Manchester, January 6, 2019

Dear Professor Winguth,

We would like to thank you, Stijn de Schepper, and two anonymous reviewers for their feedback on our manuscript entitled "A new age model for the Pliocene of the Southern North Sea Basin: evidence for asynchronous shifts of marine and terrestrial climate" [cp-2019-39], and the opportunity to revise our manuscript.

The main comments from reviewer #2 related to the age tuning and placing our Hank record in a larger spatial context. Both reviewers #1 and #2 brought up the concern that the title of the manuscript did not seem to reflect the progression of the discussion and conclusion sections. Finally, both reviewers and Stijn de Schepper raised issues with statements involving the influence of the North Atlantic Current (NAC) on the North Sea that we inferred using the dinocyst species *Operculodinium centrocarpum*. As can be seen in our revised manuscript and the author responses that we submitted previously, we followed most of the suggestions by the reviewers to further improve the manuscript. In addition, we have merged sections 4 and 5 of the Discussion to better reflect the focus of the paper, and also to limit repetition of the results. The integrated changes in the manuscript are visible by track changes.

The most important changes are:

- We have edited the title of the manuscript to "A new age model for the Pliocene of the Southern North Sea Basin: a multi proxy climate reconstruction", and restructured the discussion sections to better reflect the focus of the paper. The restructured discussion section combines the old Sections 4 and 5, which also leads to less repetition in the revised manuscript. (comments from reviewers #1 and #2)
- We have added paleoenvironmental information from the neighboring Poederlee and Lillo formations in Belgium (Section 4.2). This also aids us in providing an age constraint for the mid-Pliocene Warm Period. (comment from Stijn de Schepper)
- More speculative language is used regarding the influence of the NAC on the North Sea. We also adjusted our interpretation of the species *Operculodinium centrocarpum* as evidence for the influence of the NAC in our setting, as this species may not hold the same link with the NAC in the Pliocene North Sea as it does in the Pliocene North Atlantic. (Stijn de Schepper comment)
- Updated the figures, specifically Figures 4 (now Fig. 3) and 5, which now show a depth scale, following the remarks of reviewers #1 and #2. We have also added supplementary figures (S1 and S3) to the supplementary section, which show detailed tuning (Fig. S1), and comparison of the UK37 record with those of Naafs et al. (2010) and Lawrence et al. (2009; Fig. S3) to accommodate the comment of reviewer #2.

We hope that you find the revised manuscript acceptable for publication in Climate of the Past.

On behalf of all co-authors,

Yours sincerely,

Emily Dearing Crampton-Flood

Reviewer #1 Response:

A well written paper which presents a multi-proxy based reconstruction of Pliocene marine sea surface temperatures and terrestrial climate of the Southern North Sea Basin. The core was taken in a marginal marine setting, and the interpretation particularly of the lipid biomarker proxy record is difficult as the signal is influenced by a multitude of marine and terrestrial factors. The authors are generally aware of the potential implications and the manuscript contains a thoughtful and careful discussion of the potential controls and limitations.

A: We thank Anonymous Reviewer #1 for their kind comments about the manuscript and the proceeding comments which will help us in improving the manuscript. We reply to specific comments below.

However, the authors final conclusion about marine and terrestrial climate evolution during the mid Piacenzian warm period (mPWP) and reorganization of the North Atlantic Current does not seem to be supported by data. I disagree with the statement that lipid biomarker and palynology-based temperature proxies suggest a stable warm climate during the mPWP. In fact, the lipid biomarker shows mean annual temperatures ranging from 7 to 12◦C during the mPWP (Fig. 6) and only between 3.17 Ma and 3.1 Ma a plateau. No conclusion on terrestrial climate variability during the mPWP can be drawn from the terrestrial pollen and spores as this 300 ka long interval is only covered by 4 samples.

A: Thank you for the comment. We agree with the reviewer that the proxy records indicate that the early part of the mPWP (>3200 ka) does not seem to have been very stable. However, this presumed instability may be an artefact of a disturbance in the record related to the recovery of the M2 or the M2 event itself (see discussion in response to Stijn de Schepper). Such a disturbance is also indicated by the coinciding peak in Osmunda pollen, which may indicate a sea level drawdown. In our discussion, we chose to focus on the period that we have been able to constrain with our new age model, and only covers a part of the mPWP, from ~3.18 Ma to ~3.0 Ma (black circles on Fig. 6), during which terrestrial climate appears stable. In the revised version of the manuscript, we will stress that the age tie-point represented by the red circle in Fig. 6 (~3.26 Ma) is based on biostratigraphy, and should therefore be interpreted with caution due to the large uncertainty associated with the last occurrence datum (LOD) of Melitasphaeridium choanophorum in the North Atlantic and the Nordic Seas, on which this point is based (see Dearing Crampton-Flood et al., 2018). Hence, we will also modify Fig. 6 to only shade the region that falls within the constraints of the updated age model based on $\delta^{18}O$ presented in this study. The proxy records that we discuss in Section 5 of the paper are associated with this shaded region on which we have the best age control.

Furthermore, based on this comment and the remarks of Stijn de Schepper we will review the possible influence of the North Atlantic Current on the study site from the discussion in the revised version of the manuscript, adding more speculative language.

TEX86, which has been interpreted as representing winter temperatures, shows relatively constant temperatures during the mPWP, while UK37 indicates very variable summer SSTs. However, the authors point out that the high values could in part be caused by freshwater algae that have little or no correlation with temperature. In fact, there are several indicators suggesting that at least some of the major changes in proxy values are controlled by the changing depositional environment and associated fluvial input. The statement of an overall "asynchronous shift of marine and terrestrial climate" indicating a reorganization of the NAC during the mPWP appears to be an unnecessary over-interpretation of the otherwise very interesting data.

A: Thank you. In light of the comments made by yourself, Stijn de Schepper and the second anonymous reviewer we will amend the title of the revised manuscript to: "A new age model for the Pliocene of the Southern North Sea Basin: a multi proxy climate reconstruction". As mentioned above, we will tone down the discussion in the manuscript that you and the other reviewers have identified as being too *speculative, e.g. the influence of the NAC on the study area. In the revised manuscript, we will add the possible influence of the NAC as a hypothetical reason for the observed variability in SSTs recorded by lipid biomarkers.*

Minor comments: Line 18 and 48: Be consistent with mPWP which is called in the abstract mid-Pliocene Warm Period and Introduction mid-Piacenzian Warm period. As the mPWP is part of the late Pliocene, the latter seems to be more appropriate.

A: We thank the reviewer for pointing out the inconsistency for the mPWP references. We will consistently refer to the mPWP as the mid-Piacenzian Warm Period in the revised manuscript.

Line 196: dinocysts and sporomorphs (or pollen and spores) were counted

A: Thank you, we will amend the sentence.

Line 260 ff.: Can the lipid biomarker method part be shortened?

A: We will shorten the specification and GDGT analysis method paragraph substantially, and will refer to Dearing Crampton-Flood et al. (2018; EPSL) for more details on the biomarker extraction methods and the GDGT analysis. The proceeding two paragraphs outlining the analysis of the long chain diols and alkenones have not yet been reported elsewhere and will be kept as is.

Line 327 and figures: “Heather” which represent the actual plants of the family Ericaceae is better than “heath” which normally means the entire heathland habitat.

A: Thank you for your suggestion, we will change the reference from ‘Heath’ to ‘Heather’ in the text and in Fig. 3G.

Line 329: The authors counted approximately 200 pollen and spores per sample and excluded the bisaccate taxa from the pollen sum. I am wondering how many angiosperm pollen are actually left? Please provide more details on the total pollen sum (e.g. in Fig S1) and the pollen sum which has been used to calculate non-bisaccate pollen percentages.

A: The pollen sum is not high, which is why we refrain from detailed paleoclimatological interpretations based on the pollen data. The main aim was to highlight the main quantitative trends, for which this pollen sum is adequate in a marine setting with no local vegetation variability. The pollen sum with and without bisaccates averages 250, and 60, respectively. The pollen sum includes all taxa except bisaccate conifers and Osmunda spores which were highly overrepresented in one sample. The caption of Figure S1 is incomplete, and we will adapt this. The two summary panels on the right side of the full diagram (Fig. S1) show both sums, the multi-colored panel excludes bisaccate conifers and is the primary percentage sum, and the grey shaded panel shows the bisaccate pollen as percent of the total terrestrial palynomorphs (the sum including all conifers and Osmunda). This way the abundances of all taxa can be compared without being affected by the potential transportation bias of bisaccate pollen. We will expand the caption of Figure S1 to clarify.

Line 513: Fig. 4d should be 3d

A: We assume there was a typo and the reviewer is referring to Line 413. Thank you, we will amend this.

Line 425: Why do the authors refer to Donders et al, 2007? The palynological results from the Hank borehole seem to suggest the opposite in indicating the continuous presence of warm-temperate taxa (Fig. S1). Please discuss.

A: In Donders et al. (2007), the majority of warm temperate taxa listed are shown to disappear at the Pliocene/Pleistocene transition. However, in these upland sites, the variable deltaic/fluviatile Pliocene deposits and incomplete preservation caused a hiatus of the uppermost Pliocene and lowermost Pleistocene deposits. The Hank site, however, is located in a shallow marine basin with a broader catchment and a regionally integrated signal, with a relatively more complete and reliable stratigraphy. However, the Hank site is not in contradiction to the land-based study where the earliest Pleistocene is probably not completely preserved and the last occurrences of warm-temperate taxa seem more abrupt (Donders et al., 2007). The clearest indication for this are the very low values of Taxodium-type pollen toward the top (Fig. S1). Tiglian deposits from the Netherlands, approximately dated to 2.0 Ma (Zagwijn, 1992; Quat. Sci. Rev.), still contain abundant Pterocarya, but only trace quantities of Taxodium-type and Carya (possibly reworked), and no Nyssa. From sequences in the central North Sea (Donders et al., 2018; Climate of the Past), it became clear that the earliest Pleistocene glacial-interglacials (MIS 102-92) do no longer contain Taxodium, Nyssa, or Carya, however this area receives sediment from southern Scandinavia (Eridanos), rather than the Rhine catchment. In summary, warm-temperate taxa disappeared in the earliest Pleistocene but not all at the same time, and most likely slightly above the level of the top of the Hank sequence, although warm-temperate taxa are clearly in decline as is seen in Fig. S1. We will rephrase the statement to clarify this point and add an additional reference.

Line 605 and Fig. S1: The acme of Osmunda coincides with a decline of almost all other taxa in the pollen diagram. The authors state that Osmunda has been excluded from the pollen sum, and I am struggling to see which other taxa increased. They do not seem to sum up to 100% at ca. 306 m.

A: This is explained in the point above on the pollen sum and caused by the incomplete description in the caption of Fig. S1. Osmunda increases and bisaccate taxa decline. At the same time (within the non-bisaccate total), Ericaceae, Alnus, and other fern spores increase relative to especially Taxodium-type.

Fig.2 and Fig 3: Rephrase in figure captions “The intervals corresponding to A, B C depth discussed in the text are indicated” and provide keys to colours (e.g. marine/deltaic etc).

A: We will amend the figure captions of Figs. 2 and 3 to read: ‘Intervals 1, 2 and 3 discussed in the text are indicated by green (Early Pliocene), grey (mid-Pliocene), and purple (late Pliocene-early Pleistocene).’

Fig 4. Provide proper depth scale instead of arrow.

A: We will provide a depth scale in Fig. 4.

Fig. 6 Add depth scale to age scale to allow better comparison across figures.

A: We have attempted to add a depth scale to Fig. 6, however as the sedimentation rate is not continuous in this interval (Fig. 5e), we believe that adding a depth scale would create unnecessary confusion to the reader by making the figure too ‘busy’. Instead, we will include the depth interval of the period covered by the tuning of oxygen isotopes to the LR04 stack (Fig. 5) to the figure caption.

Reviewer #2 Response:

Interesting data are presented, however, the manuscript needs major revision. It is not clear what the data actually tell us, and why. One major issue is that it is not clear what the authors actually want to present. The tittle suggest that the main aim of the paper is to present a new age model and the introduction is mainly written with a focus on the need for a new age model. Secondly, the title hints at an asynchronous relation between marine and terrestrial climate. Even though both marine and terrestrial data is presented I do not see a focus on an asynchronous relation reflected in the paper. The authors need to figure out if the aim is to present an age model paper or a climate paper, and structure the paper accordingly.

A: We thank the reviewer for their compliments on our dataset, and constructive comments on the manuscript. We appreciate their concern about what the data is telling us and why, and we add that this is quite a challenging dataset to interpret. The main focus of the paper, as you have determined from the first part of our title, is to present an age model for the Pliocene of the North Sea Basin. We have identified the need to construct an age model, which is missing from this region for the Pliocene, in order to place a variety of new and existing proxy records into context (e.g. L113-117). We agree that the discussion based on the asynchronous shifts of marine and terrestrial climate is not at the focus of the paper, and comes as part of a more speculative section near the end in section 5. Therefore, based on your comment and that of reviewer #1, we will amend the title of the paper to: "A new age model for the Pliocene of the Southern North Sea Basin: a multi proxy climate reconstruction", and adjust the focus of the discussion and conclusions accordingly.

The discussion needs to be transferred from providing statements to become a discussion. What do your results show? How can they be explained/what can they tell? Why? What is the suggested mechanism? What is the argumentation for why that possible mechanism is most likely – and for others being less likely? When stating relations to other records, why don't you show some those records as well so that it can be evaluated?

A: We are a bit confused by this comment, as we feel that we are doing this in sections 4 and 5. Section 4.1 discusses the logic and reasoning behind the age control that we present in Fig. 5, and involves the results from the palynology records, the seismic profile, the foraminifera isotopes, and the gamma ray logs ('What do the results show?', and 'How can they be explained?', and 'What is the mechanism?'). This discussion subsequently leads us to identifying the best interval suited for tuning to the LR04 benthic stack. Subsequently, section 4.2 presents a discussion on the potential confounding factors on the sea surface temperature (SST) records generated by the different lipid biomarkers, how the records should be interpreted, and why (i.e. explanation, comparison, mechanisms). We then use section 5 to discuss and interpret our multi-proxy climate records in the constrained age domain, and to place them in a global context (comparison and mechanisms). With regards to showing other records mentioned in the discussion section, see the specific reply to the comment below. Nevertheless, we will carefully read the discussion again and further clarify our lines of reasoning where possible in the revised manuscript.

The figure that presents the basis for the new age control is impossible to evaluate and needs to be redone. I would prefer to have the datasets correlated to each other shown underneath each other in the same direction so that the relations between the ups and downs of the two records are immediately visible. I would also like to see how the two records (LR04 and yours) match after correlation, showing both records towards age.

A: We feel like the gamma ray log and lithostratigraphic log on the figure are good additions for the reader to place the oxygen isotope record of Hank into context, since the foraminiferal isotopic *composition in such a shallow marine succession is dependent on other factors, such as depositional environment and hiatuses (see discussion in section 4.1). The lithostratigraphy and the gamma ray log can both give insight into these important processes (e.g. sharp inflections on the gamma ray log may indicate a hiatus). Similarly, the backdrop of the biostratigraphic age tying points is also useful to evaluate the oxygen isotope-based age model with the initial one presented in Dearing Crampton-Flood et al. (2018). Therefore, we feel that Fig. 5 warrants the addition of more information than just the age-tying points and the two oxygen isotope records. That being said, our revised evaluation of the periods where we suspect that ice volume changes may not play a big role (see discussion response to 'Do you use the d13C data at all?' below) will cause us to re-evaluate the tuning that we present in Fig. 5.*

We will add a figure with the LR04 stack and the Hank oxygen isotope record on the same x-axis (age) to the supplementary information (Fig. S2) of our revised manuscript.

Some of the figures present a lot of data in a small format. Check font sizes and make sure they are readable.

A: We apologize if the labels in the figures are difficult to read. We will assess and optimize the font size of all figures where appropriate (Figs. 3 and 5 in particular).

Do you use the d13C data at all?

A: The δ^{13}C and δ^{18}O records give an indication about possible ice volume influences, given that the trends in δ^{18}O and δ^{13}C mirror each other (deep ocean concept). This is exemplified in the record of Noorbergen et al. (2015), who observed mirroring trends in the shallow marine Quaternary sequence from Noordwijk. When the trends between the δ^{18}O and δ^{13}C records do not mirror each other, the ice volume signal is less dominant due to other factors which overrule the signal such as freshwater influence, reworking, and diagenetic influences (the latter assumed to be minimal because only well-preserved foraminifera were picked). Therefore, including the δ^{13}C record and comparing to the δ^{18}O record will aid in demonstrating where ice volume signal is recorded in the Hank record and when it is not. We will include a sentence of where the two isotope records mirror each other in the results section (section 3.1) of the revised manuscript. Further, we will include a summary of this response into the discussion section of the paper in order to improve the evidence/statements/discussion that lead to the targeting of the tuned interval and therefore the creation of the final age model.

Comments that emerged while reading the manuscript:

L23: ....costal zones, linking the costal and continental climate evolution, are lacking.

A: Thank you for the suggestion, we will make the suggested change.

L30: ... stable oxygen isotopes...

A: We will make the suggested change.

L57: Fewer and less well constrained temperature records exist for the terrestrial realm (Zagwijn, 1992; Salzmann et al., 2013), however, they all indicate that climate was warmer than present. Why do you consider them to be less well constrained? Should be specified – because of age control? Because of other issues?

A: The temperature records presented by Zagwijn (1992) and compiled by Salzmann et al. (2013) are derived from pollen assemblages. Pollen based temperature estimates are generally less constrained *than that of e.g. SST reconstructions, as i) they present a temperature range rather than an absolute temperature estimate (Coope, 1970, Ann. Rev. Ent.; Mosbrugger and Utescher, 1997, Palaeogeo. Palaeoclima., Palaeoeco.), ii) they can be skewed toward growing season (Guiot, 1990, Palaeogeo. Palaeoclima., Palaeoeco.) and, iii) if based on terrestrial sediment sequences, can suffer from poor age control, as terrestrial outcrops are more difficult to date than marine sediment sequences. We will add this brief explanation to the appropriate section (introduction) in the revised manuscript.*

L106: I would be more careful than to say that the infaunal species are unaffected. They can trace large scale climate inflicted changes equally well as epifaunal species, e.g. detect brine signals during glacial times (e.g. Dokken et al., 2013). Furthermore, you discuss a potential fresh water influence later on, so some inconsistence here.

A: We thank the reviewer for noticing this inconsistency. We will modify the sentence in the revised manuscript to read: "The depth habitat of endobenthic foraminifera in the sediment provides a moderate degree of shelter from disturbances such as reworking by bottom currents and freshwater input". This revised sentence provides a more accurate view of the role that the endobenthic foraminifera play in climate reconstructions.

L118: What is relative land cover?

A: We use the term relative land cover to describe the prevailing vegetation cover on the nearby continent during the time of deposition. We change this into 'prevailing vegetation' in the revised version of our manuscript.

L134: Your site is very close to the coast and I would expect much lower water depths than in the central basin. Do you have any idea about what the water depth was at your site? In such a shallow setting the water depth have implications for how to interpret your records.

A: According to the height of the clinoform as observed in the seismic profile (Fig. 4), the water depth in the interval ~300–200 m is approximately 80–100 m. The clinoform stacking suggests a continuous westward progradation of the coastal system, such that this location became progressively infilled by sediment. Note that this estimate does not refer to the downdrop which we associate with the (possible) M2 event or recovery thereof. We will add a few words to the end of the sentence to remind the reader that the Hank site in the Southern North Sea Basin is expected to have water depths lower than that predicted for the central basin. Later in the results and the discussion section where the seismic section is introduced and described we will specify the estimated water depth for the Upper Oosterhout formation (80–100 m).

L145: Why is it an advantage that you get a smoothed record?

A: The advantage of this method of core collection is that the 1 m resolution leads to smoothed records compared to the relatively expansive total record (404 m for the Hank Core). The possible disturbances generated from the dynamic environmental setting of the Hank site at this time will be smoothed, which makes it easier to reveal the more regional climate signal (albeit in lower resolution).

L177: Did you rerun any of the samples you consider to be outliers? What is the argumentation for this choice for removing data point? It seems a bit arbitrary. What will the record look like if you include all measurements? What seems to be outliers can very well be true values if it just looks like the values don't belong.

A: We realize that since the $\delta^{18}O$ values of foraminifera recorded at the Hank site may not necessarily be attributed to ice volume signal alone, a different approach should be taken to identify outliers, given that freshwater input and reworking may affect the $\delta^{18}O$ signal (see reply to earlier comment). Unfortunately, we did not rerun the samples we considered to be outliers. This hampers the interpretation of the record, especially in light of the extremely high and low $\delta^{18}O$ values recorded (grey triangles in Fig. 2). Thus, we will remove the method of identification of outliers from section 2.2 in the manuscript, and update section 3.1 with revised values (ranges etc.) including the whole record. This will also involve replotting the $\delta^{18}O$ data in Fig. 2, and Fig. 5 by extension.

The tuning for the age model is not expected to change largely because the majority of the tuned interval (296–206 m) does not contain that many outliers compared to the rest of the record (grey vs. black data points in Fig. 2). The tie points that are used particularly in the depth interval ~270–240 m will not change, particularly as this is the depth interval where a mirroring trend is seen between the $\delta^{18}O$ and the $\delta^{13}C$ records (see earlier response).

L250: What about C37:4 as a fresh water indicator? Do you see similar changes there? I see that you state later that no C37:4 is present. Implications? Why do you see changes in one of your freshwater indicators but not in all?

A: As we mentioned in L558-561 we did not detect the presence of the $C_{37:4}$ alkenone in our samples. The absence of $C_{37:4}$ in the mid-Pliocene (300–200 m) part of the interval does seem to fit with the other environmental indicators such as (i) low terrestrial/marine (T/M ratios), (ii) low BIT index values, and (iii) the presence of marine biomarkers such as Crenarchaeol and long chain diols (Figs. 2, 3). However, it is perhaps surprising that no $C_{37:4}$ was detected in the interval '3' (Fig. 2), which corresponds to the late Pliocene/early Pleistocene, as the palynological data indicate a high T/M ratio and the presence of freshwater and brackish water algae species (L310-313). However, transect studies rom surface sediments in the Baltic Sea indicate that the percentage abundance of the tetraunsaturated $C_{37:4}$ alkenone only appears higher (>15 %) at salinities around 8 psu and below (Bornholm Basin; Schulz et al., 2000; GCA; Kaiser et al., Org. Geochem.). Therefore, we interpret that the salinity change that affected the Hank Site as a result of a gradual change to a more estuarine environment did not change the salinity significantly enough to lower it below 8 psu. On the other hand, a very speculative reason behind this could be the affinity for the alkenone-producing organisms to the type of estuarine environment that the Hank site progressively became over the Plio-Pleistocene transition. However, until more is known about the specific organisms that produce these lipids, not much more can be said at this time.

L255: extracted and processed for what?

A: We will change this sentence into: 'lipid biomarkers were previously extracted from the sediments (n=155) and separated into polarity fractions according to …'

L283: What/why was it challenging?

A: The low abundance of foraminifera in the crag material made it challenging to pick in that interval. We will add this explanation to the revised manuscript.

L290: Here you state a variability of approximately 1‰ while based on the information above (L285 and onwards) its closer to 2.6‰ (or 0.9 to 1.8‰ if you selectively look at specific transitions). And why would you expect the d13c variability (in amplitude) to match the d18O variability?

A: We apologize for the confusion and will remove the reference to $\delta^{18}O$ variability in L292-293, as the estimate in L286-287 is the more accurate representation of $\delta^{18}O$ variability in this record. However, in *light of including all the $\delta^{18}O$ values measured (as discussed above), the reported variability in the manuscript will change. Secondly, as far as we are concerned, we did not phrase the sentence to suggest that we expect the amplitude of $\delta^{13}C$ variability to match the $\delta^{18}O$ variability. We will rephrase this sentence as: 'Discounting the sample at 206 m, the variability in the $\delta^{13}C_{cass.}$ record is approximately ~1 ‰ (Fig. 2d).'*

Line 336: Lipid biomarkers and proxies. Why do you include "and proxies" here? The isotopes, palynology and biomarkers are all proxies.

A: We apologize for the confusion, the 'proxies' we refer to here refer to the specific proxies that are based on lipid biomarkers. We understand your confusion and will rename the section to read: 'Lipid biomarkers'.

L347: This is a very large range. Given your choice regarding "outliers" for the oxygen isotope record, why do you keep the biomarker results as measured? Supports the feeling I get that the removal of some isotope measurements are done a bit randomly– even though you have a set way of defining which points you removed.

A: Thank you for the comment. We agree that the Uk37 range we have calculated throughout the core is very large. We indeed mention the large range of reconstructed SSTs based on Uk37 in L347-353, L564-575, and L651-671, where we also compare the data with other SST records based on Uk37 in the North Atlantic, which also show a large range in SSTs. This is in contrast to the $\delta^{18}O$ data, for which the range of variation is not reported elsewhere. We feel it is appropriate to plot the samples considered 'outliers' in the record so the reader can judge for themselves. This is why we have initially plotted those $\delta^{18}O$ outliers in grey in Fig. 2c in our discussion paper, and also why we will include all $\delta^{18}O$ measurements in our record in Fig. 2 and 5 in the revised manuscript.

L355: selected

A: We will not follow this suggestion as we believe this to be the correct usage of the term 'select' in this context.

L374: Why do you get a stronger terrestrial influence towards the Pleistocene? Increased glacial erosion?

A: The stronger terrestrial influence towards the Pleistocene at this site is most likely a result of sea level drawdown caused by the increasing volume of ice build-up in the northern hemisphere. The Hank site is a shallow marine succession which borders on the area between river/delta deposits and marine sands (Fig. 1 in manuscript), thus the progradation of the Rhine-Meuse River during this time would have brought more terrestrial material to the Hank site and contributed to the changing depositional environment during the transition into the cooler Pleistocene.

Line 411: MAT. Is this short for mean annual temperature? Not mentioned before, needs to be defined. Since you refer to your 1018 paper I assume the record is published and the method is described there, however, I am still curious about how certain you are regarding the absolute values presented given that your record includes extinct species, e.g. Sciatopitys? You refer to several other terrestrial profiles – can these be shown for comparison? If they lack age control, can you really link them to your record/state that it is the same?

A: MAT is indeed short for mean annual temperature, which we will specify in our revised manuscript. The MAT record has been published in Dearing Crampton-Flood (2018) and is based on temperature-

sensitive membrane lipids of soil bacteria (branched GDGTs), which, in principle, yield absolute temperature estimates. A thorough discussion on the reliability of the absolute MAT values can be found in the same paper. Note that we have not reconstructed temperature using pollen distributions. We also note that species Sciatopitys is considered a relict taxon as it is not yet extinct (occurs in Japan). For a discussion regarding the age correlation between terrestrial profiles, see the discussion in the author responses to reviewer #1.

L438: M2 is very pronounced in some records, but there are also several sites where its less pronounced, making it an enigmatic period with large uncertainties related to the magnitude of the "glacial" event. Risebrobakken et al., 2016 consider the possibility of a hiatus as an explanation for the lack of the most extreme signature but also that it might have been a less extreme event than expected from e.g. LR04.

A: We have indeed considered whether the M2 event is a less extreme event than in some of the other areas of the world. However, there are many papers dealing with the stratigraphy of the North Sea that suggest a hiatus during MIS M2, particularly in the southern North Sea Basin (De Schepper et al., 2009, Geol. Mag.; Louwye et al., 2010, Geol. Mag.). See also the comment that Stijn de Schepper posted in the discussion. We also consider the occurrence of a hiatus during M2 at the Coralline Crag formation which is close to the Hank site (Fig. 1, manuscript), to explain the sequence boundary in the seismic profile at Hank. The position of this boundary indicates that the hiatus covers most of the M2 at the Hank site. We will expand the discussion in the revised manuscript to include the evidence for a hiatus over the M2 event in the adjacent sites in England and Belgium to support our interpretation. We will also add that Risebrobakken et al. (2016) considered that the M2 may have been a less extreme event in this region compared to other regions in the world where it is more pronounced, to provide the reader with a more nuanced view on the evidence for these different hypotheses on the M2 event in this region.

Line 443: I cannot see that the North Sea is mentioned specifically in Miller et al., 2011? Overall, estimates of sea level change during M2 varies tremendously in literature. This should be acknowledged. Also take into account the findings of Raymo et al., 2018 where they conclude that for the Pliocene, geochemical sea level proxies currently carry uncertainties too large to allow any meaningful ice volume (hence sea level estimates).

A: We apologize for the confusion; we will remove the specific reference to the North Sea in this sentence. We agree that the estimates for sea level change in the literature that correspond to the M2 event vary greatly. We also thank the reviewer for directing our attention to Raymo et al. (2018), and we will modify the sentence to read: 'There is evidence for a large global sea level drawdown (estimates of 70 m; Miller et al., 2011) during the M2, however large uncertainties in the estimation of ice volume prohibit any meaningful estimates of sea level for the Pliocene using the stable isotope measurements of foraminifera (Raymo et al., 2018).' However, the estimation of water depth at the Hank site is based on the seismic profile, and is approximately 80–100 m (see reply to earlier comment). Other estimates indicate that Pliocene sea level in the North Sea Basin was approximately 60–100 m (Overeem et al., 2001; Basin Res.), which agrees with our interpretation. These estimates however do not provide any insight into the sea level drawdown before that, associated with the possible M2 event or recovery of (corresponding to the sequence boundary in Fig. 4). We will include all relevant discussion on this point and references into the revised manuscript.

LL461-472: You should not forget that your data is from a very shallow site and hence cannot be expected to reflect the same absolute values as the intermediate and deep water records from Risebrobakken and LR04. How do you physically transfer the suggested freshwater signal from the rivers to the bottom of the North Sea? A river signal will be much less dense than a marine water mass and lay as a fresh lid on top of the denser water mass. This is one example of where knowledge of the paleo depth of your site is key to be able to make trustworthy interpretations of your data.

A: We appreciate the comment and we agree that the absolute $\delta^{18}O$ values cannot be expected to be comparable to those of other records from cores recovered from deeper depths in the open ocean. We also consider the study of Noorbergen et al. (2015), who constructed a Quaternary age model from a similarly shallow succession in the North Sea, and found that the absolute $\delta^{18}O$ values of a composite $\delta^{18}O$ record of Bulimina aculeata, Cassidulina laevigata, Cibicides lobatulus, and Elphidiella hannai, were comparable to the LR04 stack. Hence, we tried to adopt the same approach to anticipate the influence of freshwater input by only picking endobenthic foraminifera in the Hank sediments (cf. Noorbergen et al., 2015). Hank is located relatively closer to the mouth of the paleo Rhine, and thus is likely associated with a shallower water depth (see response to previous comment for paleodepth interpretation of 80–100 m), which we believe is reflected in the large range of $\delta^{18}O$ values, and thus likely also the offset compared to the LR04 stack. We will add the paleodepth interpretation to the revised manuscript. With regards to the transport of fresher water to lower depths in the North Sea, we note that the North Sea is a high energy system where wave action and winnowing contribute to the mixing of freshwater input in the relatively shallow water column (Charnock et al., Understanding the North Sea System, Springer Science and Business Media). We will include this explanation in the revised manuscript.

L479: The difference in amplitude of change between the global deep water stack and your shallow regional/costal site does not prove that the area is more sensitive to climate disturbances. Furthermore, what do you mean by climate disturbances? This is an empty term. This section is also an example of statements without discussion. You should check this throughout and make sure that your discussion is a discussion and not just statements. Discuss your results, potential explanations, reasons for why one or the other potential explanation is more or less likely, and in the end conclude on what you find to be the most likely solution and why. The mechanisms are important. E.g. how do you physically make the fresh water reach the bottom of the North Sea in order to explain light benthic isotope values by fresh water influence.

A: The larger amplitudes ($\Delta\ \delta^{18}O > 2.5$ ‰) observed in the Hank record are not the result of a dominant single climate factor such as ice volume. This is in contrast to case in deep ocean settings. At the Hank site, freshwater influence is more likely to lead to the large observed amplitude in $\delta^{18}O$. We will therefore adjust all language referring to 'climate disturbances' in the revised manuscript, and include the interpretation of the large amplitude as a result of periods where the Hank site was particularly sensitive to freshwater input, probably deriving from the proto Rhine-Meuse system. A literature search shows that similar observed amplitudes and associated low benthic and planktic $\delta^{18}O$ values were recorded in marine sediments from the Ionian Sea, and were interpreted as freshwater influence that coincided with sapropel deposition (Schmiedl et al., 1998; Paleoceanography). We will inspect the discussion section carefully and include a more thorough discussion into this perceived freshwater input, with appropriate evidence and references. Further, the interpreted paleodepth (80–100 m) during the mPWP period (~300–200 m) will be added to the revised manuscript which leads to a better supported discussion on why the Hank site was sensitive to fresh water input, due to its shallow nature.

L496: When you say that you tune the warmer periods, what exactly do you mean by that? I would never use the maxima or minima as tuning point between records, but rather go for transitions, since the character of the records you tune is bound to be different.

A: We realise that we have not followed the method that is mostly used for age model constructions, however, the coastal location of the Hank site requires a slightly different approach, as is outlined in the manuscript (section 4.1). The combination of a relatively weak influence of the Atlantic and the potential occurrence of hiatuses during cooler phases, which could also include (part of the) transitions, has led us to use the warmer periods for tuning. Warmer periods in the record are identified as the maxima in the $\delta^{18}O$ record (Pliocene interglacials: G17, G15, K1 etc. on LR04 stack). Furthermore, see the discussion above on the sampling resolution (1 m) of the Hank borehole, which may preclude the capture of any true inflection point or transition in the $\delta^{18}O$ record.

As discussed above, we will identify the intervals of the record with opposing or mirroring trends in $\delta^{18}O$ and $\delta^{13}C$ and only use those for tuning the warm intervals to. This will lead to changes the discussion section and Fig. 5. We will therefore include this discussion, and a revised and updated form of Figure 5 in the manuscript.

L505-513: From figure 5 it is impossible to evaluate the correlation between LR04 and your record and hence the basis for your age model. This figure needs to be improved. One suggestion would be to show the record so that you read them in the same way. Another thing I would require to see is a direct comparison the two isotope records vs age, following your new tuning of the record.

A: As promised in our reply to an earlier comment, we will include a figure in the supplement that shows the correlation between the LR04 and the $\delta^{18}O$ record from Hank, on (A) separate depth/age scales and on (B) the same age scale (Fig. S2).

L527-528: I would expect that a dominance of deeper dwelling organisms influencing the GDGT data will provide colder temperatures than what you will expect for the surface, even if the water depth is shallow. At what depth is the thermocline located at the site today, annually and during summer? If it's a winter signal as you argue, what is the difference between your values and the present winter temperatures (looks to be around6 C according to WOA18)? Or even better, can you compare your temperature datasets to present day measurements from the same proxy in the same site/closeby? Same for alkenones (L543) and LDI?

A: The modern thermocline depth near the Hank site is ~30 m (Richardson and Pedersen, 1998; ICES J. Mar. Sci.). In winter the water column is more isothermal and in summer is more stratified (Richardson and Pedersen, 1998), so it is difficult to pinpoint what the integrated signal throughout the year would be. Nevertheless, water column and sediment trap studies indicate that the TEX86 signal in the sediments reflects that of the subsurface, i.e. 50–300 m, consistent with their role as ammonia oxidizing archaea (Church et al., 2010, Environ. Microbiol.; Schouten et al., 2012, GCA). GDGT-producing Thaumarchaeota also occur in deeper water layers (>300 m), however, they occur in lower abundances, and a clear mechanism that can explain their transport to the sediment is lacking (Wuchter et al., 2005; Paleoceanography). Given the shallow water column of the Pliocene North Sea, the influence of deep(er) dwelling organisms can be ignored. Regardless, a potential contribution of deeper dwelling organisms can be recognized by a high (>5) ratio of GDGT-2/GDGT-3 (Tyler et al., 2013; Glob. Planet. Change), which we calculate for our data and discuss on L529-535 of the discussion manuscript.

Present day TEX86 SST reconstructions for the North Sea range between 4.1 – 9.1°C using the TEX86H calibration of Kim et al. (2010; GCA). These reconstructed SSTs correspond to observed SSTs of 10.3 – 11.3 °C (WOA18). Therefore, core stop sediments in the North Sea are likely to underestimate the true SST; however, this statement may only be partly accurate insofar as the error on the proxy is ~2.5 °C (Kim et al., 2010). The Pliocene data from Hank hovers around ~9–12 ºC for most of the record, which is in agreement or slightly higher than present day reconstructed SSTs using the same calibration. If it is interpreted as a winter signal as we argue, then the Hank Pliocene SSTs are approximately 3–6 ºC higher than modern (van Aken, 2008; J. Sea Res.), which is in agreement with the data present in the manuscript in section 4.2.

Present day UK37 SST reconstructions for the North Sea: No suitable sites were found in the compilation of Tierney and Tingley (2018) of Uk37 recorded in surface sediments. The North Sea is a relatively underrepresented area in the UK37 calibration. However, reconstructed SSTs using alkenones from surface sediments from the Skagerrak region near the opening to the Baltic Sea record SSTs of 10–12 ºC, approximately 1–2 ºC higher than observed annual SST, and resemble those of May-June SST more (Blanz et al., 2005; GCA). Thus there is evidence for Uk37 recording summer temperatures (coinciding with bloom periods of haptophytes) in the circum-area North Sea.

Unfortunately, the core top calibration for the LDI SST proxy does not include core tops from the North Sea region. Therefore, we cannot compare our record to present day estimates of North Sea SSTs using the LDI proxy. This is due to the fact that the LDI is a relatively new proxy (Rampen et al., 2012; GCA), so it is not yet widely applied, especially not in combination with TEX86 and the Uk37. Indeed, the dataset presented in this manuscript is among the first paleo multi-proxy application studies of this proxy.

We will include a version of this discussion and comparisons of proxy-derived SSTs to modern SSTs in the revised version of the manuscript.

L540: Can you show a comparison towards some of these other records? All of these would relate to bottom water temperatures at your site–again, even if it is shallow there will be a clear difference between the top surface and the bottom water, especially if there is any seasonal biases. What does the temperature profiles look like today?

A: The temperature estimates of Wood et al (1993), Kuhlmann et al (2006), Johnson et al (2009) and Williams et al (2009) are not records of temperature over the whole of the Pliocene or mPWP intervals, but rather represent 'snapshots' of temperatures within these intervals. Thus it is not possible to plot our SST records and their reconstructed temperatures to directly compare SST evolution. However, it is possible to annotate Figures 2 and/or 6 in order to show the reconstructed temperatures based on these references in order to compare absolute values of temperatures reconstructed using the various proxies for approximately the same time interval. We will annotate Figure 6 to include annotations to the reconstructed temperatures of Wood et al (1993), Kuhlmann et al (2006), Johnson et al (2009) and Williams et al (2009), or a select few of the temperature estimates.

L550: Okhotsk and Rhode Island are quite different settings from your site. Are there any more local relevant studies to take into account?

A: We assume that by 'relevant' the reviewer means closer to the study site. In the revised manuscript, we will discuss the study of Blanz et al. (2005; GCA), who determined Uk37 values in a transect from the North Sea to the Baltic Sea and determined that for the Baltic Sea proper, there was no relationship between the alkenone UK37 indices with SST, whereas only the samples from Skagerrak plotted within 1 C of the global calibration of Müller et al. (1998; GCA). We will therefore add this discussion to section 4.2 in addition to these two sites.

L624: What is the present ocean circulation regime of the area? Should be presented in the introduction part of the paper. How large a fraction of the NAC enters the North Sea through the English Channel relative to north of Great Britain? Given the Pliocene geography of the area how different do you expect the circulation regime to have been?

A: The ocean circulation regime of the North Sea Basin today is dominated by wind-driven processes. The prevailing westerly winds on the north-west European shelf lead to a cyclonic anti-clockwise circulation, with the main input of water into the North Sea being from the north (Sündermann 2003; Oceanologia). We will add this information into the introduction of the paper. In the modern system, the modelled transport estimates from the HYCOM model indicate that the mean English Channel inflow is only 0.16 Sv (1 Sv = 10^6 m^3/s) versus the total mean inflow at the northern boundary of 2.22 Sv (Winther and Johannessen, 2006; J. Geophys. Res.: Oceans). In addition, the English Channel inflow varies intraannually, being weaker in winter and stronger in summer (Winther and Johannessen, 2006), meaning that the English Channel does not represent an important input of Atlantic water into the North Sea in the modern day. Given that the English Channel may or may not have been totally established in the Pliocene (Funnel, 1996; Quat. Sci. Rev.), and more than certainly closed during the M2 event, the NAC inflow would have originated entirely from the northern boundary *during the Pliocene. See also discussion in the author response to the comment posted by Stijn de Schepper. Scant evidence for a Pliocene connection of the North Sea to the North Atlantic via the English Channel is observed in the Pliocene-age Coralline Crag fauna and flora, which indicate planktonic elements, as well as bryozoan-dominated deposits that bear resemblance to modern deposits (Funnel, 1996). We will include a brief discussion on this observed evidence for and against a Pliocene connection from the North Sea to North Atlantic via English Channel in the revised manuscript.*

L639: Why? How? The full section here where you link the Zagwijn data to your data without showing them and without really making it clear if you can or cannot do this seems speculative to me.

A: We tentatively correlate the Zagwijn Taxodium-type curve to our MAT record in the text, however since the Pliocene stages defined by Zagwijn are probably incomplete (as we state), we cannot be 100% definite in our correlation. A more solid conclusion that we do make in the revised manuscript is the match between the stratigraphy concept of Zagwijn and the Hank data. We will include a brief description and discussion on this in the revised manuscript.

L652/L656: Can the variability be linked to the colder and warmer isotope stages? Does your variability compare to the changes seen in these other records?

A: We will explore the possibility that the variability in the SST biomarker records may be related to colder and warmer isotope stages in the global stack and in the local oxygen isotope record at Hank.

L661: The variability discussed by Bachem et al., 2017 and linked to gateway changes in not related to mPWP.

A: Thank you for clarification. We will remove the reference to Bachem et al. (2017) in this instance.

L663: The freshwater influence suggested for Clotten et al. 2018 cannot be used as direct support for fresh water influence at your site.

A: We understand the reviewer's point, however L661-663 outline a possible reason that Clotten et al. (2018) determined as a contributor for the high variability in their Uk37 SST record in Iceland. We did not mean to translate their explanation as evidence for sea ice-derived fresh water influence at our site in the North Sea. To clarify, we will modify the sentence to read: 'The high variability of $U^{K'}_{37}$ *SSTs at the Hank Site during the Pliocene is most likely due to a combination of factors, including the shallow depth of the SNSB, potential changes in the direction and strength of the NAC, and varying freshwater influence.'*

L684-687: What is the argumentation and reasoning behind this statement? It is not clear how you support this conclusion.

A: See comments and author response to Stijn de Schepper, and our response to earlier comments on the possible influence of the NAC. We have decided to re-evaluate the statements we make regarding the influence of the NAC in the North Sea Basin as a result of these comments. We will revise this sentence in the revised manuscript and make the potential influence of the NAC on our site more tentative. It will read: 'Regardless, the high variability and warming trend in two out of the three organic SST proxies in the Pliocene North Sea indicate that the area was very sensitive to environmental changes, of which the specific climatic drivers remain unclear.'

L703: If this is the case you should show it. All the records you refer to are available online and can be plotted together with your data to document this statement. I would also like to see this relative to LR04 and your own d18O record, with the individual isotope stages visualized.

A: We will endeavour to obtain the SST data in order to plot a comparison of the variability of the records of Naafs et al. (2010), Bachem et al. (2017), and Lawrence et al., (2009), with our SST Uk37 record from the Hank site in order to show the similar variability in SSTs over the Pliocene. We will follow the suggestion to make a figure with the SST Uk37 record from Hank relative to the LR04 and the d18O record from Hank with the individual isotope stages visualized.

Stijn de Schepper Response:

A comment to MIS M2 in the southern North Sea Basin: A hiatus in sedimentation during MIS M2 was already suggested in papers that deal with the stratigraphy of the southern North Sea Basin. Studies by Head (1998), De Schepper et al. (2009, Geological Magazine) and Louwye et al. (2004, 2010, Geological Magazine) place the Belgian (Kattendijk, Lillo, Poederlee Fm) and English (Coralline Crag, Red Crag) Pliocene formations into one coherent stratigraphy. In De Schepper et al. (2009) and Louwye et al. (2010), MIS M2 is identified as a sequence boundary, de facto a hiatus, in the southern North Sea Basin. These papers have not been taken into account, but would mostly support the conclusions here. See also the stratigraphic summary of De Schepper and Mangerud (2018, Norwegian Journal of Geology, Figure 7), which compares the northern North Sea Utsira Formation with Pliocene deposits in Iceland, England and Belgium.

A: We thank Stijn de Schepper for the suggestions of the literature to be taken into consideration when discussing the MIS M2 in the revised manuscript. We will incorporate references to the relevant publications in the revised manuscript, particularly with reference to the base of the Poederlee Formation in Belgium which correlates with a sequence boundary Pia1 at approximately 3.21 Ma (De Schepper et al., 2009; Louwye et al., 2010; Geological Mag.). We agree that this would strengthen the interpretation of a hiatus taking place at the Hank site over the dramatic interval of MIS M2. We will add the appropriate references to the reference list.

For L440: Rather than comparing with the Norwegian Sea record, it would be more relevant to compare here with records from the southern North Sea Basin (England, Belgium).

A: Thank you for the comment. We agree that comparing the discussion in section 4.1.2 with records more adjacent to the Hank site in England and Belgium is a good idea, and will adjust our discussion in the revised manuscript accordingly.

A comment to the mPWP in the southern North Sea Basin: The Poederlee and Lillo Formation correspond to the interval 3.2–2.7 Ma. The paleoenvironmental information from those formations (De Schepper et al. 2009; Louwye et al. (2010) would be a valuable addition to the interpretations from the Hank core and be a major step forward towards a comprehensive summary of the climate and environmental evolution of the North Sea Basin during the mPWP and Late Pliocene.

A: We agree with Dr. de Schepper that a more detailed comparison of the environmental conditions during deposition of the Poederlee and Lillo formations in Belgium to the records in the Hank core would be a valuable addition to the paper. We will therefore incorporate and discuss the paleoenvironmental interpretations that are proposed in the above two manuscripts into the discussion of our revised manuscript and figures where appropriate.

A comment to the influence of the NAC in the North Sea: The influence of the NAC in the Hank record is not convincing. Observing comparable SST variability is no proof for a causal relation (L40, L655 onwards). The common factor between the North Atlantic and the North Sea may be via the atmosphere (i.e. NAO). Note that while the SST variability in the eastern North Atlantic and Norwegian Sea correspond to the NAC (Naafs, Bachem, Lawrence), the cited SST variability in the

Iceland Sea is related to the EGC (Clotten et al. 2018) (L655–659). Furthermore, most water from the North Atlantic flows into the North Sea Basin from the north. But in the manuscript, it is claimed that the NAC has a direct influence on the southern North Sea Basin through the shallow connection in the south (Channel/Dover) (L622-624). While an open connection after MIS M2 is possible, it remains speculative. Certainly because the presence of O. centrocarpum (sensu Wall and Dale 1966) in the Hank core is considered as evidence for the NAC influence in the North Sea. This does not have to be the case, and most likely it is not - this is a cosmopolitan species. It is true that in the modern North Atlantic, O centrocarpum sensu Wall and Dale (1966) (aka. cysts of Protoceratium reticulatum) can be considered as good indicator for the NAC (e.g. Harland et al. 2016 in Helyon and refs therein). It has been used as an indicator for the NAC in the Pliocene eastern North Atlantic, in the region where the NAC flows (e.g. De Schepper et al. 2009 Paleoceanography, 2013 PLoS One, Hennissen et al. 2014 Paleoceanography). But today, when the Channel is open, it is not a common species in the North Sea (Marret et al. 2003 RPP, Zonneveld et al. 2013 RPP). Given that O centrocarpum (sensu Wall and Dale 1966) is foremost a cosmopolitan species, tolerant to wide range of SST, SSS, nutrients, etc., its occurrence in the North Sea may not be a simple function of North Atlantic water inflow.

A: Thanks for the constructive comment, insight, and relevant literature concerning the presence of O centrocarpum (sensu Wall and Dale, 1966) and its modern and Pliocene occurrences. We refer to the author response to reviewer #2 who raised a similar concern, and also questions whether the influence of the NAC can be recorded in the North Sea using O. centrocarpum. We agree that there is scarce evidence for an open channel from the North Sea to the Atlantic via the English Channel, and that based on the evidence presented here by Stijn de Schepper, there may be little evidence to connect the trends in O. centrocarpum in the Hank record with influence of the NAC. Therefore, we will rewrite the discussion that links the occurrence of O. centrocarpum to the NAC in the revised version, making sure to refer to key literature and explain the reasons why using this strategy may be problematic in this North Sea setting.

Regarding the high SST variability observed in the Hank record, we believe that the similarities between the high variability recorded at the Hank site and other nearby records should be mentioned in the discussion, and the possible causes for high variability in the other records be outlined. However, as the link between the NAC and SST variability is too speculative and cannot be fully constrained, we will be more cautious in section 5.2 of the revised manuscript with regards to attributing the SST variability at the Hank site to any one specific factor, such as influence of the NAC.

Minor comments L127, L621: It is not impossible, but it remains speculation whether a connection was established after MIS M2. The connection was likely only temporarily opened during the Pliocene when SL was high (e.g. see more recent papers by Van Vliet-Lanoë et al. 2002; Gibbard and Lewin 2016, Geologica Belgica).

A: Thanks for this addition and references. We will definitely consider this in the revised version, and add more recent references when referring to the circulation and openings in the North Sea during the Pliocene.

L317–318: Barssidinium is not the best example for a (sub)tropical taxon, as it occurs in Iceland in the Pleistocene (e.g. Verhoeven et al. 2011, Paleo-3).

A: We will remove the reference to '(sub)tropical' in the sentence. We will also add the following sentence afterwards: '(Sub)tropical species like Lingulodinium machaerophorum, Operculodinium israelianum, Spiniferites mirabilis, Tectatodinium pellitum and Tuberculodinium vancampoae are missing at this depth.'.

L625–630: O. centrocarpum (sensu Wall and Dale 1966) is foremost a cosmopolitan species recorded from different environments and tolerant to wide range of SST, SSS, nutrients, etc. Its occurrence in the North Sea shelf environment is thus not necessarily evidence for NAC influence.

A: As per our reply to the major comment raised above, we will rewrite the discussion to tentatively connect the presence and trends in O. centrocarpum in the Hank record to the strength of the NAC in the revised manuscript. We do see an interesting feature in the O. centrocarpum record insofar as a large abundance (~40 %) that occurs at 305 m, directly after the high abundance of Osmunda spores and % Cold Dinocysts at 306 m. We interpret this increase in O centrocarpum as a possible restoration of (mostly) marine conditions at the Hank site after sea level drawdown which we interpret at 306 m. This period also correlated with low mean annual air temperatures (~ 6 °C), and decreased abundance of Taxodium-type pollen species (Fig. 6). We are not sure how best to interpret this, the best possible explanation we have at this stage is to connect the high abundance of O centrocarpum with the inflow of Atlantic Water when sea levels rose after the M2 event. We believe that the revised manuscript could benefit from some discussion on this observed feature in Section 5, we will make sure to refer to literature presented here about O centrocarpum in order to provide a more tentative and speculative explanation of this link.

L629: Boessenkool et al. (2001) studied surface sediments offshore SE Greenland. The study does not provide evidence for a relationship between O.centrocarpum and the NAC. Please use more appropriate references.

A: We will remove the references that tie the presence of O. centrocarpum to the NAC (see above) in the revised manuscript, thus the reference of Boessenkool et al. (2001) will also be deleted (and removed from the reference list).

A new age model for the Pliocene of the Southern North Sea Basin: ~~evidence for asynchronous shifts of marine and terrestrial climate~~ a multi proxy climate reconstruction

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Abstract

The mid-~~Pliocene~~ Piacenzian Warm Period (mPWP, 32~~5~~64–3025 ka) represents the most recent interval in Earth's history where atmospheric CO_2 levels were similar to today. The reconstruction of sea surface temperatures (SSTs) and climate modelling studies have shown that global temperatures were 2–4 °C warmer than present. However, detailed reconstructions of marginal seas and/or coastal zones, ~~that enable~~ linking the coastal and continental climate evolution, ~~climate evolution in the marine realm to that on the continents~~ are lacking. This is in part due to the absence of precise age models for coastal sedimentary successions~~zones~~, as they are generally formed by dynamic depositional systems with varying sediment and fresh-water inputs. Here, we present a multi-proxy record of Pliocene climate change in the coastal Southern North Sea Basin (SNSB) based on the sedimentary record from borehole Hank, the Netherlands. The marginal marine setting of the Hank borehole during the late Pliocene provides an excellent opportunity to correlate marine and terrestrial signals, due to continental sediment input mainly derived from the proto-Rhine-Meuse river. We improve the existing low-resolution palynology-based age model for the Hank borehole using stable oxygen and carbon ~~stable~~ isotope ~~measurements~~ (δ^{18}O and δ^{13}C) measurements of the endobenthic foraminifera species *Cassidulina laevigata*, integrated with biochrono- and seismostratigraphy. Identification of hiatuses and freshwater effects in the record allows us to ~~accurately~~ isolate glacial-interglacial climate signals to tune the~~. that can be linked to a reference global benthic δ^{18}O stack. In tandem with the biostratigraphic age control~~ ~~the~~ endobenthic oxygen stable isotope record ~~can be tuned~~ to a ~~reference~~ global benthic δ^{18}O stack. T~~t~~his results in a tuned~~n~~ age framework for the SNSB for the Late Pliocene (~31~~2~~9~~0~~0–27~~8~~7~~0~~0 ka). Our multi-proxy climate reconstruction for the ~~tuned mPWP~~ interval which covers part of the mPWP (~3190–3000 ka)~~mPWP~~ shows a strong agreement between lipid biomarker and palynology-based terrestrial temperature proxies, which suggest a stable climate, 1–2 °C warmer than present. In the marine realm, however, biomarker-based SSTs show a large range of variation (10 °C). Nevertheless, the fluctuation is comparable to other SST records from the North Atlantic and Nordic Seas, suggesting that a common factor, possibly ocean circulation, ~~, most likely variations in the North Atlantic Current,~~ exerted a strong influence over SSTs in the North Atlantic and the North Sea at this time.

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1. Introduction

The Pliocene epoch (5.33–2.6 Ma) is a frequently targeted interval for palaeoenvironmental reconstructions because it is considered an analogue for future climate change. For example, atmospheric CO_2 concentrations (380–420 ppmv; Seki et al., 2010; Zhang et al., 2013) and continental configurations during the Pliocene were largely similar to present. Detailed proxy and model comparisons for the so-called mid-Piacenzian Warm Period (mPWP, 32~~5~~64–3025 ka) have been the focus of the Pliocene Research, Interpretation and Synoptic Mapping (PRISM) group (Dowsett et al., 2010, 2013), and reveal that global temperatures were on average 2–4 °C warmer than present (Haywood et al., 2013). This makes the mPWP an excellent interval to investigate a warmer world associated with the scenarios for our (near) future summarized by the Intergovernmental Panel on Climate Change (IPCC, 2014).

Our understanding of Pliocene climate is largely based on sea surface temperature (SST) reconstructions (e.g. Dowsett et al., 2012), which indicate that global SSTs were 2–6 °C warmer than present. ~~Only a~~Relatively fewer temperature records exist for the terrestrial realm

(Zagwijn, 1992; Salzmann et al., 2013).~~,~~ These records also ~~which also~~ indicate climate was warmer than present, ~~but~~ however, these temperatures are less well constrained due to potential confounding influence of humidity on the temperature reconstructions (Guiot, 1990), and the poorer age control on terrestrial sediment sequences. There are even fewer studies that examine the phase relations and amplitude of variability in coupled land-sea changes (e.g. Kuhlmann et al., 2006), although this information is of key interest for understanding heat transport and the hydrological cycle during the Pliocene. Sediments on continental shelves receive inputs from both the terrestrial and marine environment, and would thus contain an archive of land-sea climate evolution. The North Sea Basin shelf is a site that potentially hosts a combined record of SST evolution and climate change in the North Western (NW) European continent during the Pliocene due to input of terrestrial material by large European rivers and the active subsidence that provides sediment accumulation space (Gibbard, 1988). Moreover, significant warming of its waters since the second half of the 20th century (0.6 °C rise on average in the period 1962–2001; Perry et al., 2005) indicates the sensitivity of the area for recording climate change. The region has been a type area for Pliocene and early Pleistocene terrestrial stages (see overview in Zagwijn, 1992), but most studied sections lack absolute dating and land-sea correlation as they target ~~deltaic deposits~~fragmentary fluvial successions (Donders et al., 2007; Kemna and Westerhoff, 2007). However, the shallow marine deposits of the Southern North Sea Basin (SNSB) allow better chronostratigraphy building through integrated palaeomagnetic, isotope, and biostratigraphic approaches (e.g. Kuhlmann et al., 2006; Noorbergen et al., 2015; Donders et al., 2018).

Despite the promising preconditions that should enable Pliocene climate reconstruction using the sedimentary archive of the SNSB, the generation of an independently calibrated age model for coastal zone sediments is often complicated by complex interactions between sea level, sediment supply, and biotic factors (e.g. Krantz, 1991; Jacobs, 2008; Noorbergen et al., 2015; Donders et al., 2018), which may alter sedimentation rates or cause hiatuses resulting from periods with erosion or non-deposition. Indeed, the Pliocene SNSB was a dynamic system in which multiple westward advances of the Eridanos and Rhine-Meuse Rivers generated clinoform successions (Jansen et al., 2004; Kuhlmann and Wong, 2008; Harding, 2015)~~,~~. ~~and t~~The sedimentary record thus needs to be critically evaluated on its stratigraphic continuity before it can be compared with records from adjacent areas, such as the Nordic Seas and the North Atlantic. Munsterman (2016) reported a Pliocene-age sequence of coastal marine sediments from Hank, located in the South West of the Netherlands. The current age framework for the sequence is based on first (FODs) and last occurrence dates (LODs) of dinoflagellate cysts (Dearing Crampton-Flood et al., 2018). Due to the lack of an independent age constraint in the SNSB, FODs and LODs were inferred from those in the Nordic Seas and the North Atlantic, introducing an unknown range of age uncertainty to the biostratigraphic age model (Dearing Crampton-Flood et al., 2018). Furthermore, the resolution of the age model is too low (9 biostratigraphic age tie points for the interval ~ 4.5–2.5 Ma) to identify possible hiatuses or changes in deposition, preventing comparison of the record to other archives from the Northern Hemisphere.

The established method for age model construction involves measuring the stable oxygen isotope content ($\delta^{18}O$) of foraminiferal tests and matching the variability to a global benthic $\delta^{18}O$ reference stack, such as LR04 (Lisiecki and Raymo, 2005). However, in ~~more~~ coastal settings this method is complicated due to isotopically lighter fresh~~-~~water input, which alters the $\delta^{18}O$ value of the foraminiferal tests (Delaygue et al., 2001; Lubinski et al., 2001). Recently, Noorbergen et al. (2015) were successful in creating a tuned age model for the early Quaternary shallow marine interval of borehole Noordwijk, also located in the SNSB, using the $\delta^{18}O$ and $\delta^{13}C$ values of ~~particularly~~ the endobenthic foraminifera (*Bulimina aculeata*, *Cassidulina laevigata*, and *Elphidiella hannai*). The depth habitat of endobenthic foraminifera in the sediment provides a moderate degree of ~~s~~shelter~~s~~ ~~these species~~ from disturbances~~,~~ such as reworking by bottom currents and freshwater input. Although vital and microhabitat effects still influenced the absolute $\delta^{18}O$ values of these foraminifera and caused an offset towards more positive values, the trends in $\delta^{18}O$ at Noordwijk clearly resembled those of LR04 (Lisiecki and Raymo, 2005; Noorbergen et al., 2015).

In this study, we follow the approach of Noorbergen et al. (2015) and ~~use~~ establish $\delta^{18}O$ and $\delta^{13}C$ records~~values~~ measured from~~of~~ the endobenthic foraminifera *Cassidulina laevigata* in the Hank borehole to improve the current low-resolution biostratigraphic age model (Dearing Crampton-Flood et al., 2018) for the Pliocene SNSB~~ of Dearing Crampton-Flood et al. (2018)~~. Reconstruction of the age model is further supported by the identification of hiatuses based on seismic information and gamma ray logging. Subsequently, we complement the existing mean annual temperature (MAT) ~~terrestrial air temperature~~ record for Pliocene NW Europe based on soil bacterial membrane lipid distributions stored in the Hank sediments (~~from~~ Dearing Crampton-Flood et al., 2018), with multi-proxy records of SST, prevailing ~~relative land cover~~vegetation, and terrestrial input based on lipid biomarker proxies, pollen, and dinoflagellate cysts. This enables us to for the first time directly compare marine and terrestrial climate evolution of the SNSB and continental NW Europe during the mid-Piacenzian Warm Period.

2. Methods

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2.1 Geological setting and study site

The Pliocene North Sea was confined by several landmasses, except towards the North, where it opened into the Atlantic (Ziegler, 1990). At times, there may have also been a connection via the English Channel to the North Atlantic, ~~evidence of which is based on~~indicated by planktonic elements and bryozoan-dominated deposits ~~that bear resemblance to modern deposits observed~~ in the Pliocene Coralline Crag formation in Eastern England (Fig. 1; Funnel, 1996) that bear resemblance to modern deposits. However, the connection of the North Sea to North Atlantic via the English Channel ~~remains speculative~~may only have existed during periods of high sea level (Gibbard and Lewin, 2016). –Modern modelled transport estimates from the Hybrid Coordinate Ocean Model (HYCOM) indicate that the total mean inflow at the northern boundary is approximately 14 times higher than that of the English Channel (Winther and Johannessen, 2006). Thus, water inflow/outflow through ~~from~~ the English Channel was probably limited, regardless of whether there was an opening to the North Atlantic or not. ~~does not represent an important input of Atlantic water into the North Sea in the Pliocene.~~ In addition to a main marine water supply via the North Atlantic, the Eridanos River, draining the Fennoscandian shield, and the proto-Rhine-Meuse River, draining North Western Europe delivered freshwater to the North Sea in the Pliocene (Fig. 1). The proto-Rhine-Meuse river system existed for a large part of the Pliocene, initially draining the Rhenish Massif and ~~finally~~later making a connection with the Alps in the latest Pliocene (Boenigk, 2002). During the Pliocene, the sediment supply by the Eridanos River system to the Ruhr Valley Rift system was limited, such that the Rhine-Meuse river system was the predominant supplier of sediments in the study area (Westerhoff, 2009). The water depth of the North Sea during the Pliocene and the Pleistocene was approximately 100~~–~~–300 m in the central part of the basin (Donders et al., 2018), and approximately 60–100 m in the southern North Sea Basin (Overeem et al., 2001). ~~Modern circulation in the North Sea is dominated by wind-driven processes, which leads to a cyclonic anti-clockwise circulation.~~ ~~In addition to a main marine water supply via the North Atlantic, the Eridanos River, draining the Fennoscandian shield, and the Rhine-Meuse River, draining North Western Europe delivered freshwater to the North Sea (Fig. 1). The proto-Rhine-~~

~~Meuse river system existed for a large part of the Pliocene, although it did not drain the Alps until the latest Pliocene (Boenigk, 2002). During the Pliocene, the sediment supply by the Eridanos River system to the southern area of the SNSB was limited, such that the Rhine-Meuse river system was the predominant source of sediments in the Roer Valley Rift system (Westerhoff, 2009). The water depth of the North Sea during the Pliocene and the Pleistocene was approximately 100 – 300 m in the central part of the basin (Donders et al., 2018)~~

~~.~~

The study site (51°43′N, 4°55′E) is located within the current Rhine-Meuse-Scheldt delta in the municipality of Hank, the Netherlands. The Hank site is located within the R~~o~~uh~~e~~r Valley Rift: a region that experienced relatively high tectonic subsidence during the late Cenozoic (Van Balen et al., 2000). The current drainage area of the Rhine-Meuse-Scheldt river system is 221,000 km^2, however it was likely smaller in the Pliocene (van den Brink et al., 1993; Boenigk, 2002). In 2001, ~~A~~air-lifting well technology was used to drill the Hank borehole (B44E0146) to a base of 404 m~~ in 2001~~. Intervals were drilled every 1 m, such that each sample taken from the meter intervals is an integrated mixture. ~~One advantage of this drilling technique is that it leads to smoothed records. ~~The gamma ray log of the borehole is readily accessible from an online database (dinoloket.nl). In addition, a seismic section is available and covers an east-west transect of the River Meuse (Maas2002 survey, nlog.nl). The lithology of the Hank borehole (Fig. 2a) is described by the Geological Survey of the Netherlands (TNO) and Dearing Crampton-Flood et al. (2018). In short, the base of the succession corresponds to the upper part of the shallow marine Breda Formation, followed by the sandy, occasionally silty and clay-rich marine delta front deposits sometimes containing shell fragments, or so-called ‘crags’, belonging to the Oosterhout Formation. The overlying Maassluis Formation contains silty shell bearing deltaic to estuarine deposits. For this study, the interval 404–136 m was considered, covering ~4.5–~~ to ~~~2.5 Myr based on the biostratigraphic age model of Dearing Crampton-Flood et al. (2018).

2.2 Stable isotopes

Deep sea δ^{18}O and δ^{13}C records generally oscillate in anti-phase during the Quaternary, due to the waxing and waning of large ice caps on the Northern Hemisphere (e.g. Ruddiman, 2001). During glacial periods, benthic foraminifera incorporate relatively more δ^{18}O in their calcite test, since more ^{16}O has been stored in the ice sheets and bottom water temperatures are cold. At the same time, they also incorporate more ^{12}C because the total amount of vegetation on land has been reduced during glacial periods causing an enrichment of the dissolved inorganic carbon (DIC) pool of the oceans. Besides, a reduced thermohaline circulation (THC) during glacial periods may have reduced the contribution of ^{12}C-depleted North Atlantic Deep Water to the deep ocean with respect to the ^{12}C-enriched Antarctic Bottom Water component. Hence, for the intervals that the trends in $\delta^{18}O$ and $\delta^{13}C$ records of the Hank borehole move in anti-phase, we interpreted these changes as being the result of glacial-interglacial variability. However, when the $\delta^{18}O$ and $\delta^{13}C$ are not inversely related, i.e. show a positive correlation, other factors such as riverine freshwater inflow, reworking, and diagenetic influences were most likely the dominant control.

Sediment samples (n = 269) from the interval ~~between~~ 404 – ~~and~~ 136 m were washed and passed over a series of sieves, after which the >125 µm and >63 µm fractions were collected and dried at 40 °C. Well preserved (i.e. shiny tests) foraminifera of the endobenthic species *Cassidulina laevigata* ~~(i.e. shiny tests)~~ of around the same size were picked from the >125 µm fraction. Due to the scarcity of foraminifera in some samples, tests were left uncrushed in order to conserve enough material for isotope analysis. The foraminifera were washed ultrasonically in water before weighing.~~,~~ B~~and b~~etween 10 and 60 µg of intact tests were weighed per sample. The $\delta^{18}O$ and $\delta^{13}C$ values were measured on a Thermo Gas Bench II (Thermofisher Scientific) connected to a Delta V mass spectrometer. An in-house NAXOS standard and an internationally accepted NBS-19 standard ($\delta^{18}O = -2.20‰$, $\delta^{13}C = 1.95‰$) were used to calibrate measured isotope ratios to the Vienna Pee Dee Belemnite (VPDB) standard. ~~Oxygen isotope ratios were calculated according to the following equation (replacing $\delta^{18}O$ by $\delta^{13}C$ for the calculation of carbon isotope ratios):~~

~~$\delta^{18}O = \frac{\delta^{18}O_s - \delta^{18}O_{standard}}{\delta^{18}O_{standard}} * 1000‰$ (1)~~

~~Where:~~

- ~~$\delta^{18}O$ resembled the eventual data (in ‰) used for comparison with the benthic oxygen isotope stack (Lisiecki and Raymo; 2005).~~
- ~~$\delta^{18}O_s$ was the isotope value of the sample measured by the mass spectrometer.~~

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~~$\delta^{18}O_{standard}$ was the isotope value measured on the standard.~~

~~Outliers were identified when measurements exceeded the range of the upper and lower boundaries of the standard deviation added to and subtracted from a 7 point moving average of the isotope record. Since the isotope analysis is coupled, the corresponding value of $\delta^{18}O$ or $\delta^{13}C$ was removed if either value was identified as an outlier.~~

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2.3 Palynology

Organic-walled dinoflagellates that form a cyst during their life cycle are referred to as dinocysts, and they are preserved in sediments (Head, 1996). Dinocyst assemblages in marine sediments are ~~linked~~ investigated to infer environmental parameters such as temperature and productivity in surface waters (Rochon et al., 1999; Zonneveld et al., 2013), and can be used as such to reconstruct past climate changes in downcore sediment records (e.g. Pross and Brinkhuis, 2005; Hennissen et al., 2014; 2017). Terrestrial palynomorphs are derived from vegetation and are delivered to coastal marine sediments through wind or river runoff. The pollen and spore (or sporomorph) assemblage in a downcore sediment record like the coastal marine Hank site can thus indicate the type of vegetation in the nearby continent, which can then be used to infer precipitation and/or temperature regimes of the source area (e.g. Heusser and Shackleton, 1979; Donders et al., 2009; Kotthoff et al., 2014).

Standard palynological techniques were used to process 82 selected samples. HCl and HF digestion followed by 15 µm sieving were carried out according to Janssen and Dammers (2008). Both ~~marine~~ dinocysts and ~~spores~~ sporomorphs were counted under a light microscope at 400x magnification until a minimum of 200 specimens was found. Rare species were identified during a final scan of the microscope slide. For dinocysts, the taxonomy of Williams et al. (2017) is used.

Some dinocyst taxa prefer cooler (sub)polar waters, hence we ~~may~~ take the sum of those taxa and use that as an indicator for SST in the SNSB. We calculate % cold-adapted dinocysts as the sum of the following species over the sum of all dinocysts in the Hank borehole: *Bitectatodinium* spp., *Habibacysta tectata*, *Filisphaera filifera*, *Headinium* spp., *Filisphaera* spp., *Islandinium* spp., *Habibacysta* spp., *Islandinium euaxum*, and *Bitectatonium tepikiense* following the approach adopted by Versteegh and Zonneveld (1994), Donders et al. (2009; 2018), and De Schepper et al. (2011).

A subset of 25 samples was analysed for detailed pollen assemblages to provide independent long-term trends in climate and vegetation cover. Late Neogene pollen types can, in most cases, be related to extant genera and families (e.g. Donders et al., 2009; Larsson et al., 2011). Percent abundances are calculated based on total pollen and spores excluding bisaccate taxa, freshwater algae, and *Osmunda* spores due to peak abundance in one sample of the latter. Bisaccate pollen abundances are excluded because they are heavily influenced by on- to offshore trends (Mudie and McCarthy, 1994), and therefore do not primarily represent tree abundance.

The terrestrial/marine (T/(T+M)) ratio of palynomorphs takes the sum of all sporomorphs and divides by the sum of all sporomorphs and dinocysts. The sum of sporomorphs excludes bisaccate taxa. The T/M ratio is commonly used as a relative measure of sea level variations and therefore distance to the coast (e.g. Donders et al., 2009; Kotthoff et al., 2014).

2.4 Lipid biomarkers and proxies

We use three independent organic temperature proxies for sea surface temperature based on different lipid biomarkers. The TEX_{86} is a proxy based on the temperature sensitivity of isoprenoidal glycerol dialkyl glycerol tetraethers (isoGDGTs), membrane lipids of marine archaea (Schouten et al., 2002). An increase in the relative abundance of isoGDGTs containing more cyclopentane moieties was found to correlate with SSTs (Schouten et al., 2002). ~~Several transfer functions exist to translate TEX_{86} values into SSTs (e.g. Kim et al., 2010; Tierney and Tingley, 2014).~~ Here we use the global core-top calibration of Kim et al. (2010) to translate TEX_{86} values to SSTs. Since isoGDGTs are also produced in soils, albeit in minor amounts, they may alter the marine temperature signal during periods with large contributions from land. The relative input of (fluvially discharged) terrestrial organic matter (OM) can be determined using the ratio of branched GDGTs (brGDGTs), which are produced in soils (Sinninghe Damsté et al., 2000; Weijers et al., 2007) and rivers (Zell et al., 2013), with crenarchaeol, an isoGDGT exclusively produced by marine Thaumarchaeota (Sinninghe Damsté et al., 2002). This ratio is quantified in the Branched and Isoprenoid Tetraether (BIT) index (Hopmans et al., 2004), where high BIT indicates a high continental OM input and vice versa~~ for a low BIT indicates a predominantly marine source of OM~~. A BIT index >0.3 is generally used as a cut-off for the validity of TEX$_{86}$-based SST estimates (Weijers et al., 2006). Secondly, the $U^{K'}_{37}$ index is used as a proxy for SST based on the degree of unsaturation of C$_{37}$ alkenones produced by marine haptophyte algae (Prahl and Wakeham, 1987). An increased abundance of the tri- relative to the di-unsaturated C$_{37}$ alkenones, expressed as the $U^{K'}_{37}$ index, is linked with decreasing temperature, an adaptation thought to retain membrane fluidity in cooler environments (Marlowe et al., 1984). $U^{K'}_{37}$ values can be converted to SSTs using the global core top calibration of Müller et al. (1998), with a calibration error of 1.5 °C. Finally, SSTs can be reconstructed based on the relative distribution of long chain diols, which are dihydroxylated lipids with 22–38 carbon atoms. The C$_{28}$ 1,13- C$_{30}$ 1,13- and C$_{30}$ 1,15 diols are most commonly found in seawater, and have a putative phytoplankton source (Volkman et al., 1992; Rampen et al., 2007; Rampen et al., 2011). The distribution of these three diols are used to formulate the long chain diol index (LDI), which can be converted to SST using the calibration of Rampen et al. (2012), ~~of which the~~with a calibration error of~~is~~ 2.0 °C. Furthermore, since freshwater eustigmatophyte algae produce C$_{32}$ diols (Volkman et al., 1992, 1999; Gelin et al., 1997), the percentage of the C$_{32}$ diol versus that of the marine C$_{28}$ 1,13- C$_{30}$ 1,13- and C$_{30}$ 1,15 diols ~~used in the LDI~~ can be used as an indicator for freshwater discharge (Lattaud et al., 2017).

Lipid biomarkers were previously extracted from the sediments (n = 155) and separated into polarity fractions (~~according to~~ ~~Sediments (n = 155) were previously extracted and processed according to procedures outlined in~~ Dearing Crampton-Flood et al., ~~(~~2018). The polar fractions, containing GDGTs, were analysed on an Agilent 1260 Infinity ultra-high performance liquid chromatography instrument (UHPLC) coupled to an Agilent 6130 single quadrapole mass detector with settings following Hopmans et al. (2016). For more details on method and solvent program see Dearing Crampton-Flood et al. (2018). S~~Injection volume of each sample was 10 µL. GDGTs were separated using two silica Waters Acquity UPLC HEB Hilic (1.7 µm 2.1 mm x 150 mm) columns (30 °C). A flow rate of 0.2 ml/min was used for isocratic elution: starting with 82% A and 18% B for 25 min, then a linear gradient to 70% A and 30% B for 25 min (A= hexane, B=hexane:isopropanol 9:1, *v/v*). Prior to mass detection, atmospheric pressure chemical ionisation (APCI) with the following source conditions was used: vaporizer temperature 400 °C, gas temperature 200 °C, capillary voltage 3500 V, drying gas (N$_2$) flow 6L/min, nebulizer pressure 25 psi, corona current 5.0 µA. S~~elected ion monitoring (SIM) was used to detect $[M\text{-}H]^+$ ions of the isoGDGTS: *m/z* 1302, 1300, 1298, 1296, 1292.

After GDGT analysis, polar fractions were silylated by the addition of N,O-bis(trimethylsilyl)trifluoroacetamide (BSTFA) and pyridine (60 °C, 20 min). A Thermo trace gas chromatograph (GC) coupled to a Thermo DSQ mass spectrometer (MS) was used to analyse long chain diol distributions in SIM mode (*m*/z 299, 313, 327, 341) at the Royal NIOZ. The temperature program was: 70 °C for one min, then ramp to 130 °C at 20 °C/min, then ramp to 320 °C at 4 °C/min, then held for 25 minutes.

Ketone fractions, containing the C_{37} alkenones, were analysed using gas chromatography with flame ionisation detection (GC-FID). Samples were injected (1 μL) manually on a Hewlett Packard 6890 series GC system equipped with a CP-Sil-5 fused silica capillary column (25 m x 0.32 mm, film thickness 0.12 μm) and a 0.53 mm pre-column. The oven temperature program was similar to that used for long chain diol analysis.

3. Results

3.1 Stable isotopes of *Cassidulina laevigata*

Foraminifera preservation in the intervals 404–386 and 204–136 meters was either very low or non-existent. Furthermore, the low abundance and poor preservation of foraminifera in the crag material ~~were challenging to pick in the crag material~~ (220–205 m, Fig. 2c) also presented a challenge for picking. The $\delta^{18}O_{cass.}$ values of foraminifera in the sediment from the remaining intervals (n = 136) ~~before and after outlier removal~~ ranges from -1.0–3.6~~2~~ ‰ ~~and 0.3–2.9 ‰, respectively~~ (Fig. 2c). The variability in $\delta^{18}O_{cass.}$ values between ~~peaks~~ maxima and adjacent ~~troughs~~ minima in the Hank record ranges from ~1~~–0.9~~–4~~1.8~~ ‰. The stable carbon isotope record varies between -3~~2~~.8~~2~~–0.6 ‰ (Fig. 2d), and~~.~~ ~~The~~ the variability ~~in the $\delta^{13}C_{cass.}$ record ranges from~~is ~0.3–2.3 ‰. ~~, although the sample at 206 m is probably an outlier but is not removed because the outlier identifier method calculates the 7-point average of the data series (Sect. 2.2), and thus the sample at 206 m is at the upper limit of the range of the isotope record (382–204 m; Fig. 2) for which no moving average can be calculated.~~ Discounting the sample at 206 m, the variability in the $\delta^{13}C_{cass.}$ record ~~is similar than that of the $\delta^{18}O_{cass.}$ record (~~is approximately ~1 ‰ (~~,~~ Fig. 2d). The $\delta^{18}O_{cass.}$ and $\delta^{13}C_{cass.}$ records show ~~inversed~~anti-phase relationships in the intervals 378–360, 345–310, 30~~0~~4–292~~83~~, 282–279, 275–270, 252~~, and 255–~~242, 232–227, and 224–218~~218~~ m~~,~~ (~~highlighted in~~ Fig. S~~3~~1a).~~The interval with the most~~

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~~outliers for both carbon and oxygen isotopes was 311–303 m, where all samples exceeded the upper and lower range of values calculated using the 7-point average (Sect. 2.2).~~

3.2 Seismic profile

The ~15 km east to west seismic profile of the Meuse River, including the location of the Hank borehole, spans a depth of >500 m (Maas2002 survey, nlog.nl; Fig. 3~~4~~). Comparison of the formations of the Hank borehole with the seismic depth profile in Fig. 4 indicates that the Breda Formation at 404–370 m is characterized by horizontal-reflection patterns, likely indicating shallow marine conditions. The eastern continuation of the seismic line reveals that these horizontal strata can be interpreted as shelf toesets of westward prograding deltaic clinoforms.

3.3~~2~~ Palynology

The palynomorphs in the Hank sediments are well preserved. The borehole can be divided into three main intervals according to the (co)dominance of the marine/terrestrial palynomorphs: 1, 2, and 3, which roughly correspond to the early Pliocene (1), mid-Pliocene (2) and late Pliocene/early Pleistocene (3). In the deepest part of the borehole (404–330 m, 1), the marine component of the palynomorph assemblage clearly exceeds the terrestrial, as evidenced by the low T/M values (Fig. 4~~3~~c). An isolate sporomorph peak and (sub)polar dinocyst peak is visible at 383 m (Figs. 2f, 4~~3~~c). Interval 2 from 330–187 m shows a fluctuating ratio between the marine and terrestrial elements (Fig. 4~~3~~c). The cold-adapted dinocysts also show fluctuations indicating alternating warmer and cooler periods (Fig. 2f). One striking feature is the increase in cold-adapted dinocyst abundance and simultaneous *Osmunda* acme at 305 m (Figs. 2f, ~~3~~4j~~c~~). The third interval 3 spans the upper part of the borehole (187–136 m), and sporomorphs in particular dominate ~~the spectra from 187 m upward~~this interval, visible by the consistently high T/M (Fig. ~~3~~4c). Interval 3 shows an increased occurrence of coastal marine genera, like *Lingulodinium*. The increased gamma ray values at ~175 m (Fig 2b) are the result of the abundance of (shell) concretions, not clays, and as such, do not indicate a more distal environment but rather a development toward a more proximal environment. At 154–153 m, the marine indicators in the borehole are reduced to just 0.5 % of the total sum of palynomorphs. However, the highest abundance of cold- adapted dinocysts, mostly composed of taxa like *Habibacysta tectata*, is at 154 m (Fig. 2f). This depth is also marked by the complete

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disappearance of ~~several (sub)tropical species from the Pliocene, like the~~dinocyst genus *Barssidinium* spp. with an LOD at 157 m (Dearing Crampton-Flood et al., 2018). (Sub)tropical species like *Lingulodinium machaeophorum*, *Operculodinium israelianum*, *Spiniferites mirabilis*, *Tectatodinium pellitum*, and *Tuberculodinium vancampoae* are missing at this depth. The uppermost (154–136 m) interval indicates an estuarine to deltaic environment, due to the presence of freshwater and brackish water algae species *Pediastrum* and *Botryococcus*. In contrast, the freshwater indicators are (almost) absent in intervals 1 and 2. The assemblages of interval 3 are also characterized by a fluctuating abundance of cold-adapted dinocysts (Fig. 2f).

The pollen assemblages are dominated by tree pollen, particularly conifers (*Pinus*, *Picea*, *Abies*, *Taxodioidae*-type (including *Glyptostrobus* and *Taxodium*), *Sciatopitys*, and *Tsuga*), but with increasing proportions of grasses (Poaceae, Cyperaceae), and ~~heath~~ heather (Ericales) in interval 2, and significantly increased amounts of fern spores from 260 m and up (Fig. S1). Exclusion of the bisaccate types from the percentage sum (to counter effects of sea level change on the diverse transport capacity of pollen; Neves effect) causes the percentage pollen sum to be relatively low (~100 grains/sample). The current pollen record should therefore be used for main quantitative trends and not to delineate individual ranges of taxa. The angiosperm tree abundances averages about 20% and shows no significant long-term change towards the top of the sequence (Fig. 4e~~3~~). The angiosperm tree pollen record is diverse, although few taxa are continuously present, and consists mostly of *Quercus robur*-type with significant proportions of *Pterocarya*, *Fagus*, *Carpinus* and, above 240 m, *Ulmus* (Fig. S1). The *Taxodioidae*-type shows a distinct long-term decline superimposed by three shorter minima in the end of interval 2 and beginning of 3, occurring at 205, 235 and 170 m (Figs. 4d, S2~~. 3d~~).

3.4~~3~~ Lipid biomarkers ~~and proxies~~

IsoGDGTs are present in high abundances throughout the borehole, as evidenced by the high total organic carbon (TOC)-normalized concentrations of crenarchaeol (0.2–130 µg g^{-1} TOC; Dearing Crampton-Flood et al., 2018~~; Fig. 3c~~). IsoGDGT-based SSTs are reconstructed for those sediments where BIT <0.3, i.e. between 404–~~ and ~~219 m (n = 66). ~~The trends in the SSTs calculated from the Bayesian (Tierney and Tingley, 2014) and the Kim et al. (2010) calibrations are the same, however, the absolute values differ (Fig. S2).~~ TEX_{86}^{H}-reconstructed SSTs range between 7 and 13 °C, but do not show a clear trend over time (Fig. 2e).

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Alkenones are present in the majority (n = 111) of the samples. However,~~in the interval 404–250 m, however,~~ they are below the detection limit in many of the ~~overlying~~ sediments from 250–200 m. Alkenones re-emerge in the interval from 197–178 m. The $U^{K'}_{37}$ index values range between 0.30–0.83, and correspond to a~~n~~ SST range of 8–24 °C (Fig. 2e). In the early Pliocene (1), the $U^{K'}_{37}$ SST record shows the largest fluctuations in temperature (ΔT = 15 °C), and an average SST of 19 °C. Similar variability (ΔT = 14 °C) is observed in interval 2 (middle-late Pliocene), although the average SST drops slightly to 17 °C. Alkenones are present around or below the detection limit in 3 (late Pliocene/early Pleistocene), so no SSTs can be calculated. Notably, $U^{K'}_{37}$ SSTs show a warming of 11 °C during the interval between 290–260 m (Fig. 2e).

Long chain diols ~~used for calculation of the LDI index~~ are below the detection limit in a large proportion of the Hank borehole. SSTs can be reconstructed for a select few samples in ~~sections~~ intervals 1 and 3, and they show scattered temperatures in a range of 13 °C (Fig. 2e). The sediments in ~~section~~ interval 2 contain enough diols to enable a semi-continuous SST reconstruction. The range of LDI SSTs in this section2~~B~~ is 4–18 °C (Fig. 2e). The record shows a strong warming trend of ~12~~0 12~~ °C from 295–263 m, coeval with the trend in the $U^{K'}_{37}$ record (Fig. 2). The %C_{32} diol is generally high (~36–57%) in 1 and 2 (Early-Mid Pliocene; Fig ~~3~~4c), indicating a modest to strong freshwater input (cf. Lattaud et al., 2017). The %-C_{32} diol slightly decreases (10–%) over 294–264 m, indicating a gradually decreasing influence of riverine OM and/or an increase in the abundance of the C_{28} 1,13- C_{30} 1,13- and C_{30} 1,15 marine diols. In ~~section~~ interval 3, the %C_{32} diol exhibits a strong increasing (21–59–%) trend (187–136 m; Fig. 4c~~3~~).

4. ~~4.~~ Discussion

4.1 ~~Age model reconstruction~~

~~4.1.1 Environmental setting and seismic profile~~Depositional record and unconformities

The changes in depositional environment in the Hank borehole from open marine to coastal marine, and successively estuarine conditions are based upon the BIT, TOC, and $\delta^{13}C_{org}$ records presented in Dearing Crampton-Flood et al. (2018), and the biological changes in the abundances of typical marine (dinocysts and test linings of foraminifera), estuarine/freshwater

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Formatted: List Paragraph, Numbered + Level: 1 + Numbering Style: 1, 2, 3, … + Start at: 1 + Alignment: Left + Aligned at: 0.63 cm + Indent at: 1.27 cm algae species, and sporomorph assemblages (Munsterman, 2016), summarized in the T/M ratio. A transition of marine OM during the Pliocene to more terrestrial OM input towards the Pleistocene starts approximately at 190 m as evidenced by these indicators (Fig. ~~3~~4c). This reflects the increasing influence of the Rhine-Meuse R~~r~~iver to the site. This progradation of the Rhine-Meuse R~~r~~iver is confirmed by the westward progradation of the depositional (delta) system that can be seen in the seismic section (Section 3.2, Fig. 3~~4~~).

~~The ~15 km east to west seismic profile of the Meuse River, including the location of the Hank borehole, spans a depth of >500 m (Maas2002 survey, nlog.nl; Fig. 4). Comparison of the formations of the Hank borehole with the seismic depth profile in Fig. 4 indicates that the Breda Formation at 404–370 m is characterized by horizontal reflection patterns, likely indicating shallow marine conditions. The eastern continuation of the seismic line reveals that these horizontal strata can be interpreted as shelf toesets of westward prograding deltaic clinoforms.~~

Toward the long term shallowing trend in the ~~core~~borehole, several depositional changes and unconformable surfaces are recognized in the seismic profile which need to be taken into account regarding the construction of a valid age model. The transition from the Breda Formation to the overlying Oosterhout Formation is marked by a distinct angular unconformity referred to as the Late Miocene Unconformity (LMU; Munsterman et al., ~~unpublished data~~2019; Fig. ~~4~~3). The seismic data of the overlying Oosterhout Formation (Mid-Late Pliocene) indicates a twofold subdivision. The lower unit of the subdivision at 370–314~~9~~ m is characterized by convex downward reflection patterns that correspond to an open marine signature (with corresponding low sedimentation rates). This is confirmed by the transition to finer grained sediments (silts) over 381–352 m attributed to a more distal setting (Fig. 2a). This interval is also characterized by an increased abundance of dinocysts with a preference for open marine conditions, like the genus *Spiniferites*. The facies of interval 352–338 m indicates shallow to open marine conditions with a temperate to (sub)tropical SST. A coarsening upward trend is corroborated by the gradual decrease in gamma ray values (Fig. 2b). In the second Oosterhout unit from 31~~9~~4–157 m the environment is shallow marine, and several stacked clinoform sets are visible in the seismic profile (Fig. 3~~4~~). The transition between the two Oosterhout units is clearly visible as a downlap surface around 31~~9~~4~~–313~~ m that corresponds to a sequence boundary, and possible hiatus (Fig. 3~~4~~). This is coupled with a dramatic decrease in sedimentation rate in the initial age model, which places this interval within the scope of the M2 glacial event ~~(Dearing Crampton-Flood et al., 2018). The biostratigraphic age model places~~

~~this interval within the scope of the M2 glacial event~~ (~3.3 Ma; Dearing Crampton-Flood, 2018).

Above ~~this~~ the ~~transition~~sequence boundary at 314 m, an increase in water depth to ~ ~~200~~ 80–100 m can be deduced from the height of the clinoforms where the topsets represent the fluvial ~~distributary~~ system debouching at the coastline~~and the clinoform breaks the coastlines~~. This water depth estimate is comparable to the estimate for Pliocene water depth from an integrated seismo-stratigraphic study of the ~~southern North Sea Basin~~SNSB (Overeem et al., 2001). The topset beds in the Hank borehole ~~Hank~~ show an abundance of shell crag facies material corroborating the ~~near shore~~coastal setting (Figs. 2a, 3~~4~~). The stratigraphic stacking is first purely progradational (clinoforms) and changes to both progradational and aggradational higher up, suggesting progressive fluvial influence replacing the marine environment. In the Hank borehole, this change is marked by a distinct clay layer at 292–271 m (Fig. 2a). In the upper part of the second Oosterhout Formation at depths of 260 m and upwards, the increased proportion of heather and grasses is generally considered indicative of colder and drier terrestrial climate (Faegri et al., 1989; Fig. 4~~3~~). The decrease in *Taxodioidae*-type pollen over ~~section~~ interval 2~~B~~ (Fig. 4d) and the Oosterhout to the Maassluis Formations further indicates a cooling terrestrial climate, and is classically recognized as the top Pliocene (Late Reuveria~~e~~n) in the continental zonation of Zagwijn (1960), although in the onshore type area the sequences are most likely fragmented time intervals bounded by several hiatuses (Donders et al., 2007). ~~Strikingly, b~~~~Both the MAT record (Dearing Crampton-Flood et al., 2018) and the *Taxodioidae*-type pollen covary throughout the record (Fig. 44d). The pattern follows the same trends as the classic paleotemperatures profiles during the coeval Brunssumian, Reuverian, and Praetiglian terrestrial stages (Zagwijn, 1992). These paleotemperatures estimates were largely based on Taxodioidae pollen abundances and other warm-temperate elements (Zagwijn 1960; 1992), but lacked the direct chronological control available at the Hank site.~~

At the transition of the Oosterhout Formation to the Maassluis Formation, concave downward reflection patterns may reflect channel incisions into the topsets of the Oosterhout Formation (Fig. 3~~4~~). The Maassluis Formation (late Pliocene-early Pleistocene, <2.6 Ma) is composed of horizontal and channel-like strata in the seismic profile (Fig. ~~4~~3). The environment of the Maassluis Formation becomes more fluvio-deltaic, characterized by the decreased abundance of dinoflagellate cysts and steep rise in the number of sporomorphs, manifested by the high T/M values (Fig. 4~~3~~c). Further warm-temperate trees in the Maassluis interval of the record such as *Carya*, *Liquidambar*, *Nyssa* disappeared in NW Europe in the earliest

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Pleistocene (Donders et al., 2007), most likely slightly above the level of the top of the Hank sequence. In contrast, land based studies in the Dutch-German border area (cf. Donders et al., 2007; Westerhoff, 2009) are characterized by relatively more abrupt last occurrences of warm-temperate taxa due to the probably incomplete preservation of the early Pleistocene sequences.

The Plio-Pleistocene transition (2.6 Ma) occurs between 200–154 m (Dearing Crampton-Flood et al., 2018). This transition is accompanied by a peak in gamma ray values at ~175 m (Fig. 2b). However, the coastal marine depositional setting for the Hank borehole in the interval (upper Oosterhout Formation) during the late Pliocene/Early Pleistocene above 200 m strongly indicates that these successions are likely not continuous, but consist of successive fragments of sedimentation representing short time windows that are bounded by hiatuses (cf. Donders et al., 2007).

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4.2 M2 event

There is global evidence for a large sea level drawdown during the M2, but the estimates of the magnitude of its extent vary greatly (38–65 m; Dwyer and Chandler, 2009; Naish and Wilson, 2009; Miller et al., 2011; Miller et al., 2012). However, large uncertainties in the estimation of ice volume prohibit any meaningful estimates of sea level for the Pliocene using the stable isotope measurements of foraminifera (Raymo et al., 2018).

The hiatus at Hank representing the M2 glacial is also recognized in sequences from the Coralline Crag in the English North Sea (Williams et al., 2009), the Poederlee and Lillo formations in the Belgium North Sea (De Schepper et al., 2009; Louwye and De Schepper, 2010), and possibly the Nordic Seas (Fig. 1, Risebrobakken et al., 2016). In the Poederlee and Lillo formations of neighbouring Belgium (located 80 km from Hank in the present day), De Schepper et al. (2009) and Louwye and De Schepper (2010) hypothesize that the MIS M2 is correlated with a sequence boundary Pia1 at approximately 3.21 Ma. In addition, equivocal temperature/assemblage signals in the Coralline Crag Formation are hypothesized to be a result of sea-level change associated with the M2, which would have decreased or ceased sedimentation entirely (Williams et al., 2009). A Pliocene benthic δ^{18}O record adjacent to the NS in the Nordic Seas (ODP hole 642B; Risebrobakken et al., 2016) also does not record any strong evidence of the M2 event, and the authors postulated that the M2 might have occurred during a hiatus in the borehole, or may have been a less extreme event in this region compared to other regions (Lisiecki and Raymo, 2005). Due to the M2 being a globally recognized event (De Schepper et al., 2014), the records from the East of England, Belgium, and the Hank site indicates that a hiatus likely exists over the most acute part of the glacial in SNSB sediment successions. Thus, the coolest interval (with the presumed lowest sea level and high hinterland sediment supply) of the M2 might have not been recorded at Hank because of erosion.

In the sediments occurring above the hiatus marked by the sequence boundary in Fig. 3, large variability in $\delta^{18}O_{cass.}$ indicates fluctuating climate conditions that may be associated with the onset or the recovery of the M2. The fluctuations match those in the records of the BIT index and $\delta^{13}C$ of organic matter (see Dearing Crampton-Flood et al., 2018), which indicate a closer proximity of the coast to the site, likely as a result of sea level change. The major peak of *Osmunda* spores (outside of pollen percentage sum) after the hiatus at ~3210 ka (306 m) could then represent a pioneer phase of marsh vegetation related to a rapid sea level lowering. The (sub)polar dinocyst acme and increase of *Operculodinium centrocarpum* (Figs. 2, 6a) at 305 m may then represent the restoration of the location of the Hank site to a more distal marine setting within the confinement of the Rhine Valley Graben. The sea level drop associated with the M2 event may have decreased the inflow of Atlantic bottom water currents originating from the Northern opening of the North Sea (Kuhlmann et al., 2006). After the M2 event, isostasy may have then strengthened the connection to the North Atlantic (possibly also via the English Channel), which would have allowed the inflow of relatively warmer and saline Atlantic Water fed by the North Atlantic Current (NAC) into the North Sea. The dinocysts of *Operculodinium centrocarpum* are generally used as a tracer for the NAC in the North Atlantic (De Schepper et al., 2009b; Fig. 6a), and may tentatively be linked to the increasing influence of the North Atlantic to the study site after the hiatus associated with the M2 event. However, *Operculodinium centrocarpum* is a cosmopolitan species, and in the modern day with a connection via the English Channel to the North Sea, it is not commonly found (Marret et al., 2003; Zonneveld et al., 2013). Thus, the re-emergence of *Operculodinium centrocarpum* over the mPWP interval (Fig. 6) more likely reflects the restoration of marine conditions in the shallow SNSB after the M2.

The acme of *Osmunda* spores coincides with the occurrence of dinocysts characteristic of (sub)polar watermasses at ~3210 ka, further indicating cold conditions (Fig. 6). In addition, the distinct decrease in *Taxodioidae*-type pollen at the same time indicates that climate conditions were also cold(er) on the continent (Fig. 6c), which is supported by low terrestrial mean air temperatures of 6 °C, independently reconstructed based on brGDGTs (Fig. 6f;

Dearing Crampton-Flood et al., 2018). In contrast, all SST reconstructions remain stable during this M2 deglaciation/recovery period (Fig. 6d), suggesting that cold periods on land are better recorded in the sedimentary record than those in the marine realm. Indeed, terrestrial proxies should represent an integrated signal over longer time and larger space (NW Europe), compared to that of the marine proxies, which are confined to the shallow SNSB basin and potentially mostly record warm periods (Sect. 4.3).

4.~~1.~~3~~2~~ ~~Chronological constraints~~Glacial-interglacial variability and tuning

~~Deep sea δ^{18}O and δ^{13}C records general oscillate in anti-phase during the Quaternary, due to the waxing and waning of large ice caps on the Norther Hemisphere (e.g. Ruddiman, 2001). During glacial periods, benthic foraminifera incorporate relatively more δ^{18}O in their calcite test, since more ^{16}O has been stored in the ice sheets and bottom water temperatures are cold. At the same time, they also incorporate more ^{12}C because the total amount of vegetation on land has been reduced during glacial periods causing an enrichment of the dissolved inorganic carbon (DIC) pool of the oceans in ^{12}C. Besides, a reduced thermohaline circulation (THC) during glacial periods may have reduced the contribution of ^{12}C-depleted North Atlantic Deep Water to the deep ocean with respect to the ^{12}C-enriched Antarctic Bottom water component. Hence, for the intervals that the trends in δ^{18}O and δ^{13}C records of the Hank core move in anti-phase, we interpreted these changes as being the result of glacial-interglacial variability. But, when the δ^{18}O and δ^{13}C are not inversely related, i.e. show a positive correlation, other factors such as riverine freshwater inflow, reworking, and diagenetic influences were most likely in control.~~

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Based upon the age model of Dearing Crampton-Flood et al. (2018), it is clear that the sample resolution is too low to resolve a stable isotope tuning on Milankovitch time scales for the older succession including the Breda and lower Oosterhout Formations (404–330 m), but it is sufficient (i.e. <6 kyr) to resolve individual cycles in particular above 314 m. Notwithstanding the low resolution between ~~-~~390–314 m, the $\delta^{18}O_{cass.}$ and $\delta^{13}C_{cass.}$ records move in opposite directions suggesting that global glacial-interglacial ice volume changes were largely influencing the open (shallow) marine environment at Hank during that time. In the upper part of the Hank borehole (314–200 m), the trends in $\delta^{18}O_{cass.}$ and $\delta^{13}C_{cass.}$ do not show a continuous inversed relationship (Fig. S1a), indicating that the ice volume influence is likely obscured by other factors such as riverine freshwater inflow.

~~In contrast, the sample resolution is sufficient (i.e. < 6 kyr) for the depth interval above 298 m. A dramatic decrease in sedimentation rate in the initial age model (Dearing Crampton-Flood et al., 2018) is coupled with a hiatus indicated by a sequence boundary (SB) in the seismic profile (Fig. 4) around ~31430 m. The biostratigraphic age model places this interval within the scope of the M2 glacial event (~3.3 Ma; Dearing Crampton-Flood, 2018).~~

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~~In the upper part of the Hank borehole (314–200 m), the trends in $\delta^{18}O_{cass.}$ and $\delta^{13}C_{cass.}$ do not show a continuous inversed relationship (Fig. S3). When the $\delta^{18}O$ and $\delta^{13}C$ variables are not inversely related, the ice volume influence is likely obscured by other factors such as riverine freshwater inflow, and diagenetic influences.~~ The absolute values of the oxygen isotope measurements on *Cassidulina laevigata* recorded in Hank are substantially lower by approximately 1–1.5 ‰ than the composite benthic $\delta^{18}O$ values in the LR04 stack (Lisiecki and Raymo, 2005), as well as those of a nearby Pliocene benthic oxygen isotope record from the Nordic Seas (~2–3 ‰; Risebrobakken et al., 2016). The offset in absolute values is unlikely due to a species-dependant effect, as $\delta^{18}O_{cass.}$ values in a nearby Quaternary-age core from Noordwijk (Noorbergen et al., 2015) were comparable to the LR04 stack (Lisiecki and Raymo, 2005). Hence, the relatively low $\delta^{18}O_{cass.}$~~$\delta^{18}O$~~ values ~~of~~in the Hank ~~record~~sediments likely reflect the influence of freshwater input at this site, which is proximal to the mouth of the paleo Rhine-Meuse River (e.g. Delaygue et al., 2001; Lubinski et al., 2001; Westerhoff, 2009; Fig. 1). Similarly, low benthic and planktic $\delta^{18}O$ values in ~~marine~~ sediments from the Ionian Sea coinciding with sapropel deposition~~,~~ were attributed to increased ~~also yield low benthic and planktic $\delta^{18}O$ values which were interpreted as~~ freshwater influence at this time (Schmiedl et al., 1998). ~~At the delta front, wave action and winnowing contribute to the mixing of freshwater input in the relatively shallow water column, which explains why an endobenthic species may be affected by freshwater influence which results in relatively lower absolute $\delta^{18}O_{cass.}$ values at the Hank site.~~ Furthermore, the large $\delta^{18}O_{cass.}$ variability in the Hank record (~1–4 ‰) compared to that in the LR04 stack record (0.2–0.7 ‰ during the Pliocene; Lisiecki and Raymo, 2005) indicates that the $\delta^{18}O$ isotopic signature of shallow seawater at the Hank site is ~~more~~ sensitive to freshwater input~~, probably derived from the proto Rhine-Meuse River system~~. At the delta front, wave action and winnowing contribute to the mixing of freshwater input in the relatively shallow water column, which explains why an endobenthic species may be affected by freshwater influence which results in relatively lower absolute $\delta^{18}O_{cass.}$ values at the Hank site. Thus~~, in the upper interval (above 314 m) at the Hank site,~~ salinity changes and sensitivity to freshwater input affect the oxygen isotopes incorporated into *Cassidulina* species at the Hank site, regardless of the endobenthic habitat.

The upper (Plio-Pleistocene transition) and lower (M2 glacial) stratigraphic boundaries identified in Sections 4.1 and 4.2 provide a contextual framework to construct a higher resolution age model for the mPWP (3264–3025 ka) using stable isotopes of *Cassidulina laevigata*. The open marine signature and relatively horizontally deposited clinoform sets in the second unit of the Oosterhout subdivision from ~305–200 m (Fig. 3) represents a relatively continuous sedimentary record that may be suitable for age model reconstruction, keeping in mind the potential freshwater influence on the $\delta^{18}O_{cass.}$ record.

In order to use the $\delta^{18}O_{cass.}$ record ~~F~~for tuning purposes, an understanding of the North Sea hydrogeography and circulation patterns during the Pliocene must be taken into consideration. During cold periods, the North Sea circulation slows due to the reduced sea level and inflow of Atlantic water (Kuhlmann et al., 2006). Stratification in the North Sea due to freshwater input from rivers combined with the sluggish circulation and weak influence of the Atlantic waters make cooler periods problematic to tune to due to a $\delta^{18}O$~~cass.~~ signature that is probably highly localized and erratic. Moreover, Donders et al. (2007) noted that the coldest phase of glacials of the Plio-Pleistocene climate development of coastal areas in the NS is likely to be marked by substantial hiatuses caused by non-deposition and erosion, which may also preclude the use of the transition between the warmer and cooler periods as a tuning anchor. During warmer periods, an increased freshwater input from river outflows is also expected, due to the supposedly wetter climate conditions during interglacials. However, Kuhlmann et al. (2006) linked warmer periods in the Pliocene in the central section of the southern North Sea with the occurrence of *Cassidulina laevigata*, whose habitat in the modern North Sea is located in the northern part with a strong connection to the Atlantic (Murray, 1991). Thus, tuning the warmer periods in the $\delta^{18}O_{cass.}$ record at the Hank site with warm periods in the LR04 benthic stack is preferable due to the strong(er) connection to the Atlantic (Kuhlman, 2004), resulting in a relatively more regional signature of the $\delta^{18}O_{cass.}$ values (Kuhlmann et al., 2006). Moreover, the chance of disturbance/hiatuses that affect the continuity of the sediment record at Hank is decreased in warmer periods.~~, thus making them suitable for tuning.~~

Using the above reasoning, the sample with the lowest $\delta^{18}O_{cass.}$ value in each cycle between ~314–200 m in the Hank record can be tuned to the lowest $\delta^{18}O$ value between the M2 event associated with the hiatus at 314 m (~3.3 Ma) and the Plio-Pleistocene boundary (Sections

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4.1, 4.2~~.2~~) in the LR04 stack, ~~presuming~~assuming that the low δ^{18}O values in the Hank borehole represent the warmest part of each interglacial (Fig 5). Further investigation in the variation of the $\delta^{18}O_{cass.}$ cycles in the Hank borehole isotope record reveals unique saw tooth structures, ~~representing a different pattern than~~differing from the more symmetrical pattern of cyclicity that is seen in the Pleistocene interval of the LR04 stack. Specifically, cycles G19, G17, and G15 display these reversed saw-tooth patterns in the global benthic stack, and help pinpoint corresponding cycles in the Hank borehole record (Fig. 5). ~~theof the Hank borehole~~ The reconstructed time window spans ~3190–2770 ka, and thus most of the mPWP. Based on the tuned oxygen isotope age model, the LOD of *Invertocysta lacrymosa* and *Operculodinium? eirikianum* in the ~~southern North Sea~~SNSB can be constrained to ~3040 and <2768 ka, respectively (see Dearing Crampton-Flood et al., 2018).

~~This is further supported by the absence of excursions towards heavier values in the~~ ~~$\delta^{18}O_{cass.}$~~ ~~record for any point in the interval deeper than 300 m (Fig. 2c). butof magnitude of its extent~~

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~~The M2 event is most likely incomplete, or absent in the Hank borehole, and is marked by a hiatus that is also recognized in sequences from the Coralline Crag in the English North Sea (Williams et al., 2009), the Poederlee and Lillo formations in the Belgium North Sea (De Schepper et al., 2009; Louwye and De Schepper, 2010), and possibly the Nordic Seas (Fig. 1, Risebrobakken et al., 2016). In the Poederlee and Lillo formations of neighbouring Belgium (located 80 km from Hank in the present day), De Schepper et al. (2009) and Louwye and De Schepper (2010) hypothesize that the MIS M2 is correlated with a sequence boundary Pia1 at approximately 3.21 Ma. In addition, equivocal temperature/assemblage signals in the Coralline Crag Formation are hypothesized to be a result of sea-level change associated with the M2, which would have decreased or ceased sedimentation entirely (Williams et al., 2009). A Pliocene benthic~~ ~~δ^{18}O~~ ~~record adjacent to the NS in the Nordic Seas (ODP hole 642B; Risebrobakken et al., 2016) also does not record any strong evidence of the M2 event, and the authors postulated that the M2 might have occurred during a hiatus in the borehole, or may have been a less extreme event in this region compared to other regions (Lisiecki and Raymo, 2005). Due to the M2 being a globally recognized event (De Schepper et al., 2014), this indicates that a hiatus likely exists over the most acute part of the glacial. A Pliocene benthic~~ ~~δ^{18}O~~ ~~record adjacent to the NS in the Nordic Seas (ODP hole 642B; Risebrobakken et al., 2016) also does not record any strong evidence of the M2 event, and the authors postulated that the M2 might have occurred during a hiatus in the borehole. There is evidence for a large sea level drawdown of 70 m in the North Sea (Miller et al., 2011) during the M2 that would have led to a hiatus. In~~

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~~addition, equivocal temperature/assemblage signals in the Coralline Crag Formation are hypothesized to be a result of sea-level change associated with the M2, which would have decreased or ceased sedimentation entirely (Williams et al., 2009). Due to the M2 being a globally recognized event (De Schepper et al., 2014), this evidence from the in the East of England, Belgium, and the Hank site indicates that a hiatus likely exists over the most acute part of the glacial in SNSB sediment successions. This indicates that sedimentation in the SNSB was sensitive to disturbance due to its shallow depth. Overall, the combined climate data from the Nordic Seas, East of England, and the Hank site indicate that a significant hiatus (~ 319–313 m at Hank) occurred in the interconnecting basins. Thus, the coolest interval (with the presumed lowest sea level) of the M2 was not recorded.~~ 3spreferably2

~~The Plio-Pleistocene transition (2.6 Ma) occurs between 200–154 m (Dearing Crampton-Flood et al., 2018). This transition is accompanied by a peak in gamma ray values at ~175 m (Fig. 2b). The upper (Plio-Pleistocene transition) and lower (M2 event) boundaries identified here provide a contextual framework to construct a higher resolution age model for the mPWP (3254–3025 ka) using stable isotopes of *Cassidulina laevigata*. The open marine signature and relatively horizontally deposited clinoform sets in the second unit of the Oosterhout subdivision from ~305–200 m (Fig. 4) should be suitable for age model reconstruction. However, the coastal marine depositional setting for the Hank borehole in the chosen interval (upper Oosterhout Formation) during the late Pliocene/Early Pleistocene strongly indicates that successions are likely not continuous, but are stacks representing short time windows (cf. Donders et al., 2007). It is likely that these short time windows share common features, e.g. warmer or cooler intervals. This indicates that tuning the $\delta^{18}O_{cass.}$ record at~~ of ~~the Hank borehole to the LR04 stack (Lisiecki and Raymo, 2005) should correlate either the warmer or cooler intervals (Section 4.1.3).~~

~~**4.1.3 Age model tuning**~~

~~The absolute values of the oxygen isotope measurements on *Cassidulina laevigata* recorded in Hank are substantially lower by approximately 1–1.5 ‰ than the composite benthic $\delta^{18}O$ values in the LR04 stack (Lisiecki and Raymo, 2005), as well as those of a nearby Pliocene benthic oxygen isotope record from the Nordic Seas (~2–3 ‰; Risebrobakken et al., 2016). The offset in absolute values is unlikely due to a species-dependant effect, as $\delta^{18}O_{cass.}$ values in a nearby Quaternary-age core from Noordwijk (Noorbergen et al., 2015) were comparable to the LR04~~

~~stack (Lisiecki and Raymo, 2005). Hence, the relatively low $\delta^{18}O$ values of the Hank record likely reflect the influence of freshwater input at this site, which is proximal to the mouth of the paleo-Rhine (e.g. Delaygue et al., 2001; Lubinski et al., 2001; Fig. 1). Furthermore, the large $\delta^{18}O_{cass.}$ variability in the Hank record (0.9–1.8 ‰) compared to that in the LR04 stack record (0.2–0.7 ‰ during the Pliocene; Lisiecki and Raymo, 2005) indicates that the shallow and relatively fresh(er) North Sea is more sensitive to climate disturbance than ocean bottom waters. Thus, salinity changes and sensitivity to freshwater input affect the oxygen isotopes incorporated into *Cassidulina* species, regardless of the endobenthic habitat.~~

~~For tuning purposes, a detailed understanding of the North Sea hydrogeography and circulation patterns during the Pliocene must be taken into consideration. During cold periods, the North Sea circulation slows due to the reduced sea level and inflow of Atlantic water (Kuhlmann et al., 2006). Stratification in the North Sea due to freshwater input from rivers combined with the sluggish circulation and weak influence of the Atlantic waters make cooler periods problematic to tune to due to a $\delta^{18}O_{cass.}$ signature that is probably highly localized and erratic. Moreover, Donders et al. (2007) noted that the coldest phase of glacials of the Plio-Pleistocene climate development of coastal areas in the NS is likely to be marked by substantial hiatuses caused by non-deposition and erosion. During warmer periods, an increased freshwater input from river outflows is also expected, due to the supposedly wetter climate conditions during interglacials. However, Kuhlmann et al. (2006) linked warmer periods in the Pliocene in the central section of the southern North Sea with the occurrence of *Cassidulina laevigata*, whose habitat in the modern North Sea is located in the northern part with a strong connection to the Atlantic (Murray, 1991). Thus, tuning the warmer periods in the $\delta^{18}O_{cass.}$ record at the Hank site with warm periods in the LR04 benthic stack is preferable due to the strong(er) connection to the Atlantic (Kuhlman, 2004), resulting in a relatively more regional signature of the $\delta^{18}O_{cass.}$ values (Kuhlmann et al., 2006). Moreover, the chance of disturbance/hiatuses that affect the continuity of the sediment record at Hank is decreased in warmer periods, thus making them suitable for tuning.~~

~~Using the above reasoning, the sample with the lowest $\delta^{18}O_{cass.}$ value in each cycle between ~300–200 m in the Hank record can be tuned to the lowest $\delta^{18}O$ value between the M2 and the Plio-Pleistocene boundary (Sect. 4.1.2) in the LR04 stack, presuming that the low $\delta^{18}O$ values in the Hank borehole represent the warmest part of each interglacial. Further investigation in the variation of the $\delta^{18}O_{cass.}$ cycles in the Hank borehole isotope record reveals unique saw tooth structures, representing a different pattern than the more symmetrical pattern~~

~~of cyclicity that is seen in the Pleistocene. Specifically, cycles G19, G17, and G15 display these reversed saw-tooth patterns in the global benthic stack, and help pinpoint corresponding cycles in the Hank borehole record (Fig. 5). Hence, starting from the initial age constraints, we correlate lower values in our $\delta^{18}O_{cass.}$ record to those in the global benthic LR04 stacked record (Fig. 5). The reconstructed time window spans ~3200–2800 ka, and thus most of the mPWP. Based on the tuned oxygen isotope age model, the LOD of *Invertocysta lacrymosa* and *Operculodinium? eirikianum* can be constrained to ~3045 and 2600–2782 ka, respectively (see Dearing Crampton-Flood et al., 2018).~~

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4.4~~2~~ Late ~~SST proxy comparison~~~~The mid-Piacenzian Warm Period (mPWP)~~Pliocene climate reconstruction

4.4.1 Marine proxy interpretation~~ies~~

Despite the fact that all three lipid biomarker proxies (TEX_{86}, $U^{K'}_{37}$, and LDI) are calibrated to SST, the records that they generate show remarkable differences and are offset in temperature (Fig. 2e). ~~Interestingly, the TEX_{86}^{H}-derived SST record remains relatively stable throughout the tuned interval, whereas the $U^{K'}_{37}$ and LDI-based records show large variability (Fig. 2e).~~ The Pliocene TEX_{86}^{H} SSTs are 10 °C on average, which is the same temperature as the modern mean SST of the North Sea (Locarnini et al., 2013), and contrasts with other North Sea Pliocene temperature estimates based on ostracod, mollusc, foraminiferal, and dinocyst assemblages (Wood et al., 1993; Kuhlman et al., 2006; Johnson et al., 2009; Williams et al., 2009), all suggesting that the SST of the North Sea was 2–4 º~~º~~C warmer than present at that time. However, present day TEX_{86} reconstructions for core top sediments in the North Sea range between 4.1–9.1 ºC (Kim et al., 2010), and thus underestimate ~~the true~~the observed modern SST~~ in the modern day~~. Lower-than-expected TEX_{86} values found elsewhere have been explained by a contribution of isoGDGTs produced by a subsurface community (Huguet et al., 2007), but ~~G~~given the shallow water depth (80–100 m) of the SNSB in the Pliocene (~~50–200 m;~~ Hodgson and Funnel, 1987; Long and Zalasiewicz, 2011; Overeem et al., 2001; this study) ~~at the Hank site~~, it seems unlikely that ~~the isoGDGTs are influenced by the contribution of a subsurface isoGDGT-producing community~~such a community would have played a role here. This can be further confirmed by calculating the ratio of isoGDGT-2/isoGDGT-3 ([2]/[3]; Taylor et al., 2013), whose value increases with increasing isoGDGT input from subsurface dwelling archaea. The [2]/[3] ratio in the Hank borehole is 2.1 on average, and always well below the value associated with a deep-water archaea community overprint (>5; Taylor et al., 2013). Instead, the low TEX$_{86}^{H}$ SSTs are likely a result of seasonal production of isoGDGTs. In the modern North ~~Sea~~Sea, the main period of Thaumarchaeotal blooms and associated isoGDGT production is in the winter months where ammonia is available and competition with phytoplankton is minimal (Herfort et al., 2006; Pitcher et al., 2011), which likely introduces a cold bias in TEX$_{86}$-based SST estimates for the SNSB. If the TEX$_{86}$-derived SSTs are interpreted as a winter signal as we argue, then the Hank Pliocene SSTs are approximately 3–6 °C warmer than modern winter SSTs (van Aken, 2008).

Conversely, U$^{K'}_{37}$ reconstructed SSTs are 16 °C on average, and thus 2–4 °C higher than the temperature estimates based on ostracod, mollusc, and foraminiferal assemblages (Wood et al., 1993; Kuhlmann et al., 2006; Johnson et al., 2009; Williams et al., 2009) and ca. 6 °C higher than modern annual mean SST. These higher-than-expected U$^{K'}_{37}$ SSTs could in part be caused by a species effect as a result of a contribution from alkenones produced by freshwater haptophyte algae that have little to no correlation of U$^{K'}_{37}$ with temperature (Theroux et al., 2010; Toney et al., 2010). Moreover, the influence of freshwater input on salinity may alter the main alkenone producing communities in coastal regions (Fujine et al., 2006; Harada et al., 2008), and thus affect the reliability of SST estimates based on the open ocean calibration specifically adapted for Group III alkenone producers (e.g. *Emiliania huxleyi*). Indeed, strong temperature fluctuations of 10 °C in a Holocene U$^{K'}_{37}$ record from the Sea of Okhotsk were linked to periods with low sea surface salinity, which were in turn correlated to high U$^{K'}_{37}$-derived SSTs (Harada et al., 2008).~~ In contrast,~~ In contrast, a recent study showed that alkenone producers in particulate organic matter (POM) in a coastal bay in Rhode Island were unaffected by a lower salinity, further illustrated by the excellent match of the 300-year U$^{K'}_{37}$ SST record with instrumental temperature records, despite the proximity to the river (Salacup et al., 2019). Further, Blanz et al. (2005) showed that sediment samples from a salinity transect covering the Baltic Sea to the North Sea showed no relationship between U$^{K'}_{37}$ and SST in the Baltic Proper. Only in the transition zone at Skagerrak, the SSTs were within 1 ºC of the global calibration of Müller et al. (1998). Although the high variability in the U$^{K'}_{37}$ SST record and the higher-than-expected reconstructed temperatures at Hank fit with a freshwater input as observed in the Sea of Okhotsk, low BIT index values and T/M ratios in the Hank borehole (Fig. ~~3~~4) suggest that the organic matter has a primarily marine origin. In addition, the absence of the C$_{37:4}$ alkenone in the Hank sediments, a biomarker tentatively linked with coastal or freshwater haptophytes (Cacho et al., 1999), suggests that the U$^{K'}_{37}$ should mostly represent SSTs, although studies from the Baltic Sea indicate that the relative contribution of~~.~~ $C_{37:4}$ alkenones only increases at at salinities lower than 8 psu (Schulz et al., 2000; Kaiser et al., 2017). Thus, the ~~However, a~~ moderate relation between the %C_{32} diol and $U^{K'}_{37}$ derived SST ~~throughout~~ for the tuned ~~record~~ interval (n = 26; $R^2 = 0.32$), suggests that freshwater input may at times have influenced the $U^{K'}_{37}$ SSTs.

Alternatively, the higher $U^{K'}_{37}$ SSTs can be a result of increased production in the spring or summer (Chapman et al., 1996; Rodrigo-Gámiz et al., 2014). Indeed, summer temperatures in the Oosterhout Formation (Ouwerkerk, Netherlands) and contemporaneous Lillo Formation in Belgium (Valentine et al., 2011) recorded from benthic bivalves range from 14.9–20.4 °C, which is similar to the range of $U^{K'}_{37}$ SSTs in Fig. 2e. This would mean that summer SSTs were high and very variable during the Pliocene. Although quite variable in the earlier (~3250–3150 ka) part of the ~~tuned~~ record, $U^{K'}_{37}$ SSTs warmed by approximately 10 °C over the latter part of the tuned interval from 3150 to 305~~0~~0 ka (Fig. 6d). Reconstructed modern SSTs from surface sediments in Skagerrak region near the opening to the Baltic sea range from 10–12 ºC, slightly higher than observed annual SSTs, and resemble those of May to June more (Blanz et al., 2005). Thus, there is evidence in the modern North Sea adjacent area for the $U^{K'}_{37}$ recording summer temperatures (coinciding with haptophyte blooms). ~~In line with the winter-biased and warmer season-biased interpretation of the TEX$_{86}$ and $U^{K'}_{37}$ reconstructed SSTs, respectively, comparison of the average reconstructed TEX$_{86}$ (10 °C) and $U^{K'}_{37}$ (16°C) SSTs in the mPWP interval shows good agreement with the PRISM3 model reconstructions for February (10.4 °C) and August (16.7 °C; Dowsett et al., 2009).~~

~~Finally, the LDI record is not complete over the whole depth interval due to low abundances of long chain diols in various parts of the record. Nevertheless, the LDI-based SSTs show the same warming trend from ~3150–3000 ka as the $U^{K'}_{37}$ record (Fig. 6d).~~ LDI SSTs are at first 2 °C cooler than the TEX$_{86}$ record, and then increase toward the same absolute SSTs as in the $U^{K'}_{37}$ record (Figs. 2, 6d). Large discrepancies of 9 °C between TEX$_{86}$ and LDI-derived SSTs have been observed in the Quaternary of South Eastern Australia (Lopes dos Santos et al., 2013), which the authors attributed to seasonal production of isoGDGTs in the cooler months and long chain diols in the warmer months. In late Pliocene sediments from the central Mediterranean, LDI SST estimates were slightly lower than $U^{K'}_{37}$ SSTs, however this was within the error range of the proxies (Plancq et al., 2015). Due to the recent advent of the LDI proxy, and the scarcity of other multi-proxy studies (De Bar et al., 2018; Lattaud et al., 2018) comparing the LDI to $U^{K'}_{37}$ and TEX_{86} SSTs in the same sediment samples, further discussion on this topic is limited.

4.4.2 mPWP climate ~~5. Late Pliocene climate evolution in the southern North Sea Basin~~

~~5.1 The M2 event and recovery~~

~~The M2 event is most likely incomplete, or absent in the Hank record, and is marked by a hiatus that is also recognized in sequences from the Coralline Crag in the English North Sea and the Nordic Seas (Fig. 1, Williams et al., 2009; Risebrobakken et al., 2016). Nevertheless, in the sediments occurring above the hiatus marked by the sequence boundary in Fig. 4, large variability in $\delta^{18}O_{cass.}$ indicates fluctuating climate conditions that may be associated with the onset or the recovery of the M2. The fluctuations match those in the records of the BIT index and $\delta^{13}C$ of organic matter (see Dearing Crampton-Flood et al., 2018), which indicate a closer proximity of the coast to the site, likely as a result of sea level change. The major peak of *Osmunda* spores (outside of pollen percentage sum) after to the hiatus at ~3210 ka (306 m) could then represent a pioneer phase of marsh vegetation related to a rapid sea level lowering. The (sub)polar dinocyst acme and increase of *Operculodinium centrocarpum* (Fig. 2, 6a) at 305 m may then represent the restoration of the location of the Hank site to a more distal marine setting within the confinement of the Rhine Valley Graben. The acme of *Osmunda* spores coincides with the occurrence of dinocysts characteristic of (sub)polar watermasses at ~3210 ka, further indicating cold conditions (Fig. 6). In addition, the distinct decrease in Taxodioidae-type pollen at the same time indicates that climate conditions were also cold(er) on the continent (Fig. 6c), which is supported by low terrestrial mean air temperatures of 6 °C, independently reconstructed based on brGDGTs (Fig. 6f; Dearing Crampton-Flood et al., 2018). In contrast, all SST reconstructions remain stable during this M2 deglaciation/recovery period (Fig. 6d), suggesting that cold periods on land are better recorded in the sedimentary record than those in the marine realm. Indeed, terrestrial proxies represent an integrated signal over longer time and larger space (NW Europe), compared to that of the marine proxies, which are confined to the shallow SNSB basin and potentially only record warm periods (Sect. 4.1.3).~~

~~5.2 The mid-Piacenzian Warm Period~~

The mPWP is ~~practically~~ almost entirely covered by the oxygen isotope age-~~age~~ tuned interval of the Hank record, which starts after the hiatus that marks the M2 event. This mPWP interval is correlated with the Poederlee Formation and Oorderen Sands Member (of the Lillo formation) located in Belgium (De Schepper et al., 2009; Louwye and De Schepper, 2010). ~~The sea level drop associated with the M2 event may have decreased the inflow of Atlantic bottom water currents originating from the Northern opening of the North Sea (Kuhlmann et al., 2006). After the M2 event, isostasy may have then slowly opened a new connection to the North Atlantic via the English Channel, which would have allowed the inflow of relatively warmer and saline Atlantic Water fed by the North Atlantic Current (NAC) into the North Sea (Funnel, 1996). The occurrence of such an inflow is supported by the are in the North Atlantic and high abundance of dinocysts from *Operculodinium centrocarpum*, that is generally used as a tracer for the NAC (Boessenkool et al., 2001; De Schepper et al., 2009; Fig. 6a), present after the hiatus associated with the M2 event at ~3210 ka (305 m). The amount of *Operculodinium centrocarpum* cysts then decreases to zero and gradually re-emerges from 3150 ka on (Boessenkool et al., 2001; De Schepper et al., 2009; Fig. 6a), indicating a fluctuating influence of the NAC.re-emergencemore likely reflects the in the shallow SNSB~~

The average TEX_{86} (10 °C) and $U^{K'}_{37}$ (16°C) reconstructed SSTs over the mPWP interval show good agreement with the PRISM3 model reconstructions for February (10.4 °C) and August (16.7 °C; Dowsett et al., 2009).

~~4.4.2 Terrestrial climate~~

~~The presence of Taxodioidae-type pollen (*Taxodium*, *Glyptostrobus*) throughout most of the mPWP (Fig. 6c) indicates that land temperatures were generally not low enough for prolonged winter frosts. Minimum Taxodioidae-type pollen abundance of 10% has been associated with a mean temperature of the coldest month of >5 °C (Fauquette et al., 1998). The terrestrial temperature record of Dearing Crampton-Flood et al. (2018) and the increased proportion of Taxodioidae-type pollen (Fig. 6) support the presumed relatively stable climate conditions on land during the mPWP (Draut et al., 2003; Lisiecki and Raymo, 2005). Importantly, the new chronology for the Hank sediments provides an opportunity to date and quantify the local (Netherlands) qualitative Pliocene-Pleistocene Taxodioidae-type temperature curves proposed by Zagwijn (1960; 1992). Zagwijn et al. (1992) inferred mean July temperatures between 15–20 °C for the Reuverian, which he placed approximately between 3.1–2.5 Ma, with short lived cool pulses down to ~12 °C that can also be recognized in the brGDGT MAT record (Fig. 6f).~~

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~~Maximum Taxodioidae abundance and mean July temperatures in excess of 20 °C were reconstructed for the Brunssumian placed approximately between 3.4–3.1 Ma. These reconstructed summer temperatures compare broadly to the SSTs reconstructed using the (presumably) partially summer biased $U^{K'}_{37}$ proxy, which range between ~10–25 °C in the tuned interval (Fig. 6d). It should be noted that the original terrestrial Pliocene stages as summarized by Zagwijn (1992) have not yet been dated independently, and in the type area of the South East Netherlands, they likely represent much smaller intervals of time compared to the Hank sequence.~~

~~In contrast to the stable terrestrial climate, the LDI and $U^{K'}_{37}$ SST records indicate that SSTs were highly variable during the mPWP (Fig. 6d). Interestingly, the TEX_{86}^{H}-derived SST record remains relatively stable throughout the tuned interval. The large amplitude of the variation in the $U^{K'}_{37}$ and LDI SST records may be a result of the at the time relatively shallow coastal location of Hank, which is sensitive to warming and cooling. The proximity to of the site to freshwater input may also play a role, however this cannot be confirmed. (Sect. 4.3). Notably, the high variability in SSTs during the mPWP at the Hank site is also seen in all other currently available $U^{K'}_{37}$ SST records from the North Atlantic (Lawrence et al., 2009; Naafs et al., 2010; Bachem et al., 2017; Clotten et al., 20183). The proposed scenarios for the high variability in these $U^{K'}_{37}$ SST records range from a change in the strength of the NAC (Lawrence et al., 2009; Naafs et al., 2010), orbital forcing (Lawrence et al., 2009; Bachem et al., 2017) and ocean gateway changes (Bachem et al., 2017). In addition, the high variability in the $U^{K'}_{37}$ record from the Iceland Sea record was linked to the frequent occurrence of spring sea ice cover and ice-free summers linked to freshwater input (Clotten et al., 2018). Thus, the high variability of $U^{K'}_{37}$ SSTs at the Hank Site during the Pliocene is most likely due to a combination of freshwater influence, the shallow depth of the SNSB, and changes in the direction and strength of the NAC. Orbital forcing may play a role in pacing the variation of the NAC (Naafs et al., 2010), although this investigation requires further analysis, which is not possible in the Hank borehole due to the short tuned interval. Nevertheless, the common factor among the records discussed here is the influence of variations in the position of the NAC, which thus seems most likely responsible for the variation in all five $U^{K'}_{37}$ SST records discussed above.~~

~~In contrast, the variability of the $U^{K'}_{37}$ SSTs is not reflected in the TEX_{86} record, which may be due to the winter signal they record (Sect. 4.3). Regardless, a~~A common feature of the $U^{K'}_{37}$ and LDI SST records is the gradual warming between ~3150–3050~~00~~ ka (Fig. 6d), seen most clearly in the LDI record. Before the SST warming from 31~~2~~5~~0~~0–3~~1~~050 ka, %C_{32} diol decreases slowly (Fig. 6e), indicating a decrease in freshwater discharge and/or an increased distance to the coast. The low T/M ratios and the presence of a clay layer from 292–271 m in Fig. 4~~3~~c (corresponding to 3155–3~~17~~053 ~~–3070~~ ka; Fig. 6) at this time further indicate increased marine influence, likely as a result of sea level rise. Differences in the absolute degree of warming recorded by the $U^{K'}_{37}$ and LDI SST ~~organic SST~~ proxies ~~may~~ could be attributed to the different season in which they are produced, as well as by lateral transport of certain biomarkers (Benthien and Müller, 2000; Ohkouchi et al., 2002). For example, the change in currents in the North Sea after the M2 event, bringing in warmer waters from the North Atlantic may have brought alkenones and/or diols with a warmer signature to the SNSB.~~,~~ This would then further contribute to the high ~~resulting in the high~~ SSTs reflected by the $U^{K'}_{37}$ and LDI proxies compared to those recorded by the TEX_{87}^{H} (Fig. 6). ~~Regardless, the high variability and warming trend in two out of the three organic SST proxies in the Pliocene North Sea indicate that the area encompassing the North Atlantic, Nordic Seas, and North Sea was very sensitive to changing currents, probably as a result of the strength and/or direction of the NAC.environmental changesdrivers~~

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Notably, where the TEX_{86}^{H}-derived SST record suggests relatively stable winter temperatures, the LDI and $U^{K'}_{37}$ SST records reflect highly variable SSTs during the mPWP (Fig. 6d). Such high variability is also seen in all other currently available $U^{K'}_{37}$ SST records from the North Atlantic (8 ºC, Lawrence et al., 2009; 6 ºC, Naafs et al., 2010; 14 ºC, Clotten et al., 2018; Fig. S3), and has been explained by a change in the strength of the NAC (Lawrence et al., 2009; Naafs et al., 2010) and orbital forcing (Lawrence et al., 2009). In addition, high variability in the $U^{K'}_{37}$ record from the Iceland Sea was linked to the frequent occurrence of spring sea ice cover and ice-free summers linked to freshwater input (Clotten et al., 2018). At Hank, the influence of changes in the direction and strength of the NAC on $U^{K'}_{37}$ SSTs cannot be unambiguously identified, despite the re-occurrence of *Operculodinium centrocarpum* during the mPWP. Most of the variation may instead be explained by the varying influence of freshwater input from the proto-Rhine-Meuse River system in combination with the relatively shallow coastal location of Hank, which makes it sensitive to fluctuations in temperature. The influence of orbital forcing on pacing the variation of the NAC (Naafs et al., 2010), and possibly the environmental conditions in the SNSB requires further analysis, which is currently not possible in the Hank borehole due to the short length of the tuned interval.

In contrast to the variable marine climate, the terrestrial climate proxies indicate that climate of land was fairly stable. The presence of Taxodioidae-type pollen (*Taxodium*, *Glyptostrobus*) throughout most of the mPWP (Fig. 6c) indicates that land temperatures were generally not low enough for prolonged winter frosts. Minimum Taxodioidae-type pollen abundance of 10% has been associated with a mean temperature of the coldest month of >5 °C (Fauquette et al., 1998). Both the MAT record (Dearing Crampton-Flood et al., 2018) and the *Taxodioidae*-type pollen covary throughout the whole record (Fig. 4d), and the absolute MATs and the increased proportion of Taxodioidae-type pollen in the mPWP interval (Fig. 6) support the presumed relatively stable climate conditions on land (Draut et al., 2003; Lisiecki and Raymo, 2005).

Importantly, the new chronology for the Hank sediments provides an opportunity to correlate the stratigraphy concept of the local (Netherlands) qualitative Pliocene-Pleistocene Taxodioidae-type temperature curves proposed by Zagwijn (1960; 1992). It should be noted that the original terrestrial Pliocene stages as summarized by Zagwijn (1992) have not yet been dated independently, and in the type area of the South East Netherlands, they likely represent much smaller intervals of time compared to the Hank sequence. Zagwijn et al. (1992) inferred mean July temperatures between 15–20 °C for the Reuverian, which he placed approximately between 3.1–2.5 Ma, with short lived cool pulses down to ~12 °C that can also be recognized in the brGDGT MAT record (Fig. 6f). Maximum Taxodioidae abundance and mean July temperatures in excess of 20 °C were reconstructed for the Brunssumian placed approximately between 3.4–3.1 Ma. These reconstructed summer temperatures compare broadly to the SSTs reconstructed using the (presumably) partially summer-biased $U^{K'}_{37}$ proxy, which range between ~10–25 °C in the tuned interval (Fig. 6d). Further correlation and dating studies in proximal boreholes and marine sediment sequences will aid in deciphering the Reuverian A-C substages and assigning absolute ages to the zonation of Zagwijn et al. (1992).

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5. Conclusions

The age framework for the mid-to-late Pliocene of the Southern North Sea Basin (SNSB) constructed here reveals that the M2 glacial is represented as a hiatus, confirming interpretations at proximal sites in ~~the Nordic Seas~~Belgium and the English North Sea coast. ~~Our terrestrial multi-proxy climate records show a highly consistent signal between lipid biomarker temperatures and pollen assemblages, which show stable terrestrial temperatures of 10–12 °C, and the continued presence of warm-adapted tree species during the mPWPP. Importantly, the chronology presented here allows placing earlier terrestrial temperature reconstructions for Pliocene NW Europe (Zagwijn et al., 1992) in time. This indicates that the Reuverian Stage concept, characterized by abundant Taxodioidae and *Sciadopitys* and rare *Sequoia*, is dated to ~3.2–2.8 Ma. Further high-resolution analysis will subdivide and date the Reuverian A–C substages. Conversely,~~ S~~s~~ea surface temperatures were variable, which may be caused by the sensitivity of the shallow Pliocene North Sea to climate change and the influence of freshwater input on lipid biomarker SST proxies. Nevertheless, the variability in SSTs matches that in all other currently available SST records from the North Atlantic~~ and Nordic Seas~~, indicating that the marine realm was highly dynamic during the mPWP, probably as a result of shifting currents caused by a reorganization/diversion of the North Atlantic Current~~ after the M2~~. Our terrestrial multi-proxy climate records show a highly consistent signal between lipid biomarker temperatures and pollen assemblages, which show stable terrestrial temperatures of 10–12 °C, and the continued presence of warm-adapted tree species during the end of the mPWP. Importantly, the chronology presented here allows placing earlier terrestrial temperature reconstructions for Pliocene NW Europe (Zagwijn et al., 1992) in time. This indicates that the Reuverian Stage concept, characterized by abundant *Taxodioidae* and *Sciadopitys* and rare *Sequoia*, is dated to ~3.2–2.8 Ma. Further high-resolution analysis will attempt to resolve and date the Reuverian A–C substages in this marine setting. ~~Thus, our multi-proxy approach for the first time reveals that land-sea climate evolution in the SNSB was asynchronous during the mPWP.~~

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Data availability

The research data presented in this paper will soon be available on Pangaea (doi).

Author contribution

~~JSSD, FP, and~~ EDCF, FP and JSSD designed the research. CB and DS carried out the geochemical analyses under supervision of EDCF, LN, FP, LL, and JSSD. DM and THD analysed and interpreted the palynological data. JtV provided seismic interpretations. EDCF integrated the data and prepared the manuscript with contributions from all authors.

Competing interests

The authors declare that they have no conflict of interest.

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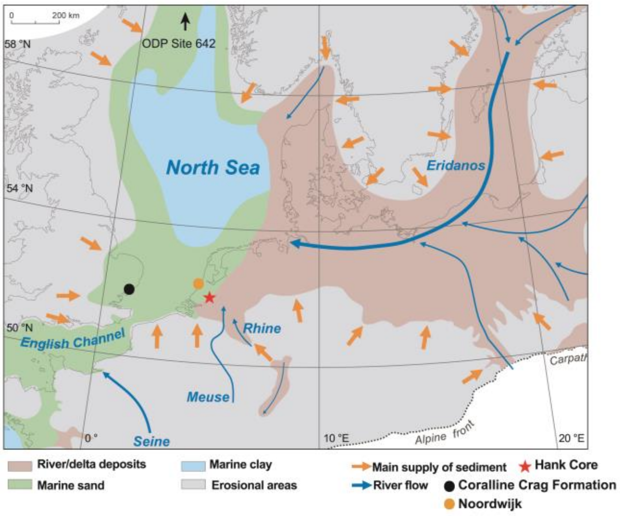


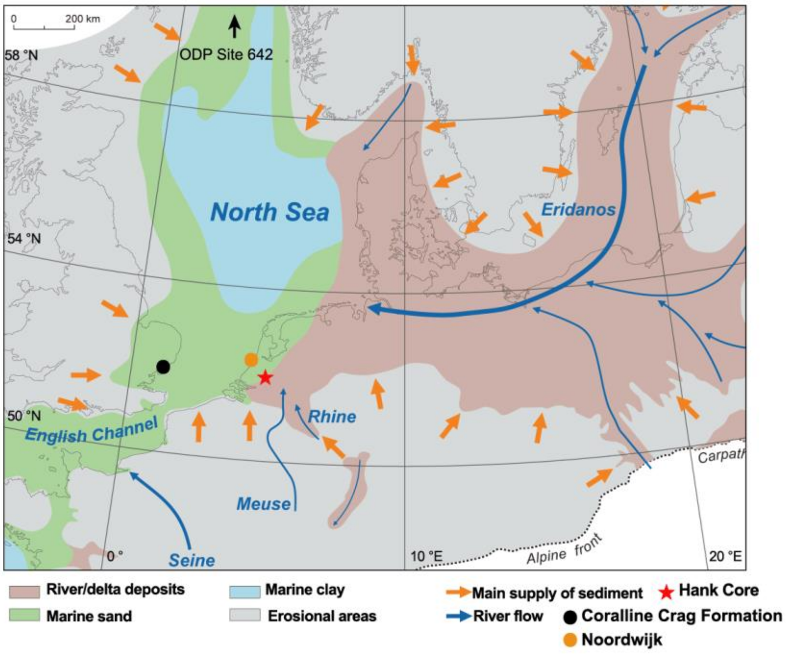
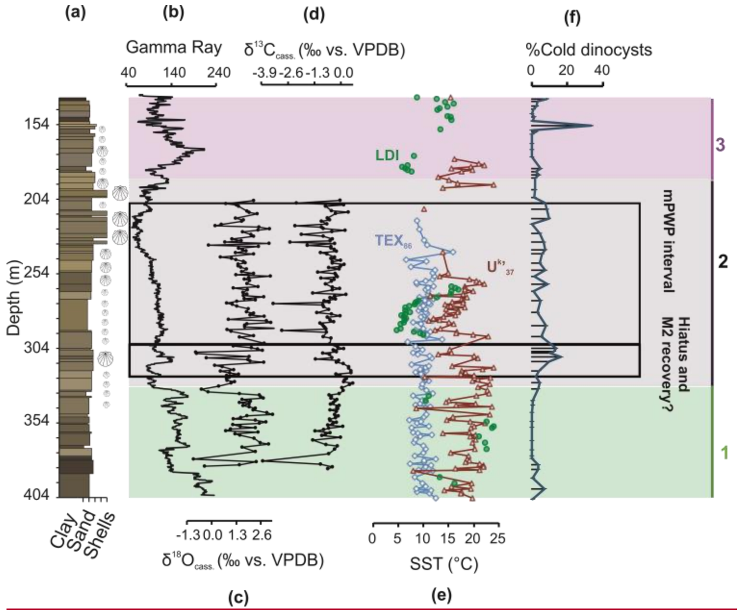


Fig. 1. Pliocene paleogeography in the North Sea basin (Gibbard and Lewin, 2003; Knox et al., 2010). The location of the Hank borehole is ~~denoted~~ represented by a red star. Major rivers and

sediment inputs are represented by blue and orange arrows, respectively. Other locations mentioned in the text are indicated. Figure modified from Gibbard and Lewin (2016).



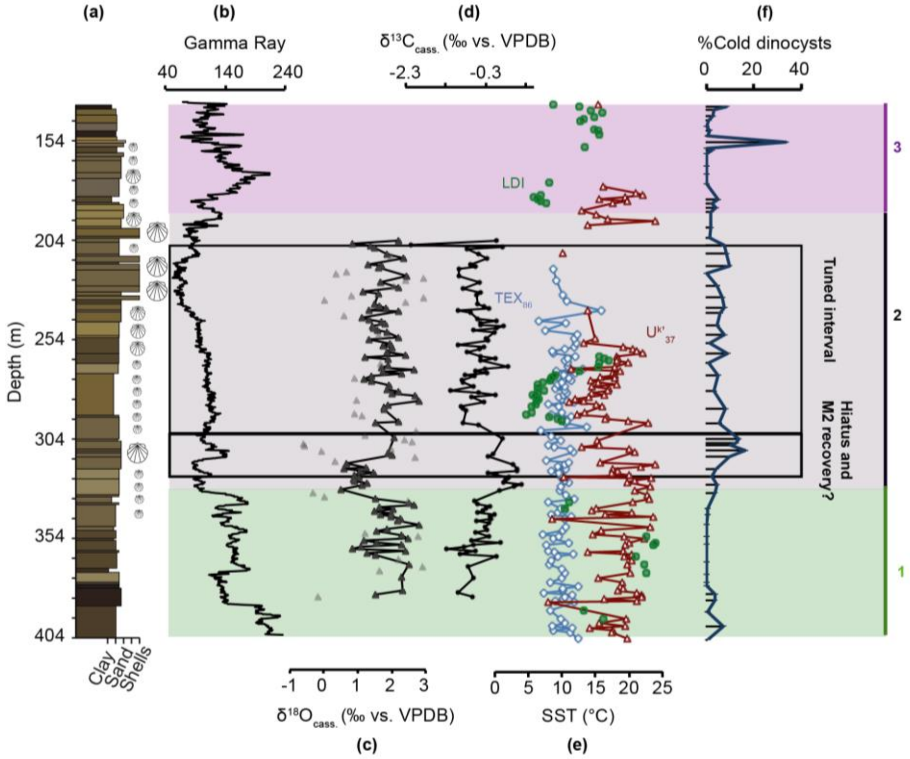


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Fig 2. Marine proxies for the Hank borehole. (a) The depth and lithology of the Hank sediments, with shell material qualitatively indicated by shell symbols. (b) The smoothed gamma ray (GR) log (dinoloket.nl). (c) Stable oxygen and (d) stable carbon isotope records for the endobenthic *Cassidulina laevigata*. ~~Outliers in the $\delta^{18}O$ record are indicated by grey triangles and the record after outlier removal is given in black.~~ (e) SST records based on TEX_{86} (blue diamonds), $U^{K'}_{37}$ (red triangles), and LDI (green ~~circles~~squares). (f) %Cold taxa of dinoflagellate cysts. ~~The intervals~~Intervals ~~corresponding to the~~ 1~~A~~, 2 and 3 ~~(green), B (grey), and C (purple)~~ ~~depths~~ discussed in the text are indicated by green (Early Pliocene), grey (mid-Pliocene), and purple (late Pliocene-early Pleistocene). The tuned interval and the position of the hiatus marking the M2 are represented by a black line.

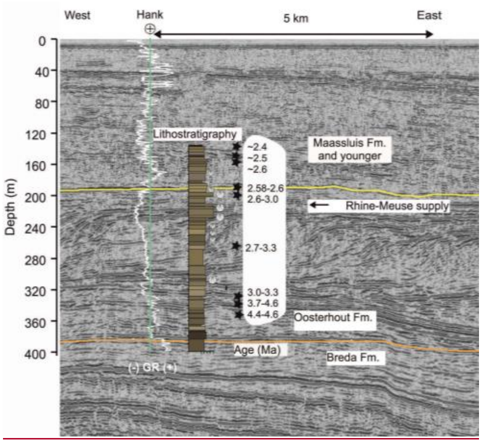

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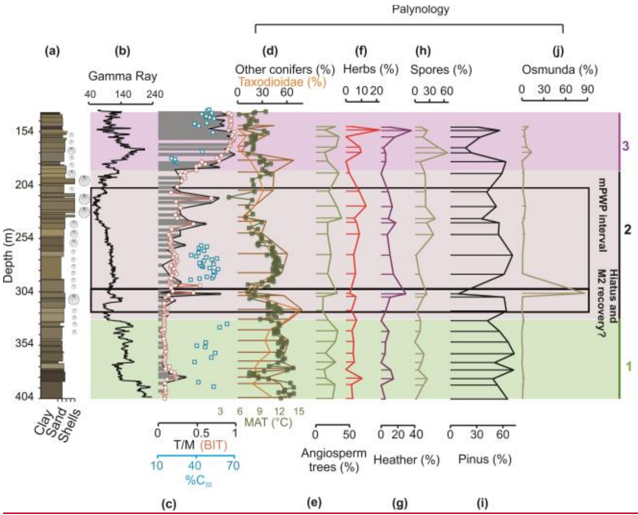
Fig. 3. Seismic east to west depth profile at the River Maas (from Maas2002 survey, nlog.nl) with the location of the Hank borehole (B44E0146) and corresponding formations indicated. The smoothed Gamma ray log (from dinoloket.nl, white), and lithology of the borehole are provided for context. Stars and age ranges refer to the biostratigraphic age model of Dearing Crampton-Flood et al. (2018). The orange and yellow lines represent the boundaries of the Breda and Oosterhout (revised), and the Oosterhout and Maassluis formations, respectively.



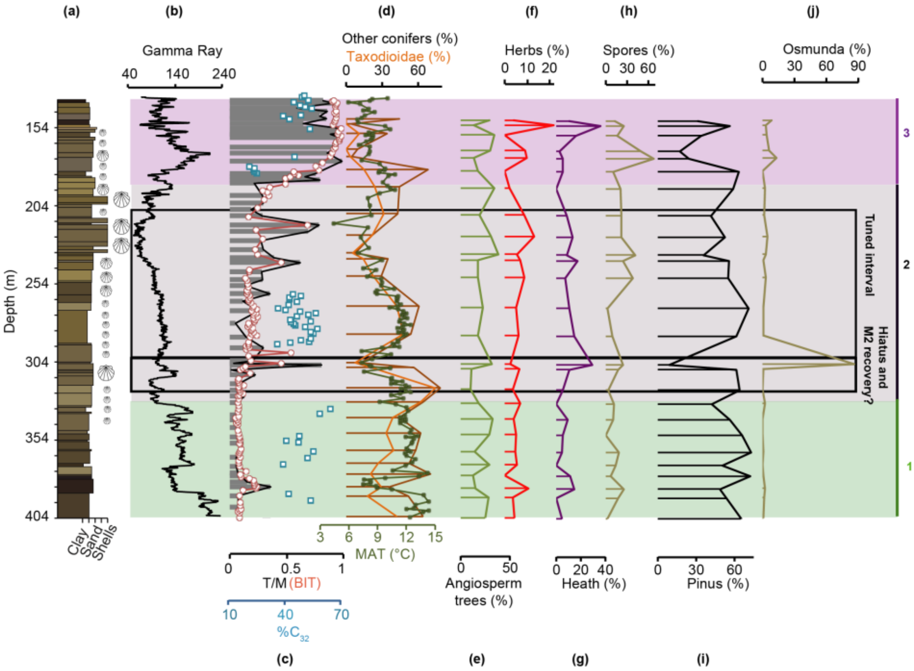


Fig. ~~3~~4. Terrestrial proxies for the Hank borehole. (a) The depth and lithology of the Hank sediments, with shell material qualitatively indicated by shell symbols. (b) The smoothed gamma ray (GR) log (from dinoloket.nl), (c) the relative input of terrestrial organic material to the Hank sediments based on the terrestrial/marine ratio of palynomorphs (black line), the

Branched and Isoprenoid Tetraether (BIT) index (orange circles), and the %C$_{32}$ diol (blue squares). Pollen records expressed as % of total pollen: (d) Other conifers (brown line), Taxodioidae (orange line) and MAT (°C; green line; Dearing Crampton-Flood et al., 2018), (e) angiosperm trees, (f) herbs, (g) heather, (h) spores, (i) Pinus, and (j) Osmunda. Intervals 1, 2 and 3 discussed in the text are indicated by green (Early Pliocene), grey (mid-Pliocene), and purple (late Pliocene-early Pleistocene).~~The intervals corresponding to the A (green), B (grey), and C (purple) depths discussed in the text are indicated.~~ The tuned interval and the position of the hiatus marking the M2 are represented by a black line.

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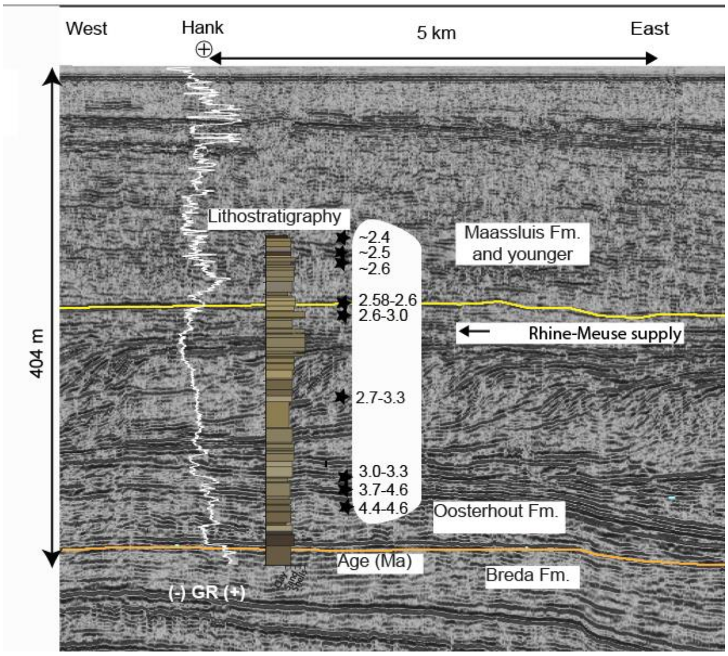

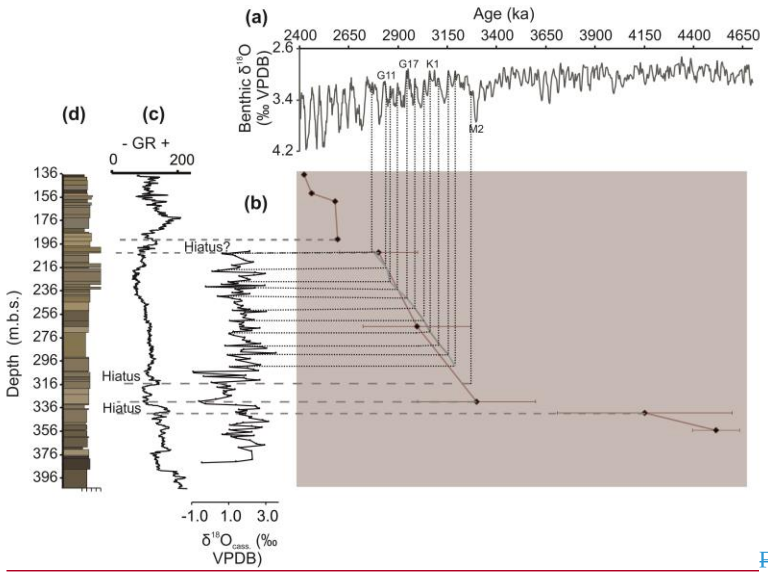

~~Fig. 4. Seismic east to west depth profile at the River Maas (from Maas2002 survey, nlog.nl) with the location of the Hank borehole (B44E0146) and corresponding formations indicated. The smoothed Gamma ray log (from dinoloket.nl, white), and lithology of the borehole are provided for context. Stars and age ranges refer to the biostratigraphic age model of Dearing Crampton-Flood et al. (2018). The yellow and orange lines represent the boundaries of the Breda and Oosterhout (revised), and the Oosterhout and Maassluis formations, respectively. The blue line represents the depth scale of the borehole (i.e. 404 m).~~

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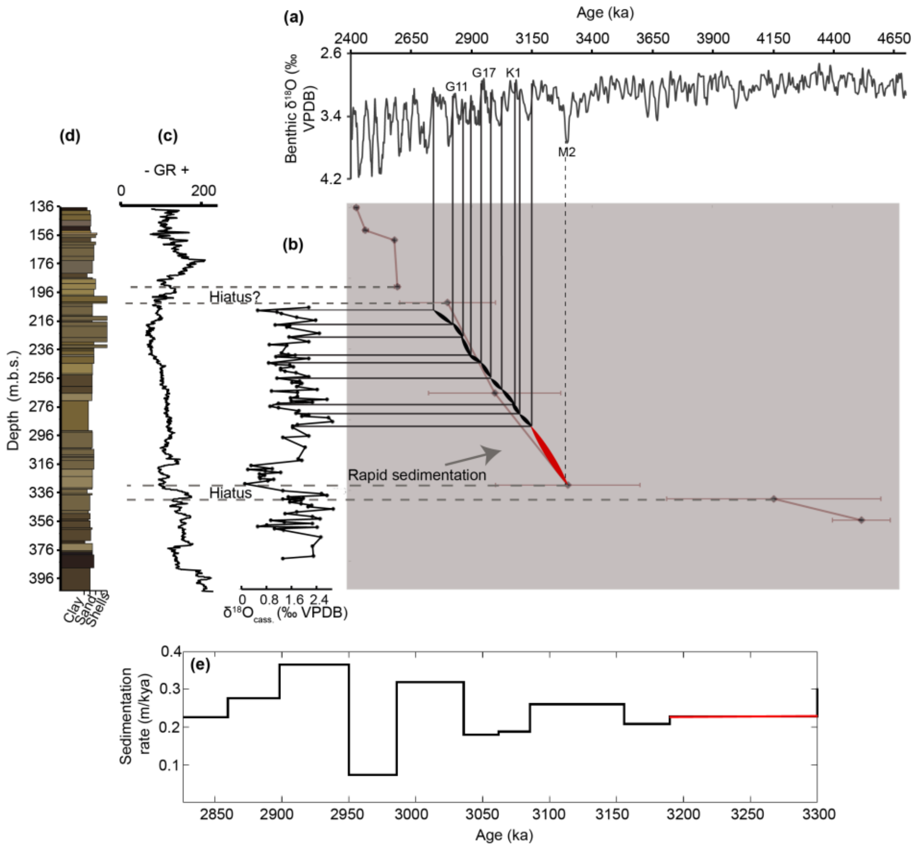
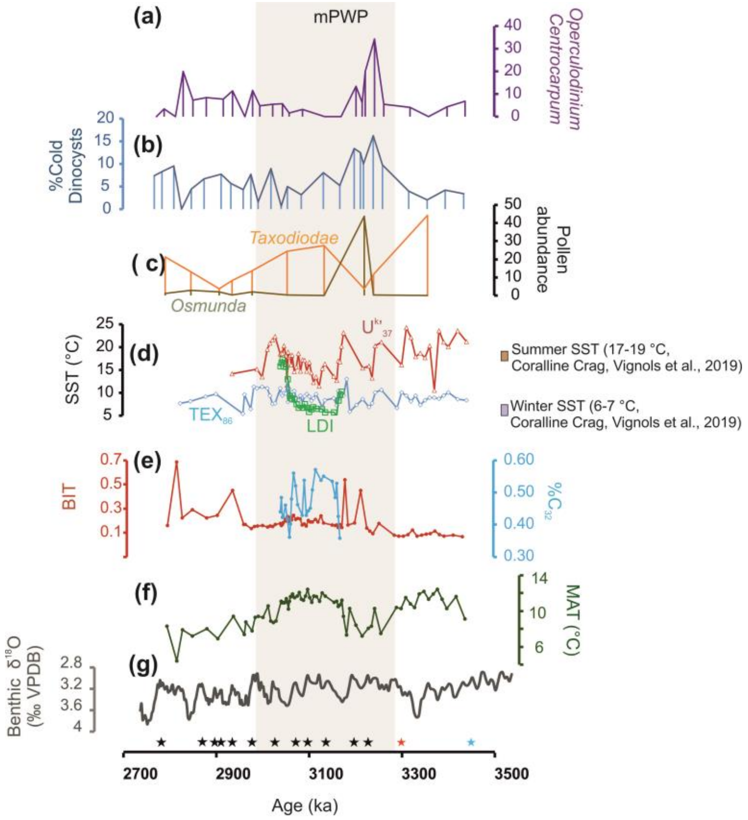


Fig. 5. Age framework for the Pliocene southern North Sea Basin. Correlations of the interglacials of the (a) LR04 stack (Lisiecki and Raymo, 2005) to the interglacials in the (b) $\delta^{18}O_{cass.}$ record for Hank. (c) Smoothed gamma ray (GR), (d) lithology, and depth of Hank sediments. Grey dotted lines indicate tie points based on $\delta^{18}O$ values, whereas the dashed line ~~red tie point is b~~ at ~314 m is based on correlation of sequence boundary with the Poederlee Formation (De Sc~~C~~hepper et al., 2009; Louwye and De Schepper, 2010).~~biostratigraphy. The other b~~Biostratigraphic age ~~points~~ estimates (Dearing Crampton-Flood et al., 2018) are ~~given~~ shown in purple. ~~(e) The sedimentation rate for the tuned interval of Hank.~~


(a)
mPWP
Operculodinium Centrocarpum
40
30
20
10
0
%Cold Dinocysts
20
15
10
5
0
(b)
Pollen abundance
50
40
30
20
10
0
(c)
Taxodiodae
Osmunda
SST (°C)
25
20
15
10
5
(d)
$U^{k'}_{37}$
TEX_{86}
LDI
Summer SST (17-19 °C, Coralline Crag, Vignols et al., 2019)
Winter SST (6-7 °C, Coralline Crag, Vignols et al., 2019)
BIT
0.7
0.5
0.3
0.1
(e)
%C_{32}
0.60
0.50
0.40
0.30
(f)
MAT (°C)
14
10
6
Benthic $\delta^{18}O$ (‰ VPDB)
2.8
3.2
3.6
4
(g)
2700
2900
3100
3300
3500
Age (ka)

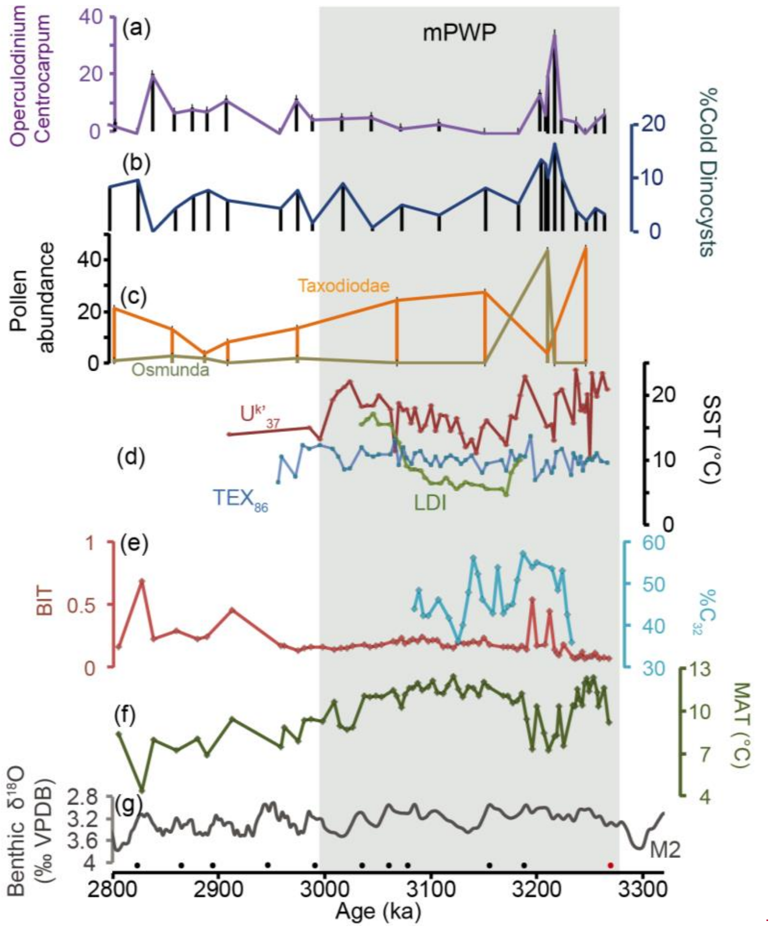


Fig. 6. Climate proxy records for the southern North Sea Basin ~~around the mPWP~~for the late Pliocene. Age tie points (stars) based on oxygen isotope stratigraphy (black), sequence boundary correlation (red), and ~~and~~ biostratigraphy (~~red~~blue) are indicated. The depth interval covered by the age tying points is 206–330 m. (a)~~ The relative abundance of *Operculodinium centrocarpum* expressed as a percent total dinocysts as marker for the North Atlantic Current. (b)~~ the relative abundance of *Operculodinium centrocarpum* expressed as a percent total of dinocysts, (b) %Cold dinocysts, (c~~e~~) pollen abundances for *Taxodioidae* (orange) and *Osmunda* (dark yellow) as a percentage of the pollen sum, (d~~d~~) SST records based on the TEX$_{86}$, U~~^{k}~~$^{K'}_{37}$ and LDI proxies, together with estimates (dotted lines) from oxygen isotope measurements of bivalves (Vignols et al., 2019), (~~e~~e) the relative input of terrestrial organic material to the Hank sediments based on the Branched and Isoprenoid Tetraether (BIT) index (~~from~~ Dearing

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Crampton-Flood et al., 2018) and the input of fresh water based on %C32 diol, (~~(f~~f) mean air temperature based on brGDGT-paleothermometry (~~from~~ Dearing Crampton-Flood et al., 2018), and (~~g~~g) the benthic oxygen isotope stack of Lisiecki and Raymo (2005).