.6°C for the temperatures 5°C – 8.5°C. Further discussion on Mg/Ca-derived BWT within this article will use the Hasenfratz's calibration (Hasenfratz et al., 2017).

The results from Mg/Ca-derived BWT and δ<sup>18</sup>O were used to calculate the water isotopic composition (δ<sub>w</sub>) using the following equation:  $\delta_w = ((\delta^{18}O_{top} - \delta^{18}O_{down}) - (T_{top} - T_{down}) * 0.23) + 0.3$ . The δ<sup>18</sup>O<sub>top</sub> is the δ<sup>18</sup>O value measured on the foraminiferal shells from the upper most sample (0-1 cm core depth) and the T<sub>top</sub> is the temperature taken from CTD measured at time of coring. The δ<sup>18</sup>O<sub>top</sub> equals 2.04 and 2.06 (‰) while T<sub>top</sub> was 5.72 and 5.34°C, respectively for the EMB046/10-4GC and EMB046/20-3GC. The δ<sup>18</sup>O<sub>down</sub> and T<sub>down</sub> is the down core δ<sup>18</sup>O and temperature as measured on the foraminifera samples. Temperature estimates based on δ<sup>18</sup>O follows Shackleton (1974), where 0.23‰ equals 1°C in the temperature interval estimated for these sites. A constant of 0.3‰ is used to correct for the difference between VPDB and δ<sub>w</sub>. No correction for an ice volume effect was applied as this is considered negligible over the last 1000 years.

The foraminiferal analysis was carried out on 5 – 10 g wet sediment, gently sieved over a 63-µm sieve and wet-counted for foraminifera immediately afterwards. The two Skagerrak records over the targeted time interval covering the last 1100 years were counted at 1 – 3 cm resolution with an exception of 7 cm interval between 89 cm and 96 cm (~ CE 1030 – 1055) for EMB046/20-3GC, and at 1 – 2 cm resolution for the entire 1100 years of the EMB046/10-4GC record. In the >63 µm fraction, at least 300 benthic and 300 planktonic (where possible) specimens were counted under a stereomicroscope and identified to a species level. Both relative (%) and absolute (individual per gram in wet sediments, as ind. g<sup>-1</sup>wet sed.) abundances were calculated. The benthic foraminiferal species were categorised depending on their relative abundance in the assemblage to dominant (>10%), accessory (5% – 10%) or rare (<5%). Only dominant and accessory species are discussed in this study (Fig. 3, Table 2). Benthic species with relative abundance of >5% in at least two samples were subject to multivariate statistics using simple CABFAC factor analysis with varimax rotation (Table 2), performed by the PAST software (Hammer et al., 2001). This statistical tool provides a reliable method to distinguish the statistically significant foraminiferal units dominated by different species (e.g. Polovodova Asteman et al., 2013). In addition, benthic foraminiferal species indicative of increased organic matter fluxes to the sea floor and, hence, algal blooms, were grouped as ‘*palaeoproductivity fauna*’ and included: *Alabaminella weddellensis*, *Brizalina skagerrakensis*, *Bulimina marginata*, *Epistominella* spp., *Nonionella iridea* and *Uvigerina* spp. (Polovodova Asteman et al., 2018 and references therein). The planktonic foraminifera are presented as total planktonic individuals.

#### 4 Chronology

A common age model has previously been established for the two cores (Polovodova Asteman et al., 2018). The two age models were set at a common depth scale based on 30 available AMS <sup>14</sup>C dates, as well as a correlation between total inorganic carbon, relative abundance of *B. skagerrakensis* and mercury (Hg) records from both cores. All dates were calibrated using Calib 7.10 (Stuiver et al., 2017), Marine13 (Reimer et al., 2013) and ΔR=0±50. The age model of Polovodova Asteman et al., (2018) is reasonable when investigating the longer-term trends over the last 4.5 ka. However, when focusing on the last 1100

years we found that there was a need for an improvement of the age model over this time period. This was achieved by increasing the number of dates and by a fine-tuning of the reservoir age. The new age model of EMB046/20-3GC, reaching back to CE 295, is based on 8  $^{14}\text{C}$  AMS dates in addition to the initial Hg increase at CE 1900 (Moros et al., 2017). The core top was set to 2013, the year of coring. A modern core top age is confirmed by a post bomb age at 5.5 cm, as well as a recording of the Cs-137 signal associated with the nuclear weapons testing period (not shown). Considering all of the information from the upper part of the core in detail makes it clear that the use of a  $\Delta R=200\pm 50$  provides a better transfer, avoiding an unlikely jump in sedimentation rate, between the modern ages and the  $^{14}\text{C}$  ages than when using a reservoir age of  $\Delta R=0\pm 50$ . Hence, when establishing the new age model, the  $^{14}\text{C}$  AMS dates were calibrated using Calib 7.10 (Stuiver et al., 2017), Marine13 (Reimer et al., 2013) and  $\Delta R=200\pm 50$ , and linear interpolation between the established tie points (Table 1; Fig. 2). The new ages calculated for EMB046/10-4GC are based on the new age model of EMB046/20-3GC and the previously established common depth scale for EMB046/10-4GC and EMB046/20-3GC (Polovodova Asteman et al., 2018) (Fig. 2). Due to the established relationship between the depth scales of the two cores (Polovodova Asteman et al., 2018), the age model for EMB046/20-3GC can be and are used to create the new age model for EMB046/10-4GC.

## 5 Results

### 5.1 Organic geochemistry of bulk sediment

Both records show low TOC values until  $\sim$  CE 1700, around 1.7 – 2.1% and 1.5 – 1.8% in EMB046/20-3GC and EMB046/10-4GC, respectively (Fig. 5). From  $\sim$  CE 1700, the TOC content strongly increases towards the core tops, where ranges 1.85 – 2.5% (EMB046/20-3GC) and 1.75 – 2.3 (EMB046/10-4GC) are recorded. When comparing the two cores, the TOC values are higher for the EMB046/20-3GC record than for EMB046/10-3GC (Fig. 5).

### 5.2 Carbon isotopes

Both  $\delta^{13}\text{C}$  records show similar long-term variations through the study interval. Between CE 1500 and 1700 there is, however, a distinct increase of  $\delta^{13}\text{C}$  values for EMB046/20-3GC and a decrease for EMB046/10-4GC. Mean  $\delta^{13}\text{C}$  values of the time interval between  $\sim$  CE 900 and 1700 are generally higher (-0.53‰ on average in EMB046/10-4GC and -0.44‰ on average in EMB046/20-3GC), than during  $\sim$  CE 1700 – 2000 when mean  $\delta^{13}\text{C}$  values of -0.73‰ (EMB046/10-4GC) and -0.58‰ (EMB046/20-3GC) are observed (Fig. 5). From  $\sim$  CE 1700 towards the present, both records show a strong decreasing  $\delta^{13}\text{C}$  trend from ca. -0.2‰ to -1.6‰, where generally lower absolute  $\delta^{13}\text{C}$  values are recorded in EMB046/10-4GC than in EMB046/20-3GC (Fig. 5).

### 5.3 Oxygen isotopes

Both Skagerrak records display similar  $\delta^{18}\text{O}$  values, ranging from around 1.7 to 2.7‰ (Fig. 4). In general, the  $\delta^{18}\text{O}$  in EMB046/20-3GC shows lower values at ~ CE 1050 – 1350, somewhat higher or variable values between ~ CE 1400 and 1550 followed by decrease until ~ CE 1700. The general trend of relatively lower  $\delta^{18}\text{O}$  values in EMB046/10-4GC between ~ CE 900 and 1550 characterised by lowest recorded  $\delta^{18}\text{O}$  at ~ CE 1350 – 1550 is interrupted by increase at ~ CE 1200 – 1350. Consequently, the  $\delta^{18}\text{O}$  long-term trend is not common for the both records, however there is one distinct period for both records of relatively high  $\delta^{18}\text{O}$  values between ~ CE 1700 and 1800 after which the  $\delta^{18}\text{O}$  gradually decrease until ~ CE 1850, and followed by the steady increased  $\delta^{18}\text{O}$  in EMB046/20-3GC and more variable but overall lower  $\delta^{18}\text{O}$  values in EMB046/10-4GC towards the core top (Figs. 4, 5).

#### 5.4 Mg/Ca analyses and BWT

The Mg/Ca values vary from 1.33 to 1.87 mmol mol<sup>-1</sup> in EMB046/20-3GC record and from 1.37 to 1.97 in EMB046/10-4GC, in general giving the estimated BTW range between 4.7 and 8.1 °C, which is within the range of instrumentally recorded temperatures (ICES, 2010; Fig. 4B). This comparison and further interpretation refer to the smoothed data, while the raw data are mostly within the range of the instrumental data, but not completely. Through the records, there is a general correlation between the BTW changes and variability of  $\delta^{18}\text{O}$  values, showing similar patterns with periods of higher BWT corresponding to those with decreased  $\delta^{18}\text{O}$  values and vice versa, except between ~ CE 1000 and 1150 in EMB046/20-3GC where both proxies show relatively high values (Fig. 4). Hence, there is a consistency between the proxies within each core but not between the cores (Figs. 4, 5). Overall, BWT in EMB046/10-4GC is characterised by relatively little variability between ~ CE 900 and 1550 followed by higher variability in the records. In contrast, BWT in EMB046/20-3GC shows first decreasing trend until ~ CE 1500, somewhat higher but variable values between ~ CE 1550 and ~ CE 1700, drop in values at ~ CE 1700 – 1800 and again warmer BWT are shown for the youngest part of the record (~ CE 1800 – 2000) (Figs. 4, 5).

#### 5.5 Water isotopic composition

The changes in  $\delta_w$  records follow the pattern in the BWTs curves in both records. The decrease in  $\delta_w$  values correspond to periods of low temperature and vice versa. Lower correlation between  $\delta_w$  and BWT was observed in the early part of the EMB046/20-3GC record (~ CE 1000 – 1150) (Figs. 4, 5).

#### 5.6 Foraminiferal assemblages

Eight planktonic foraminiferal species are identified in both records. *Globigerinita uvula* and *G. glutinata* are the most abundant species, while *Globorotalia inflata*, *Globigerina bulloides*, *Neogloboquadrina pachyderma*, *Neogloboquadrina incompta*, *Turborotalia quinqueloba* and *Orbulina universa* are less abundant. However, in this study all planktonic species are presented together as total individuals per gram of wet sediments (Fig. 3) due to their overall low absolute abundance, varying between 0 and 49 ind. g<sup>-1</sup> wet sediment (EMB046/20-3GC) and 1.6 – 110 ind. g<sup>-1</sup> wet sediment (EMB046/10-4GC).

The planktonic foraminifera are most abundant in the interval between ~ CE 900 and 1700 in EMB046/10-4GC and at ~ CE 900 – 1550 in EMB046/20-3GC, after which they decrease towards the top of the cores and almost disappear after ~ CE 1850 in both records (Figs. 3, 5).

5 The benthic foraminiferal record from the core EMB046/10-4GC is characterised by consistently high absolute abundances (123 – 455 ind. g<sup>-1</sup> wet sed.) in contrast to overall lower values in the core EMB046/20-3GC (43 – 527 ind. g<sup>-1</sup> wet sed., where the highest value represents an individual peak above 361 ind. g<sup>-1</sup> wet sed. significantly standing out from the rest of the record). In EMB046/20-3GC, the absolute abundance of benthic foraminifera is high until ~ CE 1400. At CE 1400, the values drop below 150 ind. g<sup>-1</sup> wet sediment for the next ~ 300 years. After ~ CE 1700 the absolute abundances gradually increase to reach the highest recorded values between CE 1800 and 1900. A similar absolute abundance trend is shown for agglutinated foraminifera, however, those appear in higher numbers in core EMB046/10-4GC than in EMB046/20-3GC (Fig. 3).

15 The benthic foraminiferal assemblages consist of up to 61 and 57 species in the cores EMB046/20-3GC and EMB046/10-4GC, respectively. Among those, eight species are dominant (>10%) and nine are accessory (5-10%) in the core EMB046/20-3GC while the EMB046/10-4GC record has six dominant and five accessory taxa (Table 2). The common dominant species for both cores include *Brizalina skagerrakensis*, *Cassidulina laevigata*, *Eggereloides medius*, *Nonionella iridea*, *Pullenia osloensis* and *Stainforthia fusiformis* (for a full list of dominant and accessory species see Table 2). Among benthic foraminiferal species *Brizalina skagerrakensis* shows the most prominent and consistent changes when comparing both records (Fig. 3).

20 The CABFAC factor analysis distinguished three factors for each of the cores (Fig. 3), which together explain 95% (EMB046/20-3GC) and 97% (EMB046/10-4GC) of the total variance (Table 3). The foraminiferal species with absolute value of factor scores >1 are considered to contribute significantly to the defined foraminiferal assemblages (Table 4) and are used to name the distinguished factors (assemblages). Thus, “*Pullenia osloensis* assemblage” associated with Factor 1 explains 81% (EMB046/20-3GC) and 86% (EMB046/10-4GC) of variance, and includes species *P. osloensis* and *Nonionella iridea* defined for both records with an addition of *Cassidulina laevigata* in the EMB046/10-4GC dataset. The “*Brizallina skagerrakensis* assemblage” associated with Factor 2 is dominated by species *B. skagerrakensis* and explains ~11% (EMB046/20-3GC) and ~9% (EMB046/10-4GC) of variance. Finally, factor 3 explains ~3% (EMB046/20-3GC) and ~1.8% (EMB046/10-4GC) of variance and includes *N. iridea* as a common species for both records, with *P. osloensis* as the second dominant species for the EMB046/20-3GC record and *Stainforthia fusiformis* for the EMB046/10-4GC record, consequently resulting in “*N. iridea* - *P. osloensis*” (EMB046/20-3GC) and “*N. iridea* - *S. fusiformis*” (EMB046/10-4GC) assemblages (Table 3). The individual factor weights (importance) for each counted sample are expressed by factor loading (Fig. 3). Factors with loadings above 0.5 are considered most significant. The factor analysis shows that both records are defined by a clear dominance of *P. osloensis* factor alternating with *B. skagerrakensis* factor between CE 900 and 1700. The most pronounced changes in the foraminiferal assemblages occur between CE 1700 and the present day where the *P. osloensis* factor is to a large extent replaced by *B. skagerrakensis* factor. Similar long-term variability is seen in the ‘*palaeoproductivity fauna*’ group due to a strong dominance



of *B. skagerrakensis* in this group (Fig. 3). In addition, *palaeoproductivity fauna* appears in higher abundance between ~ CE 900 and 1200. In the uppermost part (~ CE 1950) of the EMB046/10-4GC record the *N. iridea*-*S. fusiformis* factor distinctly increased, while the *N. iridea*-*P. osloensis* factor of the EMB046/20-3GC record shows less variability (Fig. 3).

## 6 Discussion

### 5 6.1 Productivity changes in the last millennium

All dominant species in our benthic foraminiferal assemblages, grouped into factors, have documented association with quality (e.g. fresh or decaying) and availability of organic matter at the sea floor (e.g. Conradsen et al., 1994; Alve and Murray, 1995, 1997; Alve, 2003; Gustafsson and Nordberg, 2001; Duffield et al., 2015). The absolute abundance of planktonic foraminifera, stable carbon isotopes and total organic carbon also inform on past variability of productivity. We combine these proxies to assess productivity changes in the Skagerrak. Two periods with different productivity in the Skagerrak region are identified: i) moderate productivity between ~ CE 900 and 1700 and ii) high productivity from ~ CE 1700 towards present (Figs. 3, 5). For each defined period, we discuss the level of and changes in primary productivity and potential causes behind this productivity variability. Throughout the discussion, we also refer to the smoothed data of stable isotopes and Mg/Ca-derived BWT records as palaeothermometry proxies.

#### 15 6.1.1 Moderate primary productivity (~ CE 900 – 1700)

The highest absolute abundance of planktonic foraminifera and a clear dominance of the *P. osloensis* factor are recorded between ~ CE 900 and 1700, indicating a period of moderate primary productivity (Fig. 3). The TOC values and  $\delta^{13}\text{C}$  values do not show any major changes within this interval and until ~ CE 1500, respectively (Fig. 5). High abundance of planktonic foraminifera is strongly correlated with nutrient-rich water, making them a good proxy for productivity changes (Boltovskoy and Correa, 2016). The *P. osloensis* factor includes species *P. osloensis* and *N. iridea*, with an addition of *C. laevigata* in EMB046/10-4GC, in line with the previously identified *C. laevigata* – *P. osloensis* cluster (Erbs-Hansen et al., 2011) and *N. iridea* – *C. laevigata* category (Alve, 2010). These three species have an ecological preference for nutrient-rich environments, preferably with oxic bottom water conditions (Alve, 2003, 2010; Duffield et al., 2015). Hence, overall nutrient-rich conditions likely prevailed in the Skagerrak during this period.

25 Furthermore, the *B. skagerrakensis* factor and *palaeoproductivity fauna* also peak occasionally in the early and the late part of this interval (~ CE 900 – 1200, ~ CE 1600 – 1700) (Figs. 3, 5). The *B. skagerrakensis* factor relates to ecological preferences of the epifaunal to shallow infaunal benthic species *B. skagerrakensis*, a species associated with high fresh phytodetritus fluxes to the sea floor accompanied by a continuously high oxygen content in the sediments (Duffield et al., 2015). The abundant occurrence of *B. skagerrakensis* in the Skagerrak and Oslofjord area is restricted to water masses with 30 temperatures between 5 and 7 °C and salinity around 35 PSU (Qvale and Nigam, 1985 and references therein; Alve and

Murray, 1995, 1997; Duffield et al., 2015). In contrast to *P. osloensis*, *N. iridea* and *C. laevigata*, taxon *B. skagerrakensis* does not feed on decaying organic matter but prefers freshly settled algal material (Duffield et al., 2015). Hence, appearance of *B. skagerrakensis* between ~ CE 900 and 1200 and ~ CE 1600 – 1700 in both records, likely indicates a periods of well-oxygenated bottom water conditions with high fresh phytodetritus fluxes, while the period from ~ CE 1200 to 1600, characterised by dominance of *P. osloensis* factor (Fig. 3) suggests that either bottom water oxygen conditions in the Skagerrak may have become somewhat less favourable for *B. skagerrakensis* or/and change to a more food-competitive environment where the herbivorous *B. skagerrakensis* was likely outcompeted by a more omnivorous to detritivorous species *C. laevigata*, *P. osloensis* and *N. iridea*, which are all able to feed on both fresh and decaying organic matter (Alve, 2010; Duffield et al., 2015).

Because the stable carbon isotope composition recorded in calcareous benthic foraminiferal shells can be used to reconstruct past bottom water environments modified by fluxes of organic matter (Rohling and Cooke, 1999; Ravelo and Hillaire-Marcel, 2007), corresponding changes of the benthic  $\delta^{13}\text{C}$  similar to those in foraminiferal assemblages would be expected. Marine organisms preferentially take up more  $^{12}\text{C}$  than  $^{13}\text{C}$  in their biomass. When this organic matter disintegrates after it is deposited at the ocean floor, more  $^{12}\text{C}$  is released to the surrounding water. Hence, enhanced degradation at the bottom, e.g. related to enhanced primary productivity in the surface waters, will increase the  $^{12}\text{C}$  concentrations in the bottom/pore water, in addition to increasing the nutrient content. Foraminifera that calcify in such a  $^{12}\text{C}$  enriched water mass will record lower  $\delta^{13}\text{C}$  values than if less degradation of organic matter took place (Ravelo and Hillaire-Marcel, 2007; Filipsson and Nordberg, 2010). Hence, while the changes in the benthic and planktonic foraminiferal assemblages at ~ CE 900 – 1700 suggest overall constant nutrient-rich conditions characteristic for the Skagerrak region, the  $\delta^{13}\text{C}$  display light values and little variability until ~ CE 1500, supporting our interpretation of moderate primary production within the interval. This coincides with studies by Hebbeln et al. (2006), where between ~ CE 700 and 1500 the increasing  $\delta^{13}\text{C}$  values after period of high productivity in the southern Skagerrak and relatively little variability in  $\delta^{13}\text{C}$  in the northern Skagerrak are recorded.

### 6.1.2 Causes of moderate primary productivity (~ CE 900 – 1700)

Within the period of moderate primary production common for both sites, the  $\delta\text{w}$ , BWT and  $\delta^{18}\text{O}$  records reveals low correlation between both cores, pointing to different water conditions in the central and western Skagerrak (Fig. 5). At the time of higher BWT in the earliest ~ 250 years of the EMB046/20-3GC record followed by decreasing temperature trend until ~ CE 1450, the temperature in EMB046/10-4GC is lower and less variable between ~ CE 900 and 1350 after which it increases. The two events of most contrasting temperature records between the cores were found at ~ CE 900 – 1100 and ~ CE 1350 – 1500. In the first event, warming in the central Skagerrak seen from higher BWT is not indicated by the  $\delta^{18}\text{O}$  which instead shows higher values and corresponds to decreases in  $\delta\text{w}$ . Since the  $\delta^{18}\text{O}$  can be induced by salinity and temperature, periods of good correlation between  $\delta^{18}\text{O}$  and  $\delta\text{w}$  but contradictory to the BWT pattern may suggest salinity imposing on the temperature signal (Brückner and Mackensen, 2006). In contrast, good correlation between all three proxies is believed to give

a fair estimation of temperature and salinity changes (Fig. 4). During the second event (~ CE 1350 – 1500), there is a general good correlation between the BTW changes and variability of  $\delta^{18}\text{O}$  values, showing similar patterns of higher BWT and  $\delta w$ , corresponding to drop in  $\delta^{18}\text{O}$  values in EMB046/10-4CG records, and low BWT and  $\delta w$  when  $\delta^{18}\text{O}$  values increase in EMB046/20-3GC (Fig. 4). These changes reflect colder bottom water temperature and lower salinity from ~ CE 1350 to 1500 in the central, than in the western Skagerrak, which interestingly coincide with event of minimum surface salinity in the northeastern Skagerrak interpreted as enhanced outflow of low saline Baltic Sea water (Hebbeln et al., 2006). Since our cores were retrieved bellow 400 m within the deep waters of Norwegian Trench we would expect to obtain similar temperature and salinity signals for both sites. Instead, cooling observed in central Skagerrak was most likely resulting from renewal of deep water by inflowing colder and denser North Sea waters which apparently did not reach the shallower located EMB046/10-4GC (Ljøen and Svansson, 1972). Thus, it is possible that recorded higher BWT in EMB046/10-4GC was rather reflecting temperature from warm Atlantic water occupying the western Skagerrak basin (Brückner and Mackensen, 2006; Butruille et al., 2017).

The above described changes in oxygen isotopes and BWT, seem to not correspond to variability seen in foraminiferal assemblages and the  $\delta^{13}\text{C}$  records. Thus, while it is difficult to find a good match between changes in palaeoproductivity and palaeotemperature proxies, the high absolute abundance of planktonic foraminifera recorded at both sites at ~ CE 900 – 1700 (Fig. 5) suggests that the primary productivity was driven by nutrient-rich Atlantic water and abundant phytodetritus fluxes rather than enhanced nutrients entering the area through the Baltic outflow feeding the NCC. This interpretation is supported by a study from the Northern North Sea, where Klitgaard-Kristensen and Sejrup (1996) argued that the Atlantic water is favourable for planktonic foraminifera, while the low salinity of the NCC reduces their abundance. Our interpretation is further supported by previous studies based on foraminiferal (Erbs-Hansen et al., 2011) and diatom (Gil et al., 2006) assemblages, as well as a multiproxy study by Hebbeln et al. (2006), which all report on an onset of enhanced Atlantic water advection to the Skagerrak at ~ CE 900. Gil et al. (2006) documented an increase in diatom species associated with high salinity water in the Skagerrak and argued for enhanced inflow of nutrient-rich water via the NJC. Moreover, water with suspended sediments and low salinity are not favourable for planktonic foraminifera (Murray, 1976), therefore the higher absolute abundance of planktonic foraminifera in EMB046/10-4GC than in EMB046/20-3GC can be explained by an advantageous exposure to Atlantic water and smaller contribution of the low salinity Baltic Sea water within the NCC in the western, than in the central Skagerrak. It has to be noticed, however, that planktonic foraminifera due to their ability to inhabit the water column down to ~ 200 m (for species found in our records) can reflect the character of both the surface and the upper intermediate water layers (Jonkers et al., 2010; Schiebel et al., 2017).

Differences in water conditions between both sites are further supported by the differences in foraminiferal assemblages at CE ~ 900 – 1700 between the cores. It is likely that the higher abundance of *C. laevigata* in core EMB046/10-4GC than in the EMB046/20-3GC reflects a higher contribution of well-oxygenated Atlantic waters to the western Skagerrak as compared to its central part (Fig. 3). The *C. laevigata* and *P. osloensis* are mostly recorded in the Skagerrak and Norwegian Trench area and are associated with Atlantic water influence (Van Weering and Qvale, 1983; Conradsen et al., 1994; Alve and

Murray, 1995; Klitgaard-Kristensen et al., 2002; Wollenburg et al., 2004). In EMB046/20-3GC, the *C. laevigata* is largely replaced by dominance of *N. iridea* which is commonly present in the Skagerrak and the Scandinavian fjord waters with a salinity >35 PSU and a temperature range of 6 – 6.5 °C (Polovodova Asteman et al., 2013 and references therein). In addition, *N. iridea* is capable of growth under hypoxic-suboxic conditions (Duffield et al., 2015). Hence the dominance of *N. iridea* over *C. laevigata* in EMB046/20-3GC may be related to the less favourable bottom water oxygen conditions in the central Skagerrak which is more exposed to the brackish and nutrient-rich water of the BC as well as to enhanced river runoff.

Based on the combined high absolute abundance of planktonic foraminifera, intermediate abundance of benthic palaeoproductivity species, occasional peaks in the *B. skagerrakensis* factor, any major changes in TOC and relatively little variability in  $\delta^{13}\text{C}$  we conclude that the time interval CE 900 – 1700 was characterised by moderate palaeoproductivity in the Skagerrak. Furthermore, we argue that palaeoproductivity does not show coherence to changes in palaeothermometry proxies (Mg/Ca,  $\delta^{18}\text{O}$ ) and that the moderate productivity at that time was largely sustained by nutrient-rich Atlantic water bathing the sites as deduced from the appearance of planktonic foraminifera.

From the discussion above it is seen that several processes took place between ~ CE 900 and 1700, including changes in bottom water circulation, oxygen and salinity fluctuation or carbon fluxes. Each of the causes may in turn have been influenced by anthropogenic, climatic and/or oceanic factors (Brückner and Mackensen, 2008; Filipsson and Nordberg, 2010). Interestingly, the beginning of the moderate productivity period characterised by peaks in the *B. skagerrakensis* factor and palaeoproductivity species (~ CE 900 – 1200) corresponds well to the overall stable and relatively warm temperatures at the Northern Hemisphere (CE 830 – 1100) (PAGES 2k Consortium, 2013) associated with the early stage of the Medieval Climate Anomaly (MCA) (e.g. Hass, 1996). Hass (1996) argued that the MCA lasted until CE 1300 in the Skagerrak area. Based on granulometric analyses he suggested that the MCA was associated with a decreased strength of south-westerly winds as a result of a more northerly located cyclonic track causing weaker bottom currents. In contrast, the North Atlantic Oscillation (NAO) reconstructions by Trouet et al. (2009), Olsen et al. (2012), Faust et al. (2016), among others, all suggest a tendency for prevailing positive NAO conditions during the MCA and hence, south-westerlies dominating the hydrographic and meteorological regimes during winter (Fig. 5). During a positive NAO phase, strong south-westerlies result in warm and wet winters over the Northern Europe (Hurrell, 1995; Hurrell et al., 2001; Trouet et al., 2009) and coincide with intensification of water mass exchange (inflows and outflows) in the Skagerrak (Winther and Johannessen, 2006). Predominant positive NAO conditions would, however, also intensify the river runoff and the outflow of brackish water from the Baltic Sea to the Skagerrak due to increased precipitation over the catchment area. Increased riverine input and Baltic Sea outflow would in turn enhance the nutrient supply to the surface waters of the Skagerrak, and hence, increase the primary production. However, our palaeoproductivity proxies do not inform on increased productivity during ~ CE 900 – 1500 and also the high absolute abundance of planktonic foraminifera recorded at the same time both Skagerrak sites (Figs. 3, 5) does not support enhanced riverine input and increased Baltic Sea outflow since their abundance usually decreases in areas with increased brackish water conditions and decreased water transparency due to e.g. runoff (Murray, 1976; Klitgaard-Kristensen and Sejrup, 1996). Therefore, the higher winter precipitation during the MCA reported from the southwestern Norway was perhaps successfully

blocked by the mountain ranges in the southern Norway which caused less precipitation reaching our study sites (Fig. 5, Bakke et al. 2008).

5 Interestingly, the long-term period of high planktonic foraminiferal abundance, depleted  $\delta^{18}\text{O}$  and overall warm BWT in the central Skagerrak correspond well with a most pronounced positive NAO phase reconstructed by Trouet et al. (2009) and Olsen et al. (2012) lasting until ~ CE 1450, which suggests a strong advection of warm Atlantic water (Fig. 5).  
10 Around that time, a period characterised by a deep water warming and particularly weaker deep and cold North Sea water inflows (deep-water renewal) was suggested for the Skagerrak (Butruille et al., 2017). The following drop in temperature and thus cooling in the central Skagerrak is consistent with a temperature decline in the North Atlantic around ~ CE 1400, marking the onset of the Little Ice Age (LIA) in northern Europe (Berstad et al., 2003; Brückner and Mackensen, 2006; Büntgen et al., 2011; Erbs-Hansen et al., 2011). Among other reconstructions, Trouet et al. (2009) proposed that during the LIA the NAO index became more negative and was characterised by weaker westerly airflows resulting in a reduction of the Atlantic water inflows. Reduced advection of warm Atlantic water coinciding with a deep-water renewal (discussed above) to the central Skagerrak may explain the colder bottom water conditions seen around ~ CE 1500 in EMB046/20-3GC record. The changing climate conditions during the transition between MCA and the LIA and later during the LIA, likely accompanied by increased storminess (Gil et al., 2006), were also important for the difference in bottom water conditions between the central and western Skagerrak records and thus perhaps could additionally explained contradictory signal between the records.

20 Hence, to conclude it is likely that moderate productivity during ~ CE 900 – 1450 was primarily driven by nutrient-rich Atlantic water likely during the predominant positive NAO associated with the warm Medieval Climate Anomaly, where the Atlantic inflow was stronger than the Baltic Sea outflow creating favourable conditions for planktonic foraminifera in the region. The second part of the moderate productivity period (~ CE 1450 – 1700) coincides with variable climate conditions, which are characteristic for the Little Ice Age, where more negative NAO likely reduced the warm Atlantic water inflow and triggered deep-water renewal.

### 6.1.3 High primary productivity (~ CE 1700 – present)

25 A prominent change in benthic and planktonic foraminiferal assemblages, the  $\delta^{13}\text{C}$  and TOC records took place around CE 1700 in both cores, suggesting a shift in environmental conditions in the Skagerrak. The palaeoproductivity related foraminiferal fauna increased and the values of *B. skagerrakensis* factor largely replaced the *P. osloensis* factor (Figs. 3, 5). The planktonic foraminifera decrease towards the top of the cores and almost disappear after ~ CE 1850 in both records. These changes in foraminiferal assemblages were accompanied by a gradual depletion of  $\delta^{13}\text{C}$  and a continuous increase in TOC in  
30 both cores (Fig. 5). All proxies suggest enhanced primary productivity from CE 1700 towards present day.

### 6.1.4 Causes of high primary productivity (~ CE 1700 – present)

In consistency to the previous period, comparison of the two cores shows that the periods of high primary productivity are common for both study sites while the BWT and oxygen isotopes generally provide negative correlation in temperature and salinity between the central and western Skagerrak. However, from ~ CE 1700 the  $\delta^{18}\text{O}$  and  $\delta w$  patterns show some similarities as comparably low values in both records and reflect increased values around ~ CE 1800, coinciding with generally low BWTs, which are again warmer at the western Skagerrak side (Figs. 4, 5). These changes suggest first a colder climate followed by warmer and more saline bottom water conditions. The cooling appears during distinctly negative NAO showing a similar relation between changes in the water masses and the NAO as the one seen at ~ CE 1350 – 1500. However, we suggest that at this time deep-water renewal reached to the western Skagerrak, consequently lowering temperature and salinity at the both sites.

The following warming of the bottom water after ~ CE 1800 reflects naturally induced environmental changes in the Skagerrak region accompanied by a gradually increasing human activity. The warming seen in our records is consistent with intensified heat transport to the Northern Hemisphere (Brückner and Mackensen, 2006), overall warm climate in Fennoscandia (Briffa et al., 1992) and warm spring conditions recorded between CE 1750 and 1920 off the Norwegian continental margin (Berstad et al., 2003). Furthermore, our results are supported by similar  $\delta^{18}\text{O}$  changes recorded in the same area and at the same time by Brückner and Mackensen, (2006), and Hass (1995). The bottom water warming was associated with the termination of the coldest LIA phase in the Skagerrak region (Berstad et al., 2003; Brückner and Mackensen, 2006), a transition to a more positive NAO mode that would entail wetter and warmer winters over Scandinavia (Hurrell et al., 2001), or both. Either way, our data demonstrate a long-term intensification of nutrient supply likely due to increased inflows of Atlantic water to the Skagerrak.

Associated with a generally more positive NAO phase it is expected that changes in atmospheric and oceanic circulation systems would result in enhanced surface water outflow from the Baltic Sea (e.g. Gustafsson and Stigebrandt, 1996; Zorita and Laine, 2000). As a consequence of increased precipitation and thus enhanced river runoff over the large Baltic Sea catchment area, the outflowing low saline Baltic Sea water would supply the Skagerrak surface water with nutrients (Svansson, 1975; Aure et al., 1998; Krossa et al., 2015). Which is in line with the decreased and almost disappearing planktonic foraminifera in our records as a result of lower salinity and transparency in the upper water layers. The total freshwater riverine discharge from the Baltic Sea together with the contributions from the major Norwegian rivers to the Skagerrak contribute with much less nutrients to the Skagerrak waters than nutrient transport via the inflows from the North Sea (Danielssen et al., 1997). However, Krossa et al. (2015) still showed a good correlation between the increased Baltic outflow and enhanced productivity in the Skagerrak on timescales longer than 1100 years, based on increased alkenone  $\text{C}_{37:4}$  concentration, a proxy for the influence of brackish water. Furthermore, Polovodova Asteman et al. (2018), documented increased palaeoproductivity over the last 1700 years that corresponded in time with the increased alkenone  $\text{C}_{37:4}$  concentration (Krossa et al., 2015). Both studies argued that the nutrient-rich water causing enhanced productivity in the central Skagerrak was to a large extent of Baltic origin. Thus, the Baltic outflow can play an important role in the Skagerrak nutrients budget.

Zillén et al. (2008) showed that a widespread oxygen deficiency in the Baltic Sea was stimulated by an increased nutrient loading associated with a growing population and intensification of land use changes, which all began around CE

1600 and were followed by an industrial development at around CE 1800. In more recent times (after ~ CE 1900), the land use changes in Scandinavia caused an increased terrestrial runoff through either sparsely cultivated lands after massive deforestation or due to an extensive farming in southern Sweden (Zillén et al., 2008 and references therein; Kaplan et al., 2009). Hence it is likely that superimposed on the natural variability in volume of the outflowing Baltic water, the concentration of nutrients in the outflowing water has changed after ~ CE 1700 towards present due to a gradually increased human impact.

At the same time as increased primary production caused eutrophication in the Baltic Sea, our data shows a clear decrease in the  $\delta^{13}\text{C}$  values at both Skagerrak sites (Fig. 5). This distinct depletion in  $\delta^{13}\text{C}$  provides evidence for a change from the ocean-atmospheric relationship established for the preceding periods towards an additional contribution of the lighter carbon isotope ( $^{12}\text{C}$ ) to the sea water from the atmosphere due to the increase in atmospheric  $\text{CO}_2$  concentration caused by anthropogenic emissions, known as the Suess effect (e.g. Cage and Austin, 2010; Filipsson and Nordberg, 2010; Eide et al. 2017). Both the increased primary productivity and the Suess effect may cause the depletion in benthic  $\delta^{13}\text{C}$ . However, the decrease of ca 0.9‰ seen in our  $\delta^{13}\text{C}$  records from ~ CE 1800 towards present is likely to a large extent explained by the Suess effect, which is in line with the ca 0.8‰  $\delta^{13}\text{C}$  decrease between the preindustrial and modern period observed in the North Atlantic Ocean (Eide et al., 2017).

To summarize, from ~ CE 1700 towards present day changes in palaeoproductivity proxies indicate increased primary productivity likely caused by a combination of inflow of warm Atlantic water, the Baltic outflow, intensified river runoff and enhanced human impact through agriculture expansion and industrial development. **This increase in primary production occurred during a high variability in temperature and NAO index.**

### **6.1.5 Changes in the last ~ 70 years**

During the last 70 years the water conditions in Skagerrak changed as indicated by changes in benthic foraminiferal assemblages. *B. skagerrakensis* starts to decrease in favour of higher *S. fusiformis* abundances (Fig. 3). *Stanforthia fusiformis* is considered as an indicator of trophic changes in Scandinavian waters due to its high tolerance of oxygen-depleted and organic-rich conditions (e.g. Alve, 2003 and references therein). This opportunistic species has the highest reproduction (up to 7 times/month) and growth rates after the phytoplankton blooms followed by an enhanced food supply to the sea floor and decay of organic matter (Gustafsson and Nordberg, 2001). This explains the taxon's food preferences recognised as both fresh phytodetritus and microbes associated with degradation of organic matter (Duffield et al., 2015). **Therefore, the increased abundance of *S. fusiformis* during the last 70 years and simultaneous drop in *B. skagerrakensis* in our records may suggest changes in quality of organic matter at the sea floor after high productivity episodes causing increased enrichment of organic matter and its enhanced degradation in the sediments. At the same time,** the continuously high nutrients content coinciding with a gradual decline in oxygen concentration has been shown for the Skagerrak fjords with sluggish bottom water circulation (e.g. Rosenberg, 1990; Johannessen and Dahl, 1996, Alve, 2003; Filipsson and Nordberg, 2004). **There are no hydrographic**

studies reporting on low oxygen conditions in the deep Skagerrak basin during the last 70 years, thus high appearance of *S. fusiformis* in our records will indicate rather higher amount of degraded food than depleted oxygen.

## 7 Conclusions

This study provides evidence for changes in primary productivity in the Skagerrak during the last millennium. Our multi-proxy records show that the time interval ~ CE 900 – 1700 was characterised by moderate primary production with nutrients largely sustained by warm Atlantic water, as revealed by high abundance of planktonic foraminifera. The first part of this interval (~ CE 900 – 1450) was likely associated with the warm Medieval Climate Anomaly during which a persistent positive NAO strengthened westerlies resulting in more frequent warm Atlantic water inflows. After ~ CE 1450, the continuously moderate productivity at the both sites is indicated by a dominance of *P. osloensis* factor, high abundance of planktonic foraminifera, relatively stable TOC, and overall not much variable  $\delta^{13}\text{C}$ , which all coincide with the variable climate conditions characteristic for the Little Ice Age. During that time, episodes of negative NAO triggered deep-water renewal, which resulted in colder bottom water temperature in the central Skagerrak, while the western Skagerrak seems to be more resistant to this cooling and instead reflects temperature of warm Atlantic water occupying this site.

Finally, the high primary productivity period between ~ CE 1700 and 2000 is documented by both increased TOC and *B. skagerrakensis* factor, high absolute abundance of palaeoproductivity fauna and decreased  $\delta^{13}\text{C}$  values. Enhanced nutrient availability was likely caused by a stronger Baltic Sea outflow, increased river runoff, intensified inflows of the nutrient-rich Atlantic water, together with agricultural and industrial expansion. Simultaneously, an increase in human induced  $\text{CO}_2$  emission caused great change in oceanic carbon isotope budget, indicated by the Suess effect, shown in our records by strongly negative  $\delta^{13}\text{C}$  values since ~ CE 1800. The most pronounced increase in primary production at ~ CE 1800 – 2000 occurred during a warm period with a more positive NAO, wetter and warmer winters in Scandinavia as shown by an increase in BWT and decrease in  $\delta^{18}\text{O}$  in our records.

A comparison between two records shows slight differences in species composition likely due to more favourable habitat in the western Skagerrak, with a less exposure to low-saline nutrient-rich NCC water while the higher TOC in the central Skagerrak mostly results from a better exposure to the Baltic outflow and nutrient rich water via NJC, and terrestrial runoff due to a more inland location. The productivity and the fluxes of organic matter to the seafloor seems to not correspond to the temperature and salinity changes recorded in the benthic *Melonis barleeanus* shells.

## Data availability

The presented data are available at [www.pangaea.de](http://www.pangaea.de).

## Competing interests

The authors declare that they have no conflict of interest



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## 10 References

- Alve, E.: A common opportunistic foraminiferal species as an indicator of rapidly changing conditions in a range of environments, *Estuar. Coast. Shelf S.*, 57, 501–514, 2003.
- Alve, E.: Benthic foraminiferal responses to absence of fresh phytodetritus: a two-year Experiment, *Mar. Micropaleontol.*, 76, 67–75, 2010.
- 15 Alve, E. and Murray, J. W.: Benthic foraminiferal distribution and abundance changes in Skagerrak surface sediments: 1937 (Höglund) and 1992/1993 data compared, *Mar. Micropaleontol.*, 25, 269–288, 1995.
- Alve, E. and Murray, J. W.: High benthic fertility and taphonomy of foraminifera: a case study of the Skagerrak, North Sea, *Mar. Micropaleontol.*, 31, 157–175, 1997.
- Andersson, L.: Trends in nutrient and oxygen concentrations in the Skagerrak-Kattegat, *J. Sea Res.*, 35, 63–71, 1996.
- 20 Aure, J. and Dahl, E.: Oxygen, nutrients, carbon and water exchange in the Skagerrak Basin, *Cont. Shelf Res.*, 14, 965–977, 1994.
- Aure, J., Danielssen, D., and Sætre, R.: Assessment of eutrophication in Skagerrak coastal waters using oxygen consumption in fjordic basins, *ICES J. Mar. Sci.*, 53, 589–595, 1996.
- Aure, J., Danielssen, D., and Svendsen, E.: The origin of Skagerrak coastal water off Arendal in relation to variations in nutrient concentrations, *ICES J. Mar. Sci.*, 55, 610–619, 1998.
- 25 Baden, S. P., Loo, L. O., Pihl, L., and Rosenberg, R.: Effects of eutrophication on benthic communities including fish: Swedish west coast, *AMBIO*, 19, 113–122, 1990.
- Bakke, J., Lie, O., Dahl, S. O., Nesje, A., and Bjune, A. E.: Strength and spatial patterns of the Holocene wintertime Westerlies in the NE Atlantic region, *Global Planet Change*, 60, 28–41, 2008.**

- Barker, S., Greaves, M., and Elderfield, H.: A study of cleaning procedures used for foraminiferal Mg/Ca paleothermometry, *Geochem. Geophys. Geos.*, 4, 8407, doi:10.1029/2003GC000559, 2003.
- Berstad, I. M., Sejrup, H. P., Klitgaard-Kristensen, D., and Haflidason, H.: Variability in temperature and geometry of the Norwegian Current over the past 600 yr; stable isotope and grain size evidence from the Norwegian margin, *J. Quaternary Sci.*, 18, 591–602, 2003.
- Boltovskoy, D. and Correa, N.: Foraminifers (Planktonic), in: *Encyclopedia of Marine Geosciences*, 1, Harff, J., Meschede, M., Petersen, S., and Thiede, J., Springer, Netherlands, 255–261, 2016.
- Boon, A. R., Duineveld, G. C. A., and Kok, A.: Benthic Organic Matter Supply and Metabolism at Depositional and Non-depositional Areas in the North Sea, Estuar Coast Shelf S., 49, 747–761, 1999.**
- Boyle, E. A.: Manganese carbonate overgrowths on foraminifera, *Geochim. Cosmochim. Ac.*, 47, 1815–1819, 1983.
- Breitburg, D. L., Hondorp, D. W., Davias, L. A., and Diaz R. J.: Hypoxia, Nitrogen, and Fisheries: Integrating Effects Across Local and Global Landscapes, *Annu. Rev. Mar. Sci.*, 1, 329–349, 2009.
- Briffa, K. R., Jones, T. S., Bartholin, D., Eckstein, F. H., Schweingruber, W. K., Zetterber, M., Karlén, W., Zetterberg, P., and Eronen, M.: Fennoscandian summers from ad 500: temperature changes on short and long timescales\*, *Clim. Dynam.*, 7, 111–119, 1992.
- Brückner, S. and Mackensen, A.: Deep-water renewal in the Skagerrak during the last 1200 years triggered by the North Atlantic Oscillation: evidence from benthic foraminiferal  $\delta^{18}\text{O}$ , *The Holocene*, 16, 331–340, 2006.
- Brückner, S. and Mackensen, A.: Organic matter rain rates, oxygen availability, and vital effects from benthic foraminiferal  $\delta^{13}\text{C}$  in the historic Skagerrak, North Sea, *Mar. Micropaleontol.*, 66, 192–207, 2008.
- Butruille, C., Krossa, V. R., Schwab, C., and Weinelt, M.: Reconstruction of mid- to late-Holocene winter temperatures in the Skagerrak region using benthic foraminiferal Mg/Ca and  $\delta^{18}\text{O}$ , *The Holocene*, 27, 63–72, 2017.
- Büntgen, U., Tegel, W., Nicolussi, K., McCormick, M., Frank, D., Trouet, V., Kaplan, J. O., Herzig, F., Heussner, K. U., Wanner, H., Luterbacher, J., and Esper, J.: 2500 Years of European Climate Variability and Human Susceptibility, *Science*, 3, 578–582., doi:10.1126/science.1197175, 2011.
- Cage, A. G. and Austin, W. E. N.: Marine climate variability during the last millennium: The Loch Sunart record, Scotland, UK, *Quaternary Sci. Rev.*, 29, 1633–1647, 2010.
- Cardinale, M. and Svedäng, H.: Modelling recruitment and abundance of Atlantic cod, *Gadus morhua*, in the eastern Skagerrak–Kattegat (North Sea): evidence of severe depletion due to a prolonged period of high fishing pressure, *Fish. Res.*, 69, 263–282, 2004.
- Carstensen, J., Conley, D. J., Andersen, J. H., and Ærtebjerg, G.: Coastal eutrophication and trend reversal: A Danish case study, *Limnol. Oceanogr.*, 51, 398–408, 2006.

- Conley, D. J., Carstensen, J., Vaquer-Sunyer, R., and Duarte, C. M.: Ecosystem thresholds with hypoxia, *Hydrobiologia*, 629, 21–29, doi:10.1007/s10750-009-9764-2, 2009.
- Conradsen, K. H., Bergsten, K. L., Knudsen, K. N., Nordberg, K., and Seidenkrantz, M. S.: Recent benthic foraminiferal distribution in the Kattegat and the Skagerrak, Scandinavia, Cushman Foundation Special Publication, 32, 53–68, 1994.
- 5 Danielssen, D. S., Edler, L., FONSEHUS, S., Hernroth, L., Ostrowski, M., Svendsen, E., and Talpsepp, L.: Oceanographic variability in the Skagerrak and northern Kattegat, May-June, 1990, *ICES J. Mar. Sci.*, 54, 753–773, 1997.
- Doney, S. C., Fabry, V. F., Feely, R. A., and Kleypas, J. A.: Ocean Acidification The Other CO<sub>2</sub> Problem, *Annu. Rev. Mar. Sci.*, 1, 169–192, 2009.
- Duffield, Ch. J., Hess, S., Norling, K., and Alve, E.: The response of *Nonionella iridea* and other benthic foraminifera to  
10 “fresh” organic matter enrichment and physical disturbance, *Mar. Miropaleontol.*, 120, 20–30, 2015.
- Eide, M., Olsen, A., Ninnemann, U. S., and Eldevik, T.: A global estimate of the full oceanic <sup>13</sup>C Suess effect since the preindustrial, *Global Biogeochem. Cy.*, 31, 492–514, doi:10.1002/2016GB005472, 2017.
- Erbs-Hansen, D. R., Knudsen, K. L., Gary, A. C., Gyllencreutz, R., and Jansen, E.: Holocene climatic development in the Skagerrak, eastern North Atlantic: foraminiferal and stable isotope evidence, *The Holocene*, 22, 301–312, 2011.
- 15 FAO (Food and Agriculture Organization of the United Nations): The State of World Fisheries and Aquaculture 2016. Contributing to food security and nutrition for all, Rome, 107–137, 2016.
- Faust, J. C., Fabian, K., Milzer, G., Giraudeau, J., and Knies, J.: Norwegian fjord sediments reveal NAO related winter temperature and precipitation changes of the past 2800 years, *Earth Planet Sc Lett.*, 435, 84–93, 2016.
- Filipsson, H. L., McCorkle, D. C., Mackensen, A., Berhard, J. M., Andersson, L. S., Naustvoll, L. J., Cabellero-Alfonso, A.  
20 M., Nordberg, K., and Danielssen, D. S.: Seasonal variability of stable carbon isotopes ( $\delta^{13}\text{C}_{\text{DIC}}$ ) in the Skagerrak and the Baltic Sea: Distinguishing between mixing and biological productivity, *Palaeogeogr. Palaeoclimatol.*, 483, 15–30, doi:10.1016/j.palaeo.2016.11.031, 2017.
- Filipsson, H. L. and Nordberg, K.: Climate Variations, an Overlooked Factor Influencing the Recent Marine Environment. An Example from Gullmar Fjord, Sweden, Illustrated by Benthic Foraminifera and Hydrographic Data, *Estuaries*, 27, 867–881,  
25 2004.
- Filipsson, H. L. and Nordberg, K.: Variations in organic carbon flux and stagnation periods during the last 2400 years in a Skagerrak fjord basin, inferred from benthic foraminiferal  $\delta^{13}\text{C}$ , in: *Fjord Systems and Archives*, Howe, J. A., Austin, W. E. N., Forwick, M., and Paetzel, M., Geol. Soc. Sp., London, 344, 261–270, doi:10.1144/SP344.18, 2010.
- Fonselius, S.: The upwelling of nutrients in the central Skagerrak, *Deep-Sea Res. II*, 43, 57–71, 1996.
- 30 Gil, I. M., Abrantes, F., and Hebbeln, D.: The North Atlantic Oscillation forcing through the last 2000 years: Spatial variability as revealed by high-resolution marine diatom records from N and SW Europe, *Mar. Micropaleontol.*, 60, 113–129, 2006.

- Greaves, M., Caillon, N., Rebaubier, H., Bartoli, G., Boharty, S., Cacho, I., Clarke, L., Cooper, M., Daunt, C., Delaney, M., DeMenocal, P., Dutton, A., Eggins, S., Elderfield, H., Garbe-Schoenberg, D., Goddard, E., Green, D., Groeneveld, J., Hastings, D., Hathorne, E., Kimoto, K., Klinkhammer, G. P., Labeyrie, L., Lea, D. W., Marchitto, T., Martinez-Boti, M. A., Mortyn, P. G., Ni, Y., Nürnberg, D., Paradis, G., Pena, L., Quinn, T., Rosenthal, Y., Russell, A., Sagawa, T., Sosdian, S., Tachikawa, K., Tappa, E., Thunell, R., and Wilson, P. A.: Interlaboratory comparison study of calibration standards for foraminiferal Mg/Ca thermometry, *Geochem. Geophys. Geosy.*, 9, Q08010, doi:10.1029/2008GC001974, 2008.
- Gustafsson, M. and Nordberg, K.: Living (stained) benthic foraminiferal response to primary production and hydrography in the deepest part of the Gullmar Fjord, Swedish west coast, with comparisons to Höglund's 1927 material, *J. Foramin. Res.*, 31, 2–11, 2001.
- 10 Gustafsson, B. and Stigebrandt, A.: Dynamics of the freshwater-influenced surface layers in the Skagerrak, *J. Sea Res.*, 35, 39–53, 1996.
- Hammer, Ø., Harper, D. A. T., and Ryan, P. D.: Past: Paleontological Statistics Software Package for Education and Data Analysis, *Palaeontol. Electron.*, 4, 9, 2001.
- Hasenfratz, A. P., Schiebel, R., Thornalley, D. J. R., Schönfeld, J., Jaccard, S. L., Martínez-García, A., Holbourn, A., Jennings, A. E., Kuhnt, W., Lear, C. H., Marchitto, T. M., Quillmann, U., Rosenthal, Y., Yu, J., and Haug, G. H.: Mg/Ca-temperature calibration for the benthic foraminifera *Melonis barleeanum* and *Melonis pompilioides*, *Geochim. Cosmochim. Ac.*, 217, 365–383, doi: 10.1016/j.gca.2017.08.038, 2017.
- 15 Hass, H. C.: Northern Europe climate variations during late Holocene: Evidence from marine Skagerrak, *Palaeogeogr. Palaeoclimatol.*, 123, 121–145, 1996.
- 20 Haynert, K., Schönfeld, J., Polovodova Asteman, I., and Thomsen, J.: The benthic foraminiferal community in a naturally CO<sub>2</sub>-rich coastal habitat of the southwestern Baltic Sea, *Biogeosciences*, 9, 4421–4440, doi:10.5194/bg-9-4421-2012, 2012.
- Hebbeln, D., Knudsen, K. L., Gyllencreutz, R., Kristensen, P., Klitgaard-Kristensen, D., Backman, J., Scheurle, C., Jiang, H., Gil, I., Smelror, M., Jones, P. D., and Sejrup, H. P.: Late Holocene coastal hydrographic and climate changes in the eastern North Sea, *The Holocene*, 16, 987–1001, 2006.
- 25 Hjalmarsson, S., Anderson, L. G., and She, J.: The exchange of dissolved inorganic carbon between the Baltic Sea and the North Sea in 2006 based on measured data and water transport estimates from a 3D model, *Mar. Chem.*, 121, 200–205, 2010.
- Hop, H., Gjørseter, J., and Danielssen, D. S.: Seasonal feeding ecology of cod (*Gadus morhua* L.) on the Norwegian Skagerrak coast, *ICES J. Mar. Sci.*, 49: 453–461, doi:10.1093/icesjms/49.4.453, 1992.
- Hurrell, J. W.: Decadal trends in the North Atlantic Oscillation: regional temperatures and precipitation, *Science*, 269, 676–679, 1995.
- 30 Hurrell, J. W., Kushnir, Y., and Visbeck, M.: The North Atlantic Oscillation. *Science* 291, 603–605, doi:10.1126/science.1058761, 2001.
- ICES: Oceanographic DataSet- temperature (57° .17–58°N, 8°–9° .79'E), Copenhagen (<http://www.ices.dk>), 2010.

- Iversen, S. A., Skogen, M., and Svendsed, E.: Availability of horse mackerel (*Trachurus trachurus*) in the north-eastern North Sea, predicted by the transport of Atlantic water, *Fish. Oceanogr.*, 11, 245–250, 2002.
- Johannessen, T. and Dahl, E.: Declines in oxygen concentrations along the Norwegian Skagerrak coast, 1927-1993: A signal of ecosystem changes due to eutrophication?, *Limnol. Oceanogr.*, 41, 766–778, 1996.
- 5 Jonkers, L., Brummer, G.-J. A., Peeters, F. J. C., van Aken, H. M., and Femke De Jong, M.: Seasonal stratification, shell flux, and oxygen isotope dynamics of left-coiling *N. pachyderma* and *T. quinqueloba* in the western subpolar North Atlantic, *Paleoceanography*, 25, PA2204, doi:10.1002/palo.20018, 2010.
- Kaplan, J. O., Krumhardt, K. M., and Zimmermann, N.: The prehistoric and preindustrial deforestation of Europe, *Quaternary Sci. Rev.*, 28, 3016–3034, 2009.
- 10 Klitgaard-Kristensen, D. and Sejrup, H. P.: Modern benthic foraminiferal biofacies across the Northern North Sea, *Sarsia*, 81, 97–106, 1996.
- Klitgaard-Kristensen, D., Sejrup, H. P., and Hafliðason H.: Distribution of recent calcareous benthic foraminifera in the northern North Sea and relation to the environment, *Polar. Res.*, 21, 275–282, 2002.
- Kristiansen, T. and Aas, E.: Water type quantification in the Skagerrak, the Kattegat and off the Jutland west coast, 15 *Oceanologia*, 57, 177–195, 2015.
- Kristjánadóttir, G. B., Lea, D. W., Jennings, A. E., Pak, D. K., and Belanger, C.: New spatial Mg/Ca-temperature calibrations for three Arctic, benthic foraminifera and reconstruction of north Iceland shelf temperature for the past 4000 years, *Geochem. Geophys. Geosy.*, 8, Q03P21, doi:10.1029/2006GC001425, 2007.
- Krossa, V. R., Moros, M., Blanz, T., Jansen, E., and Schneider, R.: Late Holocene Baltic Sea outflow changes reconstructed using  $C_{37:4}$  content from marine cores, *Boreas*, 44, 81–93, doi:10.1111/bor.12093, 2015.
- 20 Ljøen, R. and Svansson, A.: Long-term variations of subsurface temperatures in the Skagerrak, *Deep Sea Res.*, 19, 277–288, 1972.
- Mackensen, A., Schumacher, S., Radke, J., and Schmidt, D. N.: Microhabitat preferences and stable carbon isotopes of endobenthic foraminifera: Clue to quantitative reconstruction of oceanic new production?, *Mar. Micropaleontol.*, 40, 233–258, 25 2000.
- Micheli, F.: Eutrophication, Fisheries, and Consumer-Resource Dynamics in Marine Pelagic Ecosystems, *Science*, 285, 1396–1398, 1999.
- Moros, M., Andersen, T. J., Schulz-Bull, D., Häusler, K., Bunke, D., Snowball, I., Kotilainen, A., Zillén, L., Jensen, J. B., Kabel, K., Hand, I., Leipe, T., Loughheed, B. C., Wagner, B., and Arz, H. W.: Towards an event stratigraphy for Baltic Sea 30 sediments deposited since AD 1900: approaches and challenges, *Boreas*, 46, 129–142, 2017.
- Murray, J. W.: A method of determining proximity of marginal seas to an ocean, *Mar. Geol.*, 22, 103–119, 1976.

Olsen, J., Anderson, N. J., and Knudsen, M. F.: Variability of the North Atlantic Oscillation over the past 5,200 years. *Nat. Geosci.*, 5, 808–812, doi:10.1038/ngeo1589, 2012.

Olsen, E. M., Knutsen, H., Gjørseter, J., Jorde, P. E., Knutsen, J. A., and Stenseth, N. C.: Life-history variation among local populations of Atlantic cod from the Norwegian Skagerrak coast, *J. Fish Biology* 64, 1725–1730, 2004.

- 5 Olsen, E. M., Lilly, G. R., Heino, M., Morgan, M. J., Brattey, J., and Dieckmann, U.: Assessing changes in age and size at maturation in collapsing populations of Atlantic cod (*Gadus morhua*), *Can. J. Fish Aquat. Sci.*, 62, 811–823, 2005.

Qvale, G. and Nigam, R.: *Bolivina skagerrakensis*, a new name for *Bolivina cf. robusta*, with notes on ecology and distribution, *J. Foramin. Res.*, 15, 6–12, 1985.

- PAGES 2k Consortium: Continental-scale temperature variability during the past two millennia, *Nat. Geosci.*, 6, 339–346, doi:10.1038/ngeo1797, 2013.

Pingree, R. D., Holligan, P. M., Mardell, G. T., and Harris, R. P.: Vertical distribution of plankton in the Skagerrak in relation to doming of the seasonal thermocline, *Cont. Shelf Res.*, 1, 209–219, 1982.

Polovodova Asteman I., Nordberg, K., and Filipsson, H. I.: The Little Ice Age: evidence from a sediment record in Gullmar Fjord, Swedish west coast, *Biogeoscience*, 10, 1273–1290, 2013.

- 15 Polovodova Asteman, I., Risebrobakken, B., Moros, M., Binczewska, A., Dobosz, S., Jansen, E., Sławinska, J., and Bąk, M.: Late Holocene palaeoproductivity changes: a multi-proxy study in the Norwegian Trench and the Skagerrak, North Sea, *Boreas*, 47, 238–255, doi:10.1111/bor.12264, 2018.

Ravelo, A. Ch. and Hillaire-Marcel, C.: The Use of Oxygen and Carbon Isotopes of Foraminifera in Paleocyanography, in: *Developments in Marine Geology*, 1, Hillaire-Marcel, C. and de Vernal, A., Elsevier, 735–764, 2007.

- 20 Reimer, P. J., Bard, E., Bayliss, A., Beck, J. W., Blackwell, P. G., Bronk Ramsey, C., Buck, C. E., Cheng, H., Edwards, R. L., Friedrich, M., Grootes, P. M., Guilderson, T. P., Hafliðason, H., Hajdas, I., Hatté, C., Heaton, T. J., Hoffman, D. L., Hogg, A. G., Hughen, K. A., Kaiser, K. F., Kromer, B., Manning, S.W., Niu, M., Reimer, R. W., Richards, D. A., Scott, E. M., Southon, J. R., Staff, R. A., Turney, C. S. M., and van der Plicht, J.: IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP, *Radiocarbon*, 55, 1869–1887, 2013.

- 25 Rohde, J.: On the dynamics of the large-scale circulation of the Skagerrak, *J. Sea Res.*, 35, 9–21, 1996.

Rohling, E. J. and Cooke, S.: Stable oxygen and carbon isotopes in foraminiferal carbonate shells, in: *Modern Foraminifera*, Sen Gupta, B. K., Kluwer Academic Publishers, Dordrecht/Boston/London, 297, 239–258, 1999.

Rosenberg, R., Elmgre, E., Fleischer, S., Jonsson, P., Persson, G., and Dahlin, H.: Marine eutrophic case studies in Sweden, *AMBIO*, 19, 102–108, 1990.

- 30 Rosenberg, R., Gray, J. S., Josefson, A. B., and Pearson, J. H.: Petersen's benthic stations revisited. II. Is the Oslofjord and eastern Skagerrak enriched?, *J. Exp. Mar. Biol. Ecol.*, 105, 219–251, 1987.

- Rydberg, L., Ærtebjerg, G., and Edler, L.: Fifty years of primary production measurements in the Baltic entrance region, trends and variability in relation to land-based input of nutrients, *J. Sea Res.*, 56, 1–16, 2006.
- Rydberg, L., Haamer, J., and Liungman, O.: Fluxes of water and nutrients within and into the Skagerrak, *J. Sea Res.*, 35, 23–38, 1996.
- 5 Schiebel, R., Spielhagen, R. F., Garnier, J., Hagemann, J., Howa, H., Jentzen, A., Martínez-García, A., Meilland, J., Michel, e., Repschläger, J., Salter, I., Yamasaki, M., and Haug, G.: Modern planktic foraminifers in the high-latitude ocean, *Mar. Micropaleontol.*, 136, 1–13, 2017.
- Shackleton, N. J.: Attainment of isotopic equilibrium between ocean water and the benthonic foraminifera genus *Uvigerina*: isotopic changes in the ocean during the last glacial, *Colloques Internationaux du C.N.R.S.*, 219, 1974.
- 10 Sigman, D. M. and Hain, M. P.: The Biological Productivity of the Ocean, *Nature Education*, 3, 1–16, 2012.
- Skogen, M. D., Budgell, W. P., and Rey, F.: Interannual variability in Nordic seas primary production, *ICES J Mar Sci.*, 64, 889–898, doi.org/10.1093/icesjms/fsm063, 2007.
- Stuiver, M., Reimer, P. J., and Reimer, R. W.: CALIB 7.1 (*wwwprogram*), available at: <http://calib.org> (accessed 16.02.2017), 2017.
- 15 Svansson, A.: Physical and chemical oceanography of the Skagerrak and the Kattegat, Fishery Board of Sweden, Institute of Marine Research, Report, 1, 1–88, 1975.
- Van Weering, T. C. E. and Qvale, G.: Recent sediments and foraminiferal distribution in the Skagerrak, northeastern North Sea, *Mar. Geol.*, 52, 75–99, 1983.
- Winther, N. G. and Johannessen, J. A.: North Sea circulation: Atlantic inflow and its destination, *J. Geophys. Res.-Oceans*, 20 111, C12018, doi:10.1029/2005JC003310, 2006.
- Wollenburg, J. E., Knies, J., and Mackensen, A.: High-resolution paleoproductivity fluctuations during the past 24 kyr as indicated by benthic foraminifera in the marginal Arctic Ocean, *Palaeogeogr. Palaeoclimatol.*, 204, 209–238, 2004.
- Thomas, H., Bozec, Y., de Baar, H. J. W., Elkalay, K., Frankignoulle, M., Schiettecatte, L.-S., Kattner, G., and Borges, A. V.: The carbon budget of the North Sea, *Biogeosciences*, 2, 87–96, doi.org/10.5194/bg-2-87-2005, 2005.
- 25 Thomsen, J., Stapp, L. S., Haynert, K., Schade, H., Danelli, M., Lannig, G. K., Wegner, M., and Melzner, F.: Naturally acidified habitat selects for ocean acidification-tolerant mussels, *Sci. Adv.*, 3, e1602411, doi:10.1126/sciadv.1602411, 2017.
- Trouet, V., Esper, J., Graham, N. E., Baker, A., Scourse, J. D., and Frank, D. C.: Persistent positive North Atlantic oscillation mode dominated the Medieval Climate Anomaly, *Science*, 324, 78–80, 2009.
- 30 Zillén, L., Conley, D. J., Andrén, T., Andrén, E., and Björck, S.: Past occurrences of hypoxia in the Baltic Sea and the role of climate variability, environmental change and human impact, *Earth-Sci. Rev.*, 91, 77–92, 2008.

Zorita, E. and Laine, A.: Dependence of salinity and oxygen concentrations in the Baltic Sea on large-scale atmospheric circulation, *Clim. Res.*, 14, 25–41, 2000.



## Tables

**Table 1: Information about the new chronology of core EMB046-20-3GC over the last ca. 1600 years.**

Identification	Core	Sample depth (cm)	Based on/ Dated material	<sup>14</sup> C date	ΔR	Calibrated age range ±1σ BP 1950	Rel. prob	Calendar age BP 1950 (med. prob.)	Cal a. CE Tie points used	References for individual dates
	EMB046-20-3GC	0	Year of coring					-63	2013	Polovodova Asteman et al., (2018)
	EMB046-20-3GC	25	Hg (μg/kg)					50	1900	Polovodova Asteman et al., (2018)
Poz-59813	EMB046-20-3GC	5.5	Mixed foraminifera	560±40	200±50	Post bomb				Polovodova Asteman et al., (2018)
ETH-88814	EMB046-20-3GC	30.5	Mixed foraminifera	755±50	200±50	101-273	1	178	1841	This study
Poz-68082	EMB046-20-3GC	61	Mixed foraminifera	840±40	200±50	232-398	1	287	1718	Polovodova Asteman et al., (2018)
ETH-87337	EMB046-20-3GC	85	Mixed foraminifera	1045±50	200±50	412-531	1	468	1538	This study
Poz-99621	EMB046-20-3GC	112	Mixed foraminifera	1220±30	200±50	549-641	1	596	1401	This study
Poz-68083	EMB046-20-3GC	141	Mixed foraminifera	1440±60	200±50	712-872	1	789	1238	Polovodova Asteman et al., (2018)
Poz-99622	EMB046-20-3GC	200	Mixed foraminifera	1835±30	200±50	1144-1264	1	1196	806	This study
Poz-99623	EMB046-20-3GC	274,5	Mixed foraminifera	2205±30	200±50	1504-1655	1	1570	295	This study

**Table 2:** List of dominant (**bold**) and accessory benthic foraminiferal species. The species names marked by “\*” represent foraminiferal species with relative abundance >5% in only one sample, thus were excluded from statistic classification.

Core EMB046/10-3GC
<b>Brizalina skagerrakensis</b> Qvale & Nigam, 1985
<i>Bulimina marginata</i> d'Orbigny, 1826
<b>Cassidulina laevigata</b> d'Orbigny, 1826
<i>Cassidulina neoteretis</i> Seidenkrantz, 1995
<b>Eggereloides medius</b> (Höglund, 1947)
<i>Epistominella sp. including E. exigua</i> (Brady, 1884) <i>E. vitrea</i> Parker, 1953
<i>Hyalinea balthica</i> (Schröter in Gmelin, 1791)
<i>Melonis barleeanus</i> (Williamson, 1858)
<b>Nonionella iridea</b> Heron-Allen & Earland, 1932
<b>Pullenia osloensis</b> Feyling-Hanssen, 1954
<b>Stainforthia fusiformis</b> (Williamson, 1848)
Core EMB046/20-4GC
* <i>Bolivina spathulata</i> (Williamson, 1858)
<b>Brizalina skagerrakensis</b> Qvale & Nigam, 1985
* <i>Bulimina elegantissima</i> d'Orbigny, 1839
* <i>Bulimina marginata</i> d'Orbigny, 1826
<b>Cassidulina laevigata</b> d'Orbigny, 1826
<i>Cassidulina neoteretis</i> Seidenkrantz, 1995
* <i>Cassidulina norcrossi</i> Cushman, 1933
<b>Eggereloides medius</b> (Höglund, 1947)
<i>Epistominella sp. including E. exigua</i> (Brady, 1884) <i>E. vitrea</i> Parker, 1953
<b>Hyalinea balthica</b> (Schröter in Gmelin, 1791)
<i>Melonis barleeanus</i> (Williamson, 1858)
<b>Nonionella iridea</b> Heron-Allen & Earland, 1932
<b>Pullenia osloensis</b> Feyling-Hanssen, 1954
<i>Recurvoides laevigata</i> Höglund, 1947
<b>Stainforthia fusiformis</b> (Williamson, 1848)
* <i>Triloculina tricarinata</i> d'Orbigny, 1826
* <i>Trochammina sp.</i> Parker & Jones, 1859

**Table 3:** The factor results from a CAB-FAC factor analyses.

EMB046/10-4GC		
Factors	Eigenvalue	Variance (%)
1	88.665	86.08
2	9.1984	8.93
3	1.8953	1.84

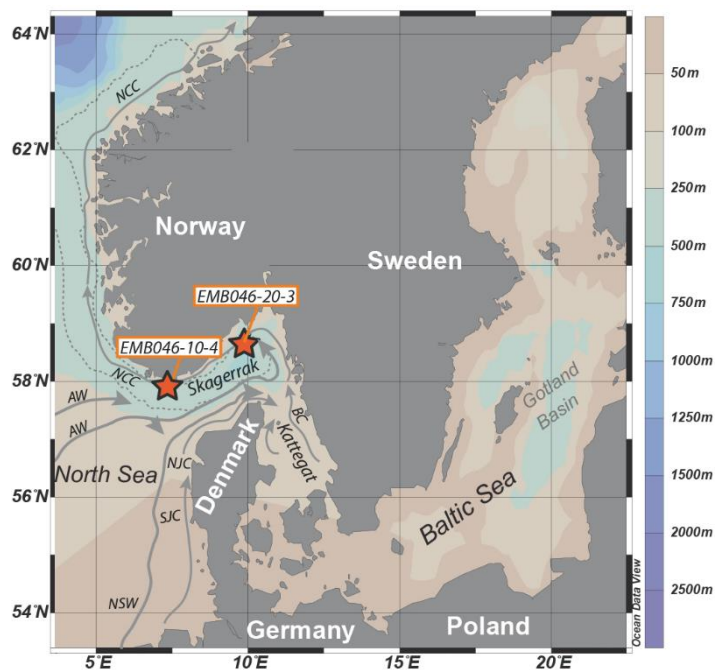
EMB046/20-3GC		
Factors	Eigenvalue	Variance (%)
1	45.2	80.72
2	6.4351	11.49
3	1.3995	2.5

**Table 4:** The varimax scores for factors 1 – 3. The bold numbers indicate foraminiferal species with absolute value of factor scores >1.

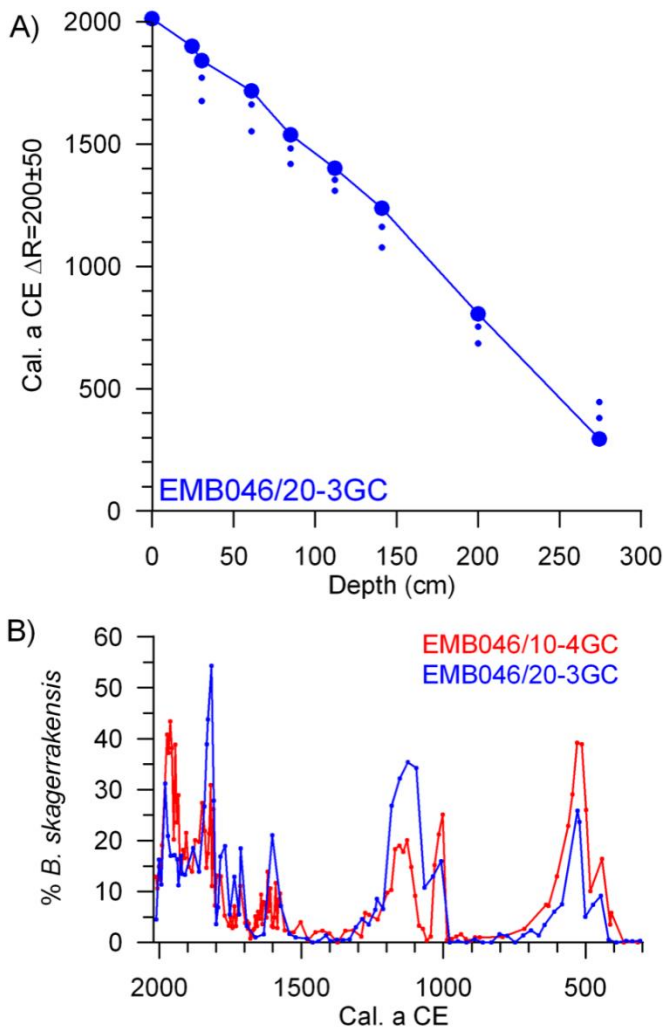
EMB046/10-4GC			
Foram. species	Factor 1	Factor 2	Factor 3
<i>B. skagerrakensis</i>	-0.95083	<b>3.1052</b>	0.11006
<i>B. marginata</i>	0.28721	0.29398	-0.18906
<i>C. laevigata</i>	<b>1.3438</b>	0.45052	<b>-1.234</b>
<i>C. neoteretis</i>	0.036824	0.15451	-0.01801
<i>E. medius</i>	0.13292	0.57788	0.48831
<i>Epistominella sp.</i>	0.18666	0.15052	0.2312
<i>H. baltica</i>	0.18637	0.35011	-0.25495
<i>M. barleeanus</i>	0.25854	0.14265	-0.13135
<i>N. iridea</i>	<b>1.0553</b>	0.25077	<b>1.8493</b>
<i>P. osloensis</i>	<b>2.4565</b>	0.68666	-0.91334
<i>S. fusiformis</i>	0.95088	0.10359	<b>2.191</b>

EMB046/20-3GC			
Foram. species	Factor 1	Factor 2	Factor 3
<i>B. skagerrakensis</i>	-0.81099	<b>3.1907</b>	-0.01581
<i>C. laevigata</i>	0.55287	0.27574	-0.19865
<i>C. neoteretis</i>	0.030673	0.23185	-0.11031
<i>E. medius</i>	0.38736	0.13685	-0.15638
<i>Epistominella sp.</i>	0.26935	0.1446	0.47431
<i>H. baltica</i>	0.31697	0.33722	0.73552
<i>M. barleeanus</i>	0.30047	0.062139	-0.09968
<i>N. iridea</i>	<b>1.8606</b>	0.35752	<b>2.357</b>
<i>P. osloensis</i>	<b>2.3155</b>	0.54091	<b>-2.0843</b>
<i>R. laevigatum</i>	0.202	0.007055	-0.31694
<i>S. fusiformis</i>	0.87063	0.33472	0.38467

## Figures

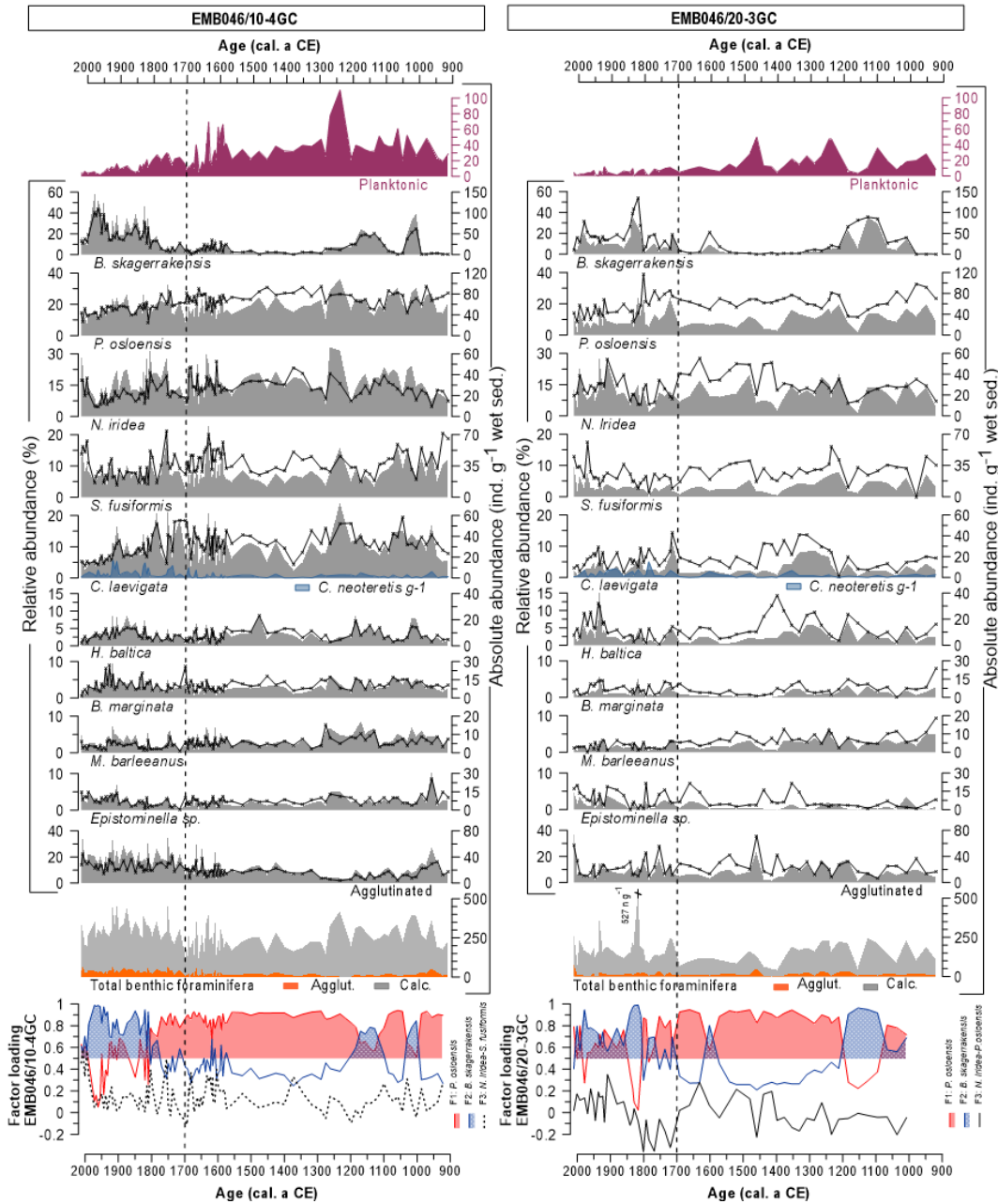


5 **Figure 1: Map of cores locations (stars) in the Skagerrak, the NE North Sea (modified from Polovodova Asteman et al. 2018). Norwegian Trench is outlined by a thin grey dotted line along the coast of Norway. Major current systems and water masses in Skagerrak are indicated by arrows: the Baltic Current (BC), Northern Jutland Current (NJC), Southern Jutland Current (SJC), Norwegian Coastal Current (NCC), North Sea Water (NSW) and Atlantic Water (AW).**



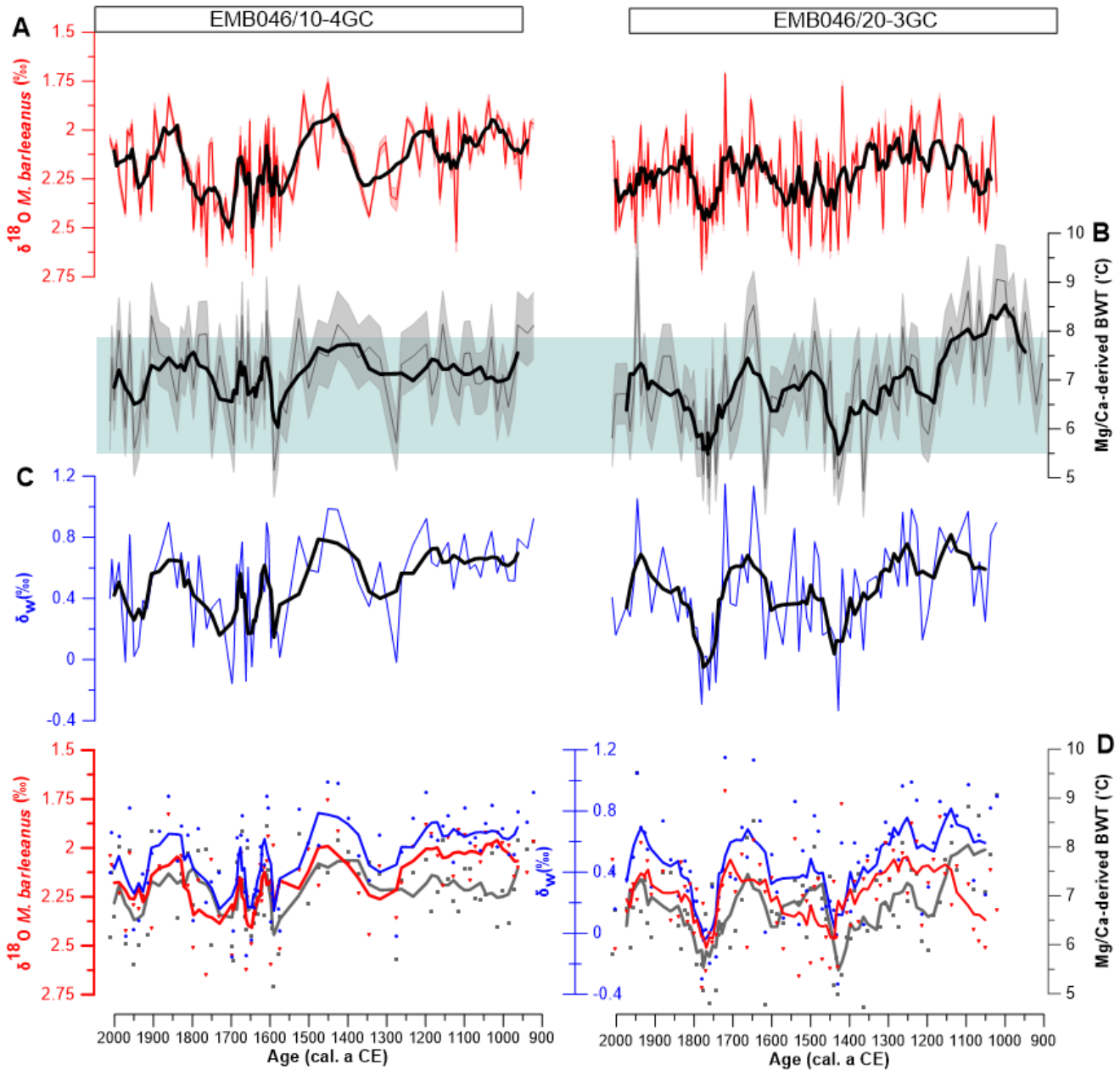
**Figure 2: (A) Linear interpolation between the established tie points for the EMB046/20-3GC age model. (B) The relationship between *B. skagerrakensis* of EMB046/10-4GC (red curve) and EMB046/20-3GC (blue curve).**

Fig. 3



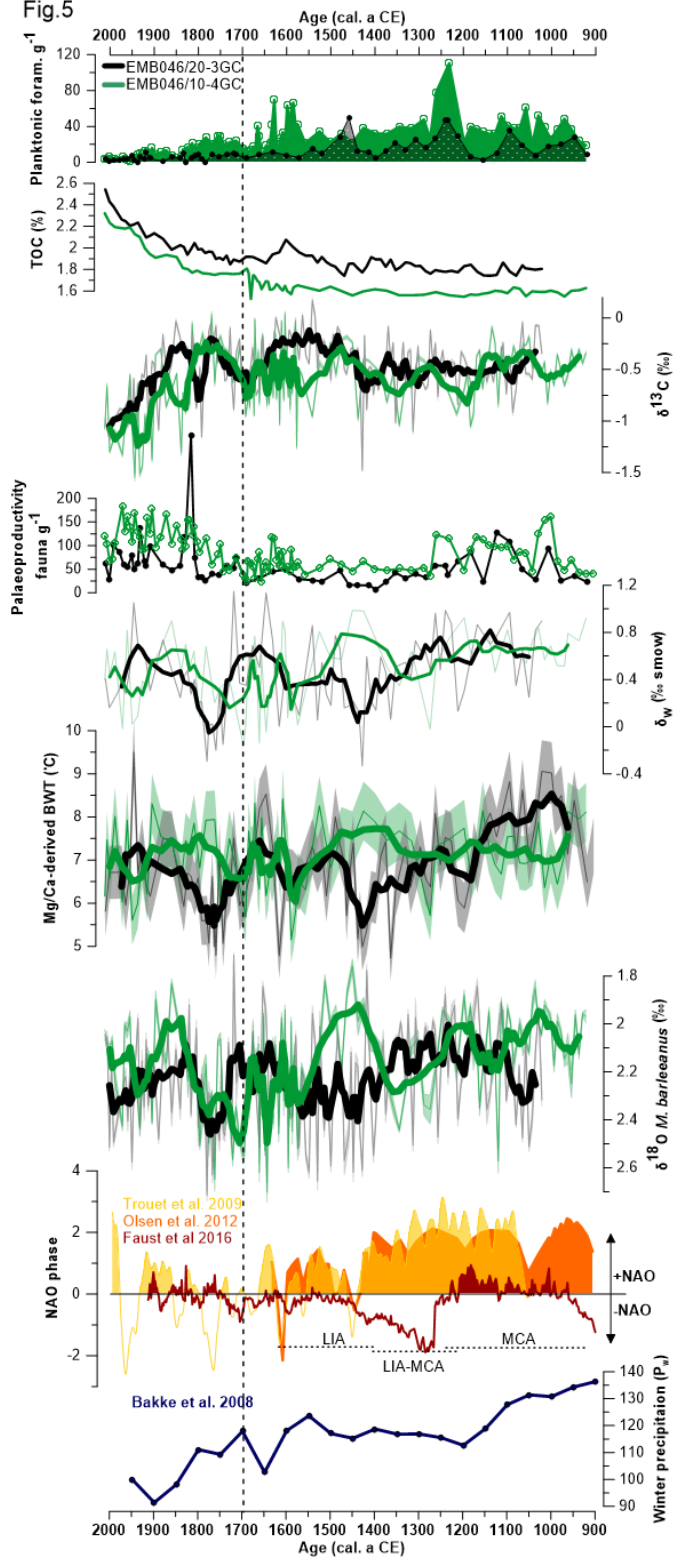
**Figure 3:** Foraminiferal assemblages including dominant and accessory benthic species for both cores (EMB046/10-4GC and EMB046/20-3GC) and CABFAC results. Absolute abundance is shown as grey filled, while relative abundance as black curve with symbols. The absolute abundance of total benthic foraminifera is a sum of all species: agglutinated (Agglut.) and calcareous (Calc.). Dashed line divides record into 2 periods of most pronounced palaeoproductivity changes, which are discussed in the text.

Fig. 4



**Figure 4:** (A) Oxygen stable isotopes ( $\delta^{18}\text{O}$ ); (B) the Mg/Ca-derived bottom water temperature (Mg/Ca-derived BWT); (C) the stable oxygen composition ( $\delta_w$ ), of both studied cores against age. The errors bands represent uncertainties of the records. (D) Figures include data from depths at which data of all proxies ( $\delta^{18}\text{O}$ , Mg/Ca-derived BWT,  $\delta_w$ ) are available (symbols). The curves correspond to 5-point running average. Light blue box indicates range of instrumentally recorded temperatures of the time period between 2009 and 1924 years from the area between  $57^{\circ}.17$ – $58^{\circ}\text{N}$  and  $8^{\circ}$ – $9^{\circ}.79'\text{E}$  at 300 – 340 dbar (ICES 2010).

Fig.5





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**Figure 5: Comparison of absolute abundances of planktonic foraminifera, total organic carbon (TOC), stable carbon isotope ( $\delta^{13}\text{C}$ ), absolute abundance of palaeoproductivity fauna, the CABFAC results, the stable oxygen composition ( $\delta\text{w}$ ), Mg/Ca-derived bottom water temperature (Mg/Ca-derived BWT), oxygen stable isotope ( $\delta^{18}\text{O}$ ) between two studied sediment cores EMB046/10-4GC (green curves) and EMB046/20-3GC (black curves). The reconstructions of the NAO index (yellow curve – Trouet et al (2009), orange curve – Olsen et al. (2012), red curve – Faust et al. (2016)) and the reconstruction of the winter precipitation (blue curve – Bakke et al. (2008)). The thicker curves correspond to 5-point running average. The errors bands represent uncertainties of the records. Dashed line divide record into 2 periods of most pronounced palaeoproductivity changes, which are discussed in the text.**