**Comments and author responses**

- Reviewer comments are in **bold**
- Author statements of changes made in revised manuscript follow in normal print

**Comments by Yige Zhang**

**Is there any Sr or Nd isotope data from these IRD that could be used to pin down the source of their detritus material? If not, maybe just point to the fact that they can be used in the future.**

We have moved part of the discussion of IRD to the methods section (now 3.3) and have added the information about the challenges of determining provenance in the specific setting of the Norwegian Sea (page 17, line 14-27).

**Comments by Clara Bolton**

**Introduction**

**The cited reference for the first sentence about Pliocene warmth (Zachos et al., 2001) is not really appropriate. Perhaps cite some Pliocene temperature papers instead that quantify warmth relative to the present.**

We have changed the introductory reference to (Lisiecki and Raymo, 2005; Fedorov et al., 2013; Herbert et al., 2016) (page 11, line 22-23).

**Discussion related to AMOC strength and North Atlantic water masses The paragraph of the introduction that discusses AMOC (starting page 2 line 12) needs significant revision, because as it is, it misrepresents the strength of paleo-evidence for a strengthening in AMOC during the warm Pliocene, between 4.6 and 4 Ma. The idea that AMOC intensified at ~4.6 Ma was originally based on an increase in d13C values measured in benthic forams and an increase in sand content at ODP Site 999 in the Caribbean Sea (Haug & Tiedemann 1998). These proxy data were interpreted as indicating that after 4.6 Ma, the Caribbean was filled (over an intermediate depth sill) with northern-component water (UNADW) rather than more corrosive, low d13C southern-component water (AAIW) – i.e. the spatial extent of UNADW increased at this time. Bell**

**et al.'s 2015 paper in Scientific Reports showed that there was no similar contemporaneous increase in the spatial extent of LNADW, and that NADW production was apparently strong both before and after 4.7 Ma.**

**Therefore, by themselves, the Haug & Tiedemann (1998) and Steph et al (2010) records (from Caribbean ODP Sites 999 and 1000, respectively) do not provide strong evidence for an intensification of AMOC, rather an increase in the spatial extent of UNADW. In the Pleistocene, the intermediate-depth Caribbean fills with more positive d13C water during glacials relative to interglacials because UNADW penetrates into the Gulf of Mexico when LNADW spatial extent reduces during cold stages (Site 502, Oppo et al., 1995, Paleoceanography), so the confidence placed in the Caribbean Pliocene data on their own as evidence for a stronger AMOC is puzzling to me.**

**Spatial changes in water masses do not have to equate to changes in AMOC strength, e.g. the NADW cell can shoal, but circulation in it (i.e. AMOC) can still be strong. During the last glacial, evidence suggests that AMOC remained relatively strong for the most part (even during most Heinrich events; Bradtmiller et al., 2014; Bohm et al., 2015) despite a much reduced spatial extent of LNADW in the deep North Atlantic at that time.**

**In summary, the language used in the manuscript leaves the reader thinking that assessment of all available evidence could still lead to the conclusion that AMOC intensified at 4.6 Ma, and I don't think it can any longer with any confidence (that is, unless analysis of their data, following suggestions below, provides new supporting evidence for the original claim). If you follow this route, I think you need to change the introduction to set up the problem more fairly, i.e. that based on Bell's new work it is no longer clear if AMOC intensified between 4.6-4 Ma.**

**Also, the authors should note that Bell et al. published a paper in 2015 in QSR, which shows that the conclusions of Zhang et al. (2013) are incorrect because in d18O-d13C space, Site 704 is bathed by northern component water, and not southern component water, with a more positive d13C value. Quote: "Zhang et al. (2013) proposed a scenario, based on model-data comparisons, whereby Southern Ocean ventilation increased, raising d13C values at Site 704, a site that has been important for inferring enhanced AMOC. A closer examination of our data, however, indicates a northern sourced influence on Site 704 d13C, thereby supporting an enhanced AMOC**

**interpretation. This is because Site 704 data lies close to Site 1264 in d18O-d13C space, while Site 929, which is sensitive to the influence of SSW, lies closer to Pacific Site 849."**

**Lastly, I would suggest you do not cite Sarnthein et al. (2009) on page 2 line 25, because this paper contains no new data in it that relate to AMOC during the mid-Piacenzian warm period, but one of the original papers (in addition to Raymo et al., 1996 already cited) that discusses evidence for an enhanced AMOC based on spatial water-mass structures such as Ravelo and Andreasen (2000). These comments on how you discuss changes in AMOC strength are also relevant to some parts of the discussion (for example page 12, in reference to Steph et al 2010).**

We have added references in the introduction and discussion, including studies that suggest AMOC stability during periods of intense climate change. We have also added more information regarding alternative hypotheses for Pliocene Atlantic climate variability besides the Central American Seaway closure, such as changes in the Greenland-Scotland Ridge sill depth during the Pliocene (page 12, line 13 to page 13, line 5).

The Sarnthein et al. (2009) reference has been removed at the specified location (page 12 line 15).

**Methods/Results**

**p5, line 25: this value is not really a regional average, as it is based on one site. I suggest changing to "Holocene average at a nearby site" or similar. Note: perhaps also worth mentioning in the methods why you use this nearby site to get Holocene values for comparison rather that the same site (I guess it's not possible?).**

We have used the suggested phrasing of "Holocene average at a nearby site" (page 18, line 1). We note that core-top data from the main study sites (Hole 642B and Site 907) were not available (page 15, line 3 to 8).

**Some description of seasonality of alkenone production/coccolithophore productivity in this region in the modern ocean would be useful here, with the methods. Perhaps this is why you only mention summer SSTs? Ok, now I see you discuss seasonality later in the "proxy interpretation" section of**

**the discussion... I would suggest incorporating this whole section in the relevant parts of the methods, so that your discussion flows better and all caveats/assumptions are already dealt with and out of the way. "Nevertheless, there is some doubt about the preservation of alkenone production seasonality signals in sediments" – this statement is a bit cryptic! Please expand and explain. Is summer SST very different to mean annual at your study site (i.e. would a summer bias make a big difference to absolute values)?**

We have moved and adjusted the discussion section regarding alkenone interpretations (previously 4.1) to the method section (now section 3.2, page 16, line 1 to 17) to help clarify our interpretation of $U^{K'}_{37}$ data in the Nordic Seas at an earlier point than previously.

We have added a clarification to the concerns voiced by Rosell-Melé and Prahl (2013) regarding the preservation of seasonality in alkenones in the sediment (page 16 line 4).

**p6 line 13: number missing**

The number has been added (page 18 line 20).

**p7 line 14: is this statement supported by biological oceanography data?**

We now address this in the methods, section 3.2, referencing Bauman et al. (2000) (page 16 line 14).

**Overall, I think the results section is lacking a basic, clear description of the key features of your new records: the existence of large-amplitude changes in SST on xx and yy timescales at Site 642 in the warm Pliocene. This finding is supportive of the ideas put forward by Kira Lawrence et al (2009) based on Site 982 further south, that the warm Pliocene high northern latitudes were characterized by this large-amplitude surface variability in SST at this time. I think the Site 982 SST record should be included in a figure for comparison (as well as the Herbert et al. (2016) Site 907 record already included, and perhaps also the Knies et al (2014) Site 910 record mentioned), even though it only overlaps with the younger part of your new record. NB: I suggest you plot the Site 982 SST data from Lawrence et al. (2009) on its original LR04 age model. One group has challenged the validity of the LR04 age model for Site 982 during your study interval (Khélifi et al.,**

**2013; CP). However, its LR04 age model has been shown to provide the best estimate of the age-depth relationship for this site (Lawrence et al., 2013; CP). In this regard, it is interesting to note that your new 642 SST record looks very similar to the 982 SST record when the latter is plotted on its LR04 age model. At the start of the SST discussion, I would then compare the new 642 record with both the Site 907 and Site 982 SST records, in terms of the amplitude of orbital-scale variability where they overlap, and the longer-term trends. This comparison should form the centerpiece of your discussion, since inferences on forcing factors, whilst interesting, remain mainly speculative at present.**

We have added a figure (new Fig. 4, page 43) comparing our data from Hole 642B, the Site 907 record (Herbert et al., 2016) and the SST data available from Site 982 (Lawrence et al., 2009; Herbert et al., 2016). Because the focus of this paper is on the development of Nordic Seas temperatures, we consider a separate figure more useful than adding the Site 982 data to the main figure (Fig. 2).

We have added a short note on this dataset in the introduction (page 13 line 28-30), and refer to Fig. 4 when discussing North Atlantic temperatures in contrast to the developments in the Nordic Seas (page 21, line 28; page 22, line 18; page 26, line 21; page 27, line 6 and 29).

**Figures**

**Figure 1: It would be nice to include modern SST contours on this map, so that the reader can gain insight into zonal and latitudinal SST gradients in the region, and the effects of the various currents on SST (which are subsequently discussed a lot for the Pliocene).**

We have added shading and contour lines to the map, indicating modern summer temperatures (from World Ocean Atlas, Locarnini et al., 2013) (page 38).

**Figure 2a: IRD records: It is confusing using different y-axis scales for the two IRD records... I would suggest putting them on the same scale (perhaps with a break in the axis at the high end so you can still see the smaller peaks clearly). Are these two records both on your new age model?**

We have scaled both datasets to the same axis (page 40). Were the Jansen et al. (1990) dataset goes beyond the length of the axis, the peak concentrations of IRD have been noted next in the figure.

**Figure 2b: the use of a dashed line makes it hard to see what is going on.**

We have made the line continuous (page 40).

**Figures 2 and 3: I suggest adding the LR04 benthic isotope stack to these graphs for reference, so the reader can more easily visualise where major SST changes and IRD peaks occur in relation to familiar Marine Isotope Stages.**

We have added the LR04 stack to Fig. 5 (page 44) (previously this was Fig. 3).

**Discussion**

**Holocene data: Relatively high variability (~4 degree range) is documented in the new Holocene Iceland Sea SST record, and this is not really mentioned because the authors go on to use a mean value for comparison with the Pliocene. Is this what one would expect within the Holocene (suggesting that local oceanography is very dynamic at this time?)? Do other Nordic Sea records show similar high SST variability during the Holocene? A short discussion of these data could be appropriate, in the context of determining whether the Pliocene SST swings (within a not dissimilar range of 4 to 6 degrees) likely represent major oceanographic/climate changes, or smaller regional shifts in currents or fronts that can have big impacts on SST at the given location. Personally, I don't like the subdivision of the Pliocene study interval into seemingly random sub-intervals of time based on changes occurring in one proxy record. I think it would be more intuitive and easier to follow if you approached the discussion using a "one paragraph, one idea to get across" method. Then for each paragraph, you can describe the new evidence from your records and supporting evidence from the literature that support that idea. Are the 6 shorter time intervals used here the same as the "climate phases/transitions" defined for the same site and time period in Risebrobakken et al., 2016? Based on a quick comparison, the intervals seem to be different, which is going to lead to lots of confusion. If you insist on using sub-divisions (other than official Pliocene stages or MIS terminology), make sure the stated intervals of time and the terminology used are identical in both**

**papers (if it doesn't make sense to use the subdivisions defined in the Risebrobakken paper, maybe this strengthens the case for not using them at all).**

We have added a comparison of Holocene SST variability and Pliocene SST variability in the beginning of the discussion (page 8 line 5-8).
We have come to the conclusion that MIS-based chronological discussion is not suited to the scale of SST changes that we discuss in this manuscript.
We believe that the revisions we have made to the manuscript provide a more SST-focused story, which relies less heavily on potential changes of the AMOC. After some deliberations, the overall chronological structure of the discussion has been preserved, because a key aspect of the SST-focused story we present here is the chronological development of the Norwegian Sea through a series of stages and transitions.

**In my opinion the discussion of the new SST record and comparisons to all other available orbital-resolution SST records covering the same interval should form the backbone of the discussion. This will naturally lead on to discussion of what is forcing the various records. For example, if CO2 changes on orbital timescales (21 kyr through to 400 kyr) drive your SST record then the same orbital-scale cooling and warming should be seen in all SST records (because this would constitute a top-down forcing everywhere). Note that orbital forcing and CO2 forcing can't really be treated separately until a reliable orbital-resolution CO2 record exists for the Pliocene, because in the Pleistocene, CO2 changes are modulated by orbital parameters. On the other hand, if circulation/northern heat transport/AMOC strength changes drove this orbital-scale variability then one might expect opposing SST patterns in different key regions on these timescales, as seen for the Pleistocene. For example, Lisiecki et al. (2008) showed that during the Pleistocene at certain orbital periods, reduced overturning as determined by benthic d13C gradients was associated with cooling at high northern latitudes and warming at low latitudes, consistent with a decrease in meridional heat transport. Similarly, if all SST records show the same patterns on long secular (»100 kyr) timescales then that would be consistent with a tectonic-driven CO2 forcing of SSTs. Or, if as you suggest tectonic changes in the CAS influenced AMOC, northern heat transport, and your**

**SST record (as well as other high northern latitude records and other sites on the path of the NAC?), then you should see opposing SST trends at high northern latitudes versus the Caribbean on such timescales. You could certainly look for these types of patterns during the Pliocene (e.g. use the Caribbean Mg/Ca SST records presented by Steph et al., 2010), and this should hopefully lead you into a clearer discussion of mechanisms driving SST variability at your site on orbital and tectonic timescales.**

We have removed the $CO_2$-focused subchapter of the discussion (previously section 4.2, page 20 line 33 to page 21 line 12). The introduction is now less focused on possible links to the Central American Seaway, offering this only as one of several proposed links. A reference to the recent study by Karas et al. (2017) was added, which emphasized the potential impacts of ocean gateway transformations during the Pliocene on the large-scale climate system (page 25 line 15). In general the idea of a CAS / AMOC causal link to Nordic Seas climate changes during the Early Pliocene has been de-emphasized in the discussion.

**p6, line 22: "notable temperature transitions" – I think you can be bolder/more specific with your language here. The SST shifts that your new record documents are large (up to 6 degrees) and well-defined.**

We have used the suggested phrasing (page 19, line 2-3).

**"extended cooling phases and relatively fast warming phases". Please quantify this statement.**

Time ranges have been added (page 19, line 7-8).

**p7 line 13: This sentence reads as if the Site 907 SST data come from all 3 references. Is that correct?**

We have removed the unnecessary references (page 21, line 26).

**p7 line 28: give an order of magnitude for "far smaller" (ideally comparing with the same/a nearby site)**

We now address this in the results section (page 18, line 21-23), setting our IRD findings into context.

**p8 line 28: which changes?**

We have removed the short introductory paragraph (previously section 4.3, page 21, line 13-20) before the chronological discussion, where this unclear statement was made.

**When discussing specific glacial events, it would be clearer to use their MIS names (rather than saying for example, the 4.9 Ma event).**

After some consideration, the time frames and transitions discussed in this paper are not well captured by the MIS terminology. The regional nature of this study also makes it more appropriate to use a regional chronology as a framework, instead of the MIS terminology which is based on globally averaged benthic oxygen isotope variability.

**I think the stand-alone CO2 paragraph of the discussion is not useful, and should be incorporated into the discussion as mentioned above.**

We have removed most of the $CO_2$ sub-section of the discussion (page 20, line 33 to page 21, line 12).

**Given that no significant variance in the obliquity band in the SST record is identified in spectral analysis, I find all the interpretations related to changes in obliquity/seasonality very speculative. Perhaps if the arguments in the rest of the discussion can be strengthened, these statements will be superfluous.**

The discussion is now less focused on potential effects of orbital variability. We removed some references to orbital variability where no actual results and conclusions could be made (previously sections 4, 4.3 and 4.3.2, page 22 line 3-4; page 21, line 18).

**Please add a reference to support the idea that there was a threshold in the closure of the CAS at 4 Ma.**

We have added more information regarding potential links between Nordic Seas warming and changes in other regions at 4.0 Ma, e.g. Karas et al. (2017). We have also added alternative interpretations (Greenland-Scotland Ridge shift) for our results here, giving less focus on the AMOC / CAS interpretation (page 25, line 14-32).

References cited in this author response:

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# Highly variable Pliocene sea surface conditions in the Norwegian Sea

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**Abstract.** The Pliocene was a time of global warmth with small sporadic glaciations, during which the Northern Hemisphere which transitioned from small, sporadic glaciation towards the larger-scale Pleistocene glacial-interglacial variability. Here, we present high-resolution records of sea surface temperature (SST) and ice rafted debris (IRD) in the Norwegian Sea from 5.32 to 3.14 Ma, providing evidence that the Pliocene surface conditions of the Norwegian Sea underwent a series of transitions in response to orbital forcing and gateway changes. Average SSTs are 2°C above the regional Holocene mean, with notable variability on millennial to orbital timescales. Both gradual changes and threshold effects are proposed for the progression of regional climate towards the Late Pliocene expansion of large-scaleintensification of Northern Hemisphere glaciation. Cooling from 4.5 to 4.3 Ma may be linked to the onset of poleward flow through the Bering Strait. This cooling was further intensified by a period of cool summers due to weak obliquity forcing. A 7˚C Warming warming of up to 7˚C of the Norwegian Sea at 4.0 Ma suggests a major increase in northward heat transport from the North Atlantic at this time, leading to an enhanced zonal SST gradient in the Nordic Seas, and which may be linked to the expansion of sea ice in the Arctic and Nordic Seas. A warm Norwegian Sea and enhanced zonal temperature gradient between 4.0 and 3.6 Ma may have been a priming factor for increased glaciation around the Nordic Seas due to enhanced evaporation and precipitation at high northern latitudes.

## 1 Introduction

The Pliocene (5.333 to 2.58 Ma) was the last epoch with extended warmth before the onset of the Pleistocene style of glacial-interglacial cycles of expanding and melting Northern Hemisphere ice sheets (Zachos et al., 2001Lisiecki and Raymo, 2005;; Fedorov et al., 2013; Herbert et al., 2016). Evidence for early small-scale glacial build-up in the Northern Hemisphere is based on IRD deposited from Greenland betweenat 38 andto 30 Ma (Eldrett et al., 2007) and at 9.5 to 7.0 Ma (Wolf and Thiede, 1991). Further isolated instances of glaciation on eastern Greenland have likely occurred since 7.0 Ma (Larsen et al., 1994), until large-scale glacial build-up is signaled by greatly increased IRD influx during the Late Pliocene (Jansen et al., 2000; St. John and Krissek, 2002). Small-scale ice rafting has been reported from the Norwegian Sea since the Miocene (Fronval and Jansen, 1996). This long history of small-scale glaciation, likely regionally confined, underlines the importance of a closer investigation of the Pliocene Northern Hemisphere climate in order to understand the transition towards large-scale Northern Hemisphere glaciation (NHG), including the growth of ice sheets. Striated IRD suggesting Pliocene glaciations have has been reported on the North American continent and in sediments western of Scandinavia at 4.9 to 4.8 Ma, 4.0 Ma, and 3.3 Ma (reviewed in De Schepper et al., 2014Jansen et al., 1990; Jansen and Sjøholm, 1991). A statistically significant increase in global ice volume from 3.6 Ma was noted by Mudelsee and Raymo (2005), who consider this to be the marker for the onset of

NHG. Furthermore, a large increase in IRD influx in the North Atlantic (Kleiven et al., 2002), and a crash of productivity in the North Pacific (Haug et al., 2005), indicated an important threshold towards intensified Northern Hemisphere ice build-up at ca. 2.7 Ma.

The processes that initiated these regional glaciations and the overall progression towards the Late Pliocene intensification of NHG remain under discussion. The main hypotheses are long-term changes in the atmospheric $CO_2$ concentration, changes in oceanic gateways and circulation, and changes in orbital forcing. Recently Schreck et al. (2013) and De Schepper et al. (2015) promoted the importance of the Nordic Seas in priming the Northern Hemisphere for glaciation through the establishment of the East Greenland Current (EGC) and the modern Nordic Seas oceanographic pattern (Fig. 1) around 4.5 Ma. The establishment of the cold EGC, as a potential response to changes in the ocean circulation through the Bering Strait, has been considered important for large-scale glaciation of Greenland because the EGC thermally isolates Greenland from the warm waters transported northward in the Norwegian Atlantic Current (NwAC) (Bohrmann et al., 1990; Sarnthein et al., 2009; De Schepper et al., 2015).

A strengthening ~~of the Atlantic Meridional Overturning Circulation (AMOC), or~~ of the oceanic heat and moisture transport to high latitudes (Macdonald and Wunsch, 1996), in conjunction with the thermally isolated Greenland ice sheet (Driscoll and Haug, 1998), likely affected the onset of NHG (Raymo et al., 1996; ~~Sarnthein et al., 2009~~Ravelo and Andreasen, 2000)~~ in conjunction with the thermally isolated Greenland ice sheet (Driscoll and Haug, 1998), although~~. T~~t~~he mechanisms and their impacts ~~continue to be debated~~are, however, continuously debated. Some studies have proposed that increased northward heat transport led to increased high-latitude precipitation and ice build-up (Driscoll and Haug, 1998; Haug and Tiedemann, 1998), while others conclude that northward heat transport~~it~~ had very little (Lunt et al., 2008a) or even the opposite effect, possibly delaying NHG by heating the high northern latitudes (Klocker et al., 2005). Stepwise strengthening of the AMOC during the Pliocene (Haug and Tiedemann, 1998; Steph et al., 2006, 2010) has been proposed~~ to be a consequence of the closing of the Central American Seaway (CAS), a response which that is supported by model studies (e.g. Maier-Reimer et al., 1990). However, the precise timing of the closure of the CAS and its potential effects on climate remain under discussionbeyond the East Pacific and Caribbean regions remain under discussion. It, and it is~~ also ~~not clear if a significant step in the closure of the CAS actually closely coincided with the timing of the proposed enhanced Pliocene AMOC and subsequent glaciation increase of NHG (Bartoli et al., 2005; Montes et al., 2015; Mudelsee and Raymo, 2005)~~. Although deep-water proxy datasets from the Caribbean support the hypothesis that the AMOC strengthened during the E~~e~~arly Pliocene (Steph et al., 2010) and during the mid-Piacenzian (ca. 3.3 to 3.0 Ma; Raymo et al., 1996~~; Sarnthein et al., 2009~~), it has been argued that this does not indicate an Atlantic-wide strengthening of the overturning circulation. ~~, the same responses could also be explained by enhanced Antarctic deep water ventilation (Zhang et al., 2013).~~ ~~Furthermore~~For example, not all benthic records from the Atlantic show the expected responses, e.g. $\delta^{13}C$ enrichment, to~~ a~~ a significant increase in ~~more vigorous Pliocene~~ AMOC intensity during the Early Pliocene (Bell et al., 2015). A stable AMOC during periods of intense Atlantic climate change has been reported by Bradtmiller et al. (2014) for transition into the Holocene and by Böhm et al. (2015) for the last glacial cycle, with casts doubt on whether strong AMOC variability can be expected during the warmer Pliocene. Alternative to the idea that a shift in the

AMOC was responsible for high-latitude climate variability, and the eventual onset of intensified NHG, it has been proposed that the sill depth of the Greenland-Scotland Ridge (GSR) had a major impact on the climate of the Nordic Seas, with deeper water over the GSR entailing higher SSTs in the Nordic Seas according to model studies (Hill, 2015; Robinson et al., 2011). ~~However, changes in the sill depth of the GSR would likely have affected the AMOC and the deep water isotope signature of NADW (Poore et al., 2006; Wright and Miller, 1996).~~

In contrast to the suggestion that a strengthened AMOC and tectonic shifts were~~is~~ important for glacial growth at high northern latitudes, a modelling study by Klocker et al. (2005) indicated that strengthening of the AMOC would lead to decreased snowfall at high northern latitudes, despite any potential increase of precipitation. These authors concluded that AMOC change is a less effective driver of NHG than changes in orbital parameters. The configuration of the orbital parameters as a decisive timing factor of NHG around 2.7 Ma has also been suggested by Maslin et al. (1998), who proposed that an extended period of high-amplitude obliquity variability may have supported the preservation of ice through summer, but this mechanism also requires low enough atmospheric $CO_2$ concentrations. Evidence exists for above Holocene (ca. 270 ppm; Indermühle et al., 1999) atmospheric $CO_2$ concentrations during most of the Pliocene, with a decreasing trend towards the L~~l~~ate Pliocene (Pliocene $CO_2$ estimates range between ca. 300 to 500 ppm; Bartoli et al., 2011; Martínez-Botí et al., 2015; Pagani et al., 2010; Seki et al., 2010). The decreasing atmospheric $CO_2$ concentration has also been proposed as the cause for gradual global cooling which ~~enab~~led to the expansion of Northern Hemisphere ice sheets during the L~~l~~ate Pliocene (e.g. Lunt et al., 2008; Martínez-Botí et al., 2015).

It is unclear in which way changes of atmospheric $CO_2$ concentration, ocean heat transport, and orbital variability interacted at high northern latitudes, and if the cooling of the Northern Hemisphere and the growth of ice sheets proceeded gradually or through more rapid transitions. Different regional patterns and timings of sea surface temperature (SST) decreases are recorded at a global scale since 4.0 Ma (Ravelo et al., 2004), with only a certain subset of sites, mainly in modern upwelling zones, showing a common trend of cooling starting at 4.0 Ma (Fedorov et al., 2013). The only existing sub-orbitally resolved Pliocene (5.1 to 3.1 Ma) climate records from the Norwegian Sea, based on the stable isotope composition of planktic and benthic foraminifers, indicate a series of distinct changes of water mass density and ventilation proposed to be driven by a combination of gateway changes and orbital forcing (Risebrobakken et al., 2016), but the authors also noted a potential impact of diagenetic overprinting which may complicate the recorded climate signals in planktic foraminifers. A recently published $U^{K'}_{37}$ SST record from the Iceland Sea shows variable surface conditions throughout the Pliocene (Herbert et al., 2016) that indicate overall above-modern temperatures, an Early Pliocene stepwise cooling trend and Late Pliocene warming. Variable but overall warm SSTs have also been reported from the North Atlantic, in the pathway of water masses that in modern-day flow into the Norwegian Sea (Lawrence et al., 2009; Herbert et al., 2016).

Here, we present high-resolution $U^{K'}_{37}$ SSTs, $C_{37:4}$ alkenone percentages (%$C_{37:4}$), and IRD counts from ODP Hole 642B in the Norwegian Sea (Fig.1) across the 5.32 to 3.14 Ma time interval. Sea surface temperatures and %$C_{37:4}$ provide insights into the changing properties of the surface water masses in the western Nordic Seas, while the IRD record indicates changes in the behavior of glacial margins extending to the Nordic Seas. The records from ODP Hole 642B provide insight on whether

Pliocene climate variability on tectonic (>100 ka) and orbital timescales (20 to 400 ka) was important for establishing favorable conditions for sporadic Northern Hemisphere glaciation during the ~~early~~ Early Pliocene (De Schepper et al., 2014), and for increasingly widespread glaciation during the L~~l~~ate Pliocene (~~Mudelsee and Raymo, 2005~~Kleiven et al., 2002; Shackleton et al., 1984).

## ~~2 Materials and Methods~~

### 2~~2.1~~ Study area and present-day oceanographic conditions

Two major surface currents dominate the Nordic Seas (Norwegian Sea, Greenland Sea and Iceland Sea), the Norwegian Atlantic Current (NwAC) and the East Greenland Current (EGC) (Fig. 1), setting up distinct meridional and zonal gradients of SSTs and salinity (e.g. Blindheim and Østerhus, 2005). The NwAC is supplied by the North Atlantic Current (NAC) with warm and saline Atlantic water (>3°C, >35 psu; Mauritzen, 1996). It flows in two bathymetrically steered branches over the Norwegian shelf and the Norwegian basin. Moving northward the Atlantic water masses of the NwAC lose heat due to exchange~~s~~ with the atmosphere. The NwAC bifurcates ~~by~~ at the Barents Sea, and again when the NwAC reaches the Fram Strait, where parts of its water masses submerge into the Arctic Ocean, while the majority of the Atlantic water is deflected westward and submerged southward below the surface of the EGC. The surface of the EGC is composed of cold and relatively fresh polar water (0 to 0.5°C, 34.8 to 34.9 psu; Mauritzen, 1996) which travels southward through the Fram Strait. The polar water flows southward along the Greenland shelf and exits the Nordic Seas through the Denmark Strait between Greenland and Iceland. Parts of the polar water are deflected into the Greenland Sea and the Iceland Sea, where they form part of the Nordic Seas deep water, feeding the North Atlantic deep water (e.g. Mauritzen, 1996). The remainder of the deep water is a mixture of deflected Atlantic water as well as recirculated Atlantic water that passed through the Arctic Ocean. In the central Nordic Seas, between the Polar water in the West and the Atlantic water in the East, a mixed region of Arctic Water extends (Blindheim and Østerhus, 2005). The Arctic water is bounded by the polar front in the west and the Arctic front in the east.

## 3~~2~~ Materials and Methods

### 3.1 Site, samples and age model

In this study, we investigate sediments from ODP Hole 642B (Eldholm et al., 1987), using material dated to the Pliocene from 85.66 to 66.99 meters below sea floor (mbsf). The study site is situated on the Vøring Plateau (67°~~-~~2'~~-~~N, 2°~~-~~9'~~-~~E) at a water depth of 1280 m. Presently Hole 642B lies beneath the western branch of the NwAC and experiences warm summer SSTs averaging 10.2°C (Locarnini et al., 2013). We apply the new Hole 642B age model developed by Risebrobakken et al. (2016), based on the magnetostratigraphy of Bleil (1989) updated to the ATNTS2012 timescale (Hilgen et al., 2012), and further constrained for the time interval between 4.147 and 3.140 Ma by tuning the benthic oxygen isotope record from Hole 642B

(*Cassidulina teretis*) to the global δ18O stack of Lisiecki and Raymo (2005). This age model gives the studied material an age range from 5.321 to 3.141 Ma.

Core-top samples from Hole 642B and Site 907 were not available for $U^{K'}_{37}$ analysis. We compare the Pliocene SSTs with Holocene mean $U^{K'}_{37}$ SSTs given by the same method at nearby sites (Fig. 1) to include more of the variability that exists within the present warm period (0 to 10 ka) when comparing to Pliocene measurements, where each value represents a much longer time span (hundreds to thousands of years) than that covered by any instrumental time series. Furthermore, this approach gives the Pliocene-Holocene difference between consistent methods instead of mixing temperature information from instrumental measurements with proxy reconstructions. We present new Holocene averaged $U^{K'}_{37}$ SST data from the Iceland Sea (Site GS15-198-62 MC-A, 70°~~–~~01'~~–~~N, 13°~~–~~33'~~–~~W, 1423 m depth; Fig. 1, this study), alongside previously published Holocene averages for Norwegian Sea site MD95-2011~~)~~ (Calvo et al., 2002).~~,~~ B~~b~~oth datasets were generated using the same methods as for Hole 642B. For core GS15-198-62 MC-A, the Holocene is identified to the upper ~~∼~~26~~0~~ cm below seafloor based on ~~stable isotopes and a~~ radiocarbon dates (Table 1) ~~that sets the bottom of the core (42.75 cm) to 16590±90 $^{14}$C years BP~~ (Saint-Macary, 2016; unpublished master intern report).

### 3~~2~~.2 Alkenone-based sea surface temperature reconstructions~~es~~

All alkenone measurements were produced at the biomarker laboratory of the Department of Geography, Durham University, UK. Alkenone-derived SSTs were measured from 333 sediment samples taken at ODP Hole 642B, extending the record of 59 samples spanning 3.264 to 3.140 Ma previously published for this site by Bachem et al. (2016). Alkenones were extracted from freeze-dried samples (1 to 2 g) using 12ml of Dichloromethane and Methanol (3:1 v/v) in a CEM MARS microwave, following the protocol of Kornilova and Rosell-Melé (2003). Extraction was aided by heating to 70°C over 2 minutes, holding the temperature for 5 minutes and cooling below 30°C before further processing. Lipids were recovered by centrifuge (to separate from sediments) and rotary evaporator (to remove solvent). Silica column chromatography was used with hexane, DCM and methanol as eluents to separate the ketones, including alkenones, from other extracted lipids (non-polar and polar compounds). We quantified the alkenones using a gas-chromatograph fitted with a flame ionization detector (FID; Thermo Scientific Trace 1310). Hydrogen was used as a carrier gas. Injector temperature was set to 280°C, FID temperature to 350°C. After injection, temperatures were increased from 70°C to 170°C at 12°C per min, then to 310°C at 6°C per min. and held at that temperature for 40 min. The $U^{K'}_{37}$ index was calculated according to Prahl and Wakeham (1987). We apply the Müller et al. (1998) calibration to convert data from the $U^{K'}_{37}$ index to SSTs. While this calibration of $U^{K'}_{37}$ to SSTs does not include sample sites further north than 60° N, it has been shown to provide reliable results in the Norwegian Sea during the Holocene) (e.g. Calvo et al., 2002; Risebrobakken et al., 2011). The resulting SSTs are considered to represent the temperature of the surface mixed layer, with best fit at 0 m (Müller et al., 1998). For the Holocene data from Site GS15-198-62 MC-A the sample preparation was performed as for 642B, then chemical ionization mass spectroscopy was used to detect the weaker alkenone signals, following the method of Rosell-Melé et al. (1995).

I~~i~~t has been suggested that there is ~~likely~~ a likely bias towards summer temperatures in $U^{K'}_{37}$ SST data in the Nordic Seas, because of the low insolation during the winter months at high latitudes (Risebrobakken et al., 2011). Nevertheless, there is some doubt about the preservation of ~~alkenone production seasonality~~seasonally biased alkenone production signals in sediments, ~~because of the lack of a clear seasonal signal in~~because a clear seasonal signal is not recorded in the alkenone flux at ~~deep~~lower depths in the water column~~-~~ (Rosell-Melé and Prahl, 2013). Assuming that a summer bias is inherent in our SST record due to the ~~very~~ low primary productivity of the Nordic Seas during winter (Andruleit, 1997; Baumann et al., 2000), we suggest that high-latitude $U^{K'}_{37}$ SST data may show the evolution of the summer mixed layer, and consequently respond to changes in the intensity of summer insolation, as it has been reported for the Holocene (Risebrobakken et al., 2011). This interpretation is supported by the late Holocene $U^{K'}_{37}$ SST~~t~~s being more comparable to instrumentally recorded summer temperatures at the studied sites than to annual mean temperatures (Locarnini et al., 2013).

~~-~~For previously published~~the~~ $U^{K'}_{37}$ SST records from ODP Site 907 in the Iceland Sea, ~~, with which we compare our SST data,~~ the authors do not assume a ~~particular~~ summer bias (Herbert et al., 2016; De Schepper et al., 2015; Schreck et al., 2013). Considering the close meridional proximity of ODP Hole 642B (67°-13.5'-N) and ODP Site 907 (69°-15.0'-N), and the similar summer peak in coccolithophorid productivity in both regions (Baumann et al., 2000), in addition to the correspondence between late Holocene SSTs and instrumentally recorded summer temperatures, it is likely that ~~the~~any seasonal bias would be~~is~~ similar in both records, and hence that the reported SSTs are comparable in this regard, even though these sites presently lie in very different water masses (Fig. 1).

~~Core-top samples from Hole 642B and Site 907 were not available for $U^{K'}_{37}$ analysis.~~ We ~~We compare the Pliocene SSTs with Holocene mean $U^{K'}_{37}$ SSTs given by the same method at nearby sites (Fig. 1 and 2), to include more of the variability that exists within the present warm period (0 to 10 ka) when comparing to Pliocene measurements~~, ~~where each value represents a much longer time span (hundreds to thousands of years) than that covered by any instrumental time series. Furthermore, this approach gives the Pliocene-Holocene difference between consistent methods instead of mixing temperature information from instrumental measurements with proxy reconstructions.~~

The tetra-unsaturated $C_{37:4}$ alkenones were quantified as a percentage of the three $C_{37}$ alkenones ($C_{37:2}$, $C_{37:3}$, $C_{37:4}$). ~~It is~~The $C_{37:4}$ alkenone is produced mainly in cool water masses (e.g. Rosell-Melé et al., 1994) and has been suggested to indicate the influence of fresh water when it exceeds 5 % (Rosell-Melé, 1998). In the Nordic Seas cool and fresh water masses are closely linked (Bendle et al., 2005; Sikes and Sicre, 2002), which is why a distinct separation of a temperature and salinity response of this proxy may not be possible. We consider increases of $\%C_{37:4}$ to be a supporting indicator for an increased influence of both colder and fresher water masses (Bendle et al., 2005; Filippova et al., 2016), in particular at instances when IRD peaks coincide with $C_{37:4}$ peaks.~~.~~ ~~The use of $\%C_{37:4}$ as a climate proxy in the Nordic Seas has been extensively discussed by Rosell-Melé (1998) and Bendle et al. (2005). These authors have proposed that a connection between $\%C_{37:4}$ and fresh water masses may exist at >5 $\%C_{37:4}$. Sikes and Sicre (2002) noted that salinity and temperature changes in the North Atlantic are so closely linked that a differentiation between these two variables using $\%C_{37:4}$ may be impossible.~~ An alternative approach exploits the co-variation of SST and salinity in the Nordic Seas, and the presence of specific surface water masses (Bendle et al., 2005) which showed that elevated %$C_{37:4}$ and low SSTs occurred in colder and less saline Arctic waters, and this is the interpretation we apply here. Instances whereof IRD peaks coincidingcoincide with %$C_{37:4}$ would also lend support to the interpretation of cooler and potentially less saline surface water masses. However, it should be noted that the IRD peaks reported here are far smaller than those associated with large-scale fresh-water influx during the late Pleistocene (e.g. Heinrich events).

### 23.3 Ice rafted debris

Ice rafted debris grains >150 µm were counted visually in 539 samples using a binocular microscope, with an average sample resolution of 3.6 ka. This extends the record of 94 samples published by Bachem et al. (2016) for the 3.264 to 3.140 Ma time interval. A previous study was performed on Hole 642B sediments of the >125 µm fraction by Jansen and Sjøholm (1991), who achieved an average sample resolution of 14.5 ka. As noted in Bachem et al. (2016), this approach misses the IRD of smaller grain sizes, but the >150 µm IRD fraction is sufficient to correlate the presence and variability of IRD in the Nordic Seas region to SSTs. The record of IRD provides data regarding the influx of coarse terrestrial material. This merely indicates the existence of calving glacial margins somewhere surrounding the Nordic Seas, and does not in itself give any further information about the properties and provenance of this ice. Provenance analysis of IRD is theoretically possible, for example through isotope analysis (e.g. White et al., 2016), but this requires feldspar IRD which was not noted in significant amounts. Cathodoluminiscence analysis of quartz IRD (Müller and Knies, 2013) may in the future be used to trace ice rafting sources and transport pathways during the Pliocene.

The record of IRD provides data regarding the influx of coarse terrestrial material. This merely indicates the existence of calving glacial margins somewhere surrounding the Nordic Seas, and does not in itself give any further information about the properties and provenance of this ice. The IRD we register at Site 642B does not exceed an estimated 1 to 2 % of the total sediment weight of a given sample, much lower than during Nordic Seas ice rafting events of late Pleistocene glacials when IRD contents reached 50 to 100 % (Heinrich, 1988). This means that any IRD influx was likely a matter of sporadic and minor ice rafting and not indicative of large-scale collapses of ice sheets comparable to those of the Late Pleistocene with associated ice streams (Marcott et al., 2011). It should also be noted that the presence of IRD is not specifically linked to the growth rate of ice sheets, but to the extent of their interaction with the ocean. Extended periods of ice growth away from the coast, i.e. without calving margins, would not be visible in the IRD record (Ruddiman et al., 1980).

## 3 4 Results

We present $U^{K'}_{37}$ alkenone SSTs from the Norwegian Sea ODP Hole 642B with an average temporal resolution of 5.6 ka (range: 0.5 to 58 ka) from 5.321 to 3.141 Ma (Fig. 2c). The average Pliocene SST was 13.2°C, about 2°C above the regional

Holocene average at a nearby site (11.2°C) (Fig. 1; Calvo et al., 2002; Site MD95-2011; 66°~~-~~58′~~-~~N, 7°~~-~~38′~~-~~E). The record documents the existence of large-amplitude changes in $U^{K'}_{37}$ alkenone SST on ~~ka~~millennial to orbital ~~and Ma~~ timescales. Some of the highest SSTs were measured in the earliest Pliocene (5.3 to 5.0 Ma; 85.66 to 83.46 mbsf), a time interval which was marked by a cooling trend from 17°C to 15°C. From 5.0 to 4.64 Ma (83.46 to 77.81 mbsf), the SST record varied between 11°C and 15°C with a period of ~10-30 ka. Following this unstable period the SSTs remained relatively stable (13.9 to 15°C) between 4.64 and 4.45 Ma (77.76 to 77.21 mbsf). A pronounced cooling began from 15°C at 4.45 Ma into an interval of sustained low Pliocene SSTs starting from 4.3 Ma and continuing to 4.0 Ma (76.61 to 73.61 mbsf, which mostly lay below the Holocene average (down to a minimum of just over 10°C, 1.2°C below the Holocene average). Significant warming, from ~11°C to ~17°C, then occurred within 70 ka from ~4.0 Ma to 3.93 Ma (73.57 to 73.01 mbsf). An extended period of warmth ~~then~~ lasted from 3.93 Ma until 3.65 Ma (70.47 mbsf), marked by SSTs between 15°C and 17°C. Ending this extended warm period, SSTs first cooled to around 13.5°C between 3.65 and 3.45 Ma (70.41 to 68.92 mbsf), succeeded by an even colder interval from 3.45 to ~3.3 Ma (68.90 to 68.42 mbsf), during which mean SSTs remained close to 12°C. From 3.3 Ma, a rapid SST increase from ~12.4°C at 3.3 Ma to 15.6°C at 3.26 Ma (68.10 mbsf) was recorded.

The percentage of tetra-unsaturated alkenone ($\%C_{37:4}$, Fig. 2b), was generally very low, lying close to the detection limit (< 1%) for much of the Pliocene. Increases in $\%C_{37:4}$ maxima of 4 to 8 % occurred during phases when SSTs were comparable to Holocene values, i.e. at 4.9 Ma, between 4.3 and 4.0 Ma, and between 3.6 and 3.3 Ma.

The IRD counted in Hole 642B consist mainly of quartz grains and metamorphic rock fragments. The new high-resolution record shown here compares well with the lower resolution IRD record from the same site by Jansen and Sjøholm (1991). Pulses of IRD >150 µm (Fig. 2a) reach the Norwegian Sea around 4.9 Ma (70 grains/g), 4.74 Ma (25 grains/g), 4.62 Ma (19 grains/g), 4.34 Ma (38 grains/g), 4.2 Ma (22~~XX~~ grains/g), and 4.0 Ma (100 grains/g). After a largely IRD-free interval from 4.0 to 3.6 Ma, IRD influx increases in variability and amount to between 0 and 81 grains/g between 3.60 and 3.14 Ma. The IRD peaks reported here are at the same order of magnitude as IRD deposition at the Vøring Plateau during the last interglacial (Risebrobakken, unpublished data, not shown), and are hence not comparable to Pleistocene glacial deposition of IRD.~~one to two orders of magnitude smaller than those associated with large-scale fresh-water influx during the late Pleistocene (e.g. Heinrich events; Heinrich, 1988).~~

~~For the Holocene SST data from Site GS15-198-62 MC-A, alkenone detection uncertainties in the deeper range allowed only for the accurate analysis of the upper 15 cm. While this depth interval does not cover the entire Holocene, as preliminary dating of deeper material to 16590±90 $^{14}C$ years BP indicates (Saint-Macary, 2016; unpublished master intern report), the resulting average SST 8.5°C (Fig. 1 insert; Fig. 2c) is most likely representative of the average state of this region during the Holocene.~~

## 4 5 Discussion

The Pliocene Norwegian Sea was on average 2°C warmer than the Holocene mean (Calvo et al., 2002), however, notable large and well-defined temperature transitions occurred at several times. These new SST data, supported by IRD and %$C_{37:4}$ records, enable us to investigate the sea surface conditions of the Norwegian Sea at orbital (20 to 400 ka) to tectonic (100 ka to several Ma) timescales.

There is no indication of stable warmth throughout the Pliocene at Hole 642B; rather, there are clear signs of several complex and extended cooling phases (e.g. long-term cooling trend between 5.3 Ma and 4.3 Ma, and between 3.6 and 3.4 Ma) and relatively fast warming phases (e.g. at 4.0 Ma and at 3.3 Ma). The likely factors to impact the climate system on the timescales we discuss are the atmospheric $CO_2$ concentration, changes in the orbital parameters, and tectonic changes, as well as the interaction between ocean, atmosphere and cryosphere.: here The Holocene datasets (Fig. 1) exhibit variability of 2-4°C, comparable to the variability seen in the Pliocene datasets (Calvo et al., 2002; Risebrobakken et al., 2010). This supports the idea that Holocene average SST data from this region can offer some baseline for the discussion of Pliocene warmth and climate variability. Here, we discuss the effects of these factorstectonic and oceanographic changes on the surface conditions on of the Norwegian Sea and consider the potential ramifications for the process of Northern Hemisphere Glaciation during the Pliocene. First, we outline our interpretations of the proxy datasets. Secondly, we discuss the overall long-term effects of the Pliocene atmospheric $CO_2$ concentration, before weWe discuss the evolution of the Pliocene climate between 5.32 and 3.14 Ma, noting which factors may have influenced the Norwegian Sea during defined time windows, following the local climate phases defined in Risebrobakken et al. (2016). Pliocene interactions between the relatively warm Norwegian Sea, sea ice, and terrestrial ice expansion may give clues to the general behavior of the high-latitude climate system during periods of increased global warmth.

Up to 63.5°C SST change is seen within the Holocene at the study location (Fig. 1). Despite such rather large SST changes during the present interglacial, the amplitude of the large-scale SST changes recorded trough the Pliocene is even larger. Furthermore, the Pliocene Hole 642B SSTs are overall warmer than those of the Holocene, but are within the range of Holocene temperatures during the colder intervals, e.g. 4.3 to -4 Ma.

### 4.1 Proxy Interpretations

Three paleoclimate proxies are applied here: alkenone SSTs, IRD and %$C_{37:4}$. As noted above, the $U^{K'}_{37}$ SST proxy is calibrated to the modern annual mean SST (0 m). However, it has been suggested that there is likely a bias towards summer temperatures in $U^{K'}_{37}$ SST data in the Nordic Seas, because of the low insolation during the winter months at high latitudes (Risebrobakken et al., 2011). Nevertheless, there is some doubt about the preservation of alkenone production seasonality signals in sediments (Rosell-Melé and Prahl, 2013). Assuming that a summer bias is inherent in our SST record due to the very low primary productivity of the Nordic Seas during winter (Andruleit, 1997), we suggest that high-latitude $U^{K'}_{37}$ SST data may show the evolution of the summer mixed layer, and consequently respond to changes in the intensity of summer insolation, as it has been reported for the Holocene (Risebrobakken et al., 2011). For the $U^{K'}_{37}$ SST record from ODP Site 907 in the Iceland Sea, with which we compare our SST data, the authors do not assume a particular summer bias (Herbert et al., 2016; De Schepper et al., 2015; Schreck et al., 2013). Considering the close meridional proximity of ODP Hole 642B (67° 13.5' N) and ODP Site 907 (69° 15.0' N) it is likely that the seasonal bias is similar in both records, and hence that the reported SSTs are comparable in this regard, even though these sites presently lie in very different water masses (Fig. 1). We compare the Pliocene SSTs with Holocene mean SSTs given by the same method at nearby sites (Fig. 1 and 2), to include more of the variability that exists within the present warm period (0 to 10 ka) when comparing to Pliocene measurements where each value represents a much longer time span (hundreds to thousands of years) than that covered by any instrumental time series. Furthermore, this approach gives the Pliocene-Holocene difference between consistent methods instead of mixing temperature information from instrumental measurements with proxy reconstructions.

The use of $\%C_{37:4}$ as a climate proxy in the Nordic Seas has been extensively discussed by Rosell-Melé (1998) and Bendle et al. (2005). These authors have proposed that a connection between $\%C_{37:4}$ and fresh-water masses may exist at >5 $\%C_{37:4}$. Sikes and Sicre (2002) noted that salinity and temperature changes in the North Atlantic are so closely linked that a differentiation between these two variables using $\%C_{37:4}$ may be impossible. An alternative approach exploits the co-variation of SST and salinity in the Nordic Seas, and the presence of specific surface water masses (Bendle et al., 2005) which showed that elevated $\%C_{37:4}$ and low SSTs occurred in colder and less saline Arctic waters, and this is the interpretation we apply here. Instances of IRD peaks coinciding with $\%C_{37:4}$ would also lend support to the interpretation of cooler and less saline surface water masses. However, it should be noted that the IRD peaks reported here are far smaller than those associated with large-scale fresh-water influx during the late Pleistocene (e.g. Heinrich events).

The record of IRD provides data regarding the influx of coarse terrestrial material. This merely indicates the existence of calving glacial margins somewhere surrounding the Nordic Seas, and does not in itself give any further information about the properties and provenance of this ice. The IRD we register at Site 642B does not exceed an estimated 1 to 2 % of the total sediment weight of a given sample, much lower than during Nordic Seas ice rafting events of late Pleistocene glacials when IRD contents reached 50 to 100 % (Heinrich, 1988). This means that any IRD influx was likely a matter of sporadic and minor ice rafting and not indicative of large-scale collapses of ice sheets comparable to those of the Late Pleistocene with associated ice streams (Marcott et al., 2011). It should also be noted that the presence of IRD is not specifically linked to the growth rate of ice sheets, but to the extent of their interaction with the ocean. Extended periods of ice growth away from the coast, i.e. without calving margins, would not be visible in the IRD record (Ruddiman et al., 1980).

### 4.2 Relation to atmospheric $CO_2$ concentration

None of the large-scale SST changes seen in the ODP Hole 642B record, e.g. the transitions into and out of the cold interval between 4.3 and 4.0 Ma, or the stepwise cooling between 3.65 Ma and 3.40 Ma, can be explicitly tied to changes in atmospheric

$CO_2$, due to the lower resolution of the existing reconstructions of Pliocene atmospheric $CO_2$ concentrations (Bartoli et al., 2011; Martínez-Botí et al., 2015; Pagani et al., 2010; Seki et al., 2010) (Fig. 2b). In addition to the lack of high resolution $CO_2$ records covering the Pliocene, different studies and methods of atmospheric $CO_2$ reconstruction provide different ranges of absolute atmospheric $CO_2$ concentration, resulting in an uncertainty of 100 to 300 ppm (Fig. 3b). Therefore, we only consider the long-term effects of the atmospheric $CO_2$ concentration on the reconstructed Pliocene SSTs. According to most $CO_2$ reconstructions for the Pliocene (e.g. Bartoli et al., 2011; Pagani et al., 2010; Seki et al., 2010), the atmospheric $CO_2$ concentration slowly decreased but remained consistently above the Holocene levels of ca. 270 ppm (e.g. Indermühle et al., 1999). While the climate sensitivity of the Pliocene is still under discussion (Howell et al., 2016; Martínez-Botí et al., 2015; Pagani et al., 2010), an overall warming effect on SSTs in the Norwegian Sea is to be expected from an above pre-industrial atmospheric $CO_2$ concentration because of the associated increase in overall radiative forcing, consistent with our reconstructed Pliocene SSTs lying ~2°C above the Holocene (Fig. 2). The overall decreasing trend displayed by Pliocene atmospheric $CO_2$ concentrations is not reflected in our SST record, which does not have a significant overall trend.

### 4.3 Pliocene sea surface changes in the Norwegian Sea

Here we subdivide our records into six shorter time intervals and discuss the Norwegian Sea surface changes for each time interval. We investigate the potential for changes in the surface water masses and currents of the Nordic Seas caused by gateway transitions of the Bering Strait and the CAS (Bohrmann et al., 1990; Haug and Tiedemann, 1998; De Schepper et al., 2015), as well as uplift events around Greenland and Scandinavia (De Schepper et al., 2014; Japsen et al., 2006; Knies et al., 2014a). We consider potential impacts of orbital forcing, with a focus on the impact of obliquity on seasonality. Our conclusion is that these changes were potentially responsible for conditioning the Northern Hemisphere for increasing amounts of glaciation towards the late Pliocene.

### 45.3.1 Gradual Eearly Pliocene cooling of Norwegian Sea SSTs, 5.3 to 5.0 Ma

Overall, SSTs in the Norwegian Sea cooled between 5.3 and 5.0 Ma. While the sample resolution is relatively low in this time interval, wWe note that the SST contrast between the Norwegian Sea (Hole 642B) and the Iceland Sea (Site 907; Herbert et al., 2016) was around 2-3°C above Holocene levels or larger during the earliest Pliocene (Fig. 4Fig. 3b) (Herbert et al., 2016; De Schepper et al., 2015; Schreck et al., 2013), indicating that the Nordic Seas were already zonally differentiated. The SST gradient between the North Atlantic and the Nordic Seas was significantly stronger than the modern $U^{K'}_{37}$ SST gradient (Fig. 5Fig. 4). Note that the age model for the Herbert et al. (2016) $U^{K'}_{37}$ SST record was revised– according to Clotten et al. (in prep.)based on Jansen et al. (2000) (Clotten et al, in review). Elevated %$C_{37:4}$ coincide with the coldest recorded temperatures at Hole 642B within the 5.3 to 5.0 Ma interval, 12.5°C at 5.19 Ma, indicating that a short-term increase in cold water masses influenced the surface of the Norwegian Sea. There was no IRD associated with the cooling and no clear driver is evident (Fig. 2).

### 45.3.2 Unstable sea surface conditions, 5.0 to 4.64 Ma

Between 5.0 and 4.64 Ma, SSTs in the Norwegian Sea are highly variable, ranging from just below the Holocene average of 11.6°C up to 15°C (Fig. 2c). The frequencies at which SSTs vary are not stable during this time period, and we were unable to detect any of the major frequencies of orbital precession, obliquity, and eccentricity through wavelet analysis (not shown). Periods of low SSTs are accompanied by increasing influx of IRD and sporadic increases in %$C_{37:4}$, indicating increased influence of cooler and possibly less saline water masses towards Hole 642B. Corresponding variability is also seen in the planktic and benthic carbon isotopes, implying changes in ocean-atmosphere exchange and bottom water ventilation (Fig. 4Fig. 3c-f; Risebrobakken et al., 2016). Similarly, the interaction between low SSTs and increased IRD at the same site during the mid-Piacenzian warm period appears to be driven largely by decreasing obliquity (Bachem et al. 2016). Although we were unable to detect orbital periodicities in our SST data, we note that between 5.0 to 4.64 Ma the high variability in SSTs also coincides with especially high variability of obliquity (Fig. 3Fig. 5ed; Laskar et al., 2004). Thehis variability in SST at Hole 642B similarly could potentially be accounted for by highly variable obliquity forcing causing successive transitions between times of stronger and weaker seasonal insolation (Berger, 1988). During times of weaker seasonality, the summers may have been cool enough to allow for the sporadic expansion of glaciers and calving of icebergs reaching the Norwegian Sea. During the 5.0 to 4.64 Ma time interval the SSTs at Site 907 (Herbert et al., 2016) are highly variable as well (Fig. 2c), and the temperature gradient between the Iceland Sea and the Norwegian Sea (Fig. 4Fig. 3b) was comparable to the Holocene average, relatively small compared to the earliest Pliocene. The SST gradient b between the North Atlantic and the Nordic Seas was, however, equally strong as before throughout most of this interval (Fig. 5Fig. 4). This indicates that the temperature contrast between Iceland Sea and Norwegian Sea was moderate during this time of high SST variability.

The IRD we register at Site 642B does not exceed an estimated 1 to 2 % of the total sediment weight of a given sample, much lower than during Nordic Seas ice rafting events of late Pleistocene glacials when IRD contents reached 50 to 100 % (Heinrich, 1988). The recorded number of grains per gram sediment are in fact comparable to the number of IRD grains recorded in the same area during the last interglacial (not shown). This means that any IRD influx was likely a matter of sporadic and minor ice rafting, more comparable to the present-day setting than to any and not indicative of large-scale collapses of ice sheets comparable to those of the Late Pleistocene with associated ice streams (Marcott et al., 2011). It should also be noted that the presence of IRD is not specifically linked to the growth rate of ice sheets, but to the extent of their interaction with the ocean. Extended periods of ice growth away from the coast, i.e. without calving margins, would not be visible in the IRD record (Ruddiman et al., 1980).

As noted in Bachem et al. (2016) for the later Pliocene, the source of IRD in the Norwegian Sea may have been Greenland rather than the more proximal Scandinavia. This contrasts with a Scandinavian IRD source in Hole 642B proposed by Jansen and& Sjøholm (1991). Our rationale is that the SSTs at Hole 642B, even though they were unstable, remained mostly above the Holocene average across the 5.0 to 4.64 Ma time interval. As Born et al. (2010) noted for the last interglacial, Scandinavian surface air temperatures had to be 3°C cooler than the Holocene average to trigger glacial inception on Scandinavia. With ocean temperatures being up to 3°C warmer than the Holocene, it is not likely that the atmospheric temperatures over Scandinavia were colder than today, and therefore, calving glaciers probably did not occur at the coast of Norway.

Within the interval from 5.0 to 4.65 Ma, the coldest Hole 642B SSTs are recorded just prior to 4.9 Ma (10.86°C) (Fig. 2c), corresponding to a glaciation event with possible global extent that took place around 4.9 to 4.8 Ma (Lisiecki and Raymo, 2005; De Schepper et al., 2014). This event at 4.9 Ma is also marked by enhanced IRD input (Fig. 2a), and cooling throughout the water column at Hole 642B as indicated by $\delta^{18}O$ data (Fig. 4Fig. 3c, d; Risebrobakken et al., 2016). The gradual SST cooling from 5.3 to 5.0 Ma culminates with the 4.9 Ma cold event (Fig. 2), which is also indicated by dinoflagellate assemblage changes (De Schepper et al., 2015). The gradual cooling may therefore have influenced the regional climate and ice growth leading up to the 4.9 Ma global glaciation event.

**45.3.3 From stable warm (15°C) to stable cold (10.5°C) Norwegian Sea SSTs, 4.64 to 4.0 Ma**

Following rather stable and warm surface conditions (~15°C) from 4.64 to 4.45 Ma, an initial cooling phase is noted at 4.45 Ma, from 15°C to 12.8°C, and a subsequent extended cold period begins at 4.3 Ma (Fig. 2c). These cold intervals coincide with an interval of especially weak amplitude in obliquity forcing between 4.4 and 4.0 Ma (Fig. 3Fig. 5d5e). The single high amplitude obliquity cycle that occurred in this time interval, at 4.2 Ma, is associated with a peak of SST. Overall, a relationship between a generally reduced seasonality (low obliquity) and low SSTs in the Norwegian Sea characterizes the average state for the 4.3 to 4.0 Ma interval. Sporadic peaks of $\%C_{37:4}$, albeit small, are associated with the coldest SSTs between 4.3 to 4.0 Ma, suggesting an enhanced influence of cool water masses in the Norwegian Sea. Peaks of IRD appear in association with the cool phase around 4.38 Ma, as well as during the 4.3 to 4.0 Ma cold interval (Fig. 2a, c). No IRD peak corresponds to the rapid cooling at 4.3 Ma, but the strongest IRD peak of the record begins at the end of the 4.3 to 4.0 Ma cool period, just before the rapid warming transition at 4.0 Ma. The combined reduced SSTs, increased $\%C_{37:4}$, and IRD support previously published records which indicated that interval between 4.4 and 4.0 Ma was relatively cold in the Norwegian Sea, with a reduced planktic-benthic $\delta^{13}C$ gradient suggesting a water mass structure not too dissimilar from that of the Holocene (Fig. 4Fig. 3e, f; Risebrobakken et al., 2016). The IRD maximum at 4.05 Ma, although dramatic for the Pliocene at this site, has to be interpreted with caution. All of the IRD peaks in our record are an order of magnitude smaller than the peaks that appear at Hole 642B and in the North Atlantic during the Pleistocene glacials (Jansen et al., 2000; Jansen and Sjøholm, 1991). Instead the IRD peaks of the Hole 642B record are comparableis comparable in magnitude to those seen in the North Atlantic during Llate Pliocene and Pleistocene times of relatively low ice rafting activity, when glacial margins were relatively stable (i.e. outside of glacial-interglacial transitions) (e.g. Kleiven et al., 2002; Mokeddem et al., 2014). The increase in IRD at Hole 642B from 4.05 Ma precedes the major increase in SSTs at 4.0 Ma (Fig. 2), therefore, increased calving did not occur as a response to this large-scale warming. The phase of weak obliquity variability from 4.3 to 4.05 Ma may have enabled the build-up of small-scale glaciation around the Nordic Seas large enough to shed icebergs into the ocean. The minor warming and increase in IRD at 4.05 Ma coincides with an increased obliquity (Fig. 3Fig. 5), suggesting a potential role for increased seasonality in causing local warming and/or the retreat of small-scale marine based glaciers existing in the Nordic Seas realm.

The change in SSTs from the stable warm conditions between 4.64 Ma and 4.45 Ma to the stable cold conditions between 4.3 and 4.0 Ma can also be seen in relation to the onset of northward through-flow in the Bering Strait (Marincovich and Gladenkov, 1999), the establishment of the EGC and the onset of modern circulation in the Nordic Seas, the latter suggested to have occurred around 4.5 Ma (De Schepper et al., 2015). The modern oceanographic pattern of the Nordic Seas is characterized by a strong zonal gradient of SST and salinity between the cold and fresh EGC to the West and the warm and saline NwAC to the East (Fig. 1). De Schepper et al. (2015) identified~~,~~ major changes in the dinoflagellate cyst assemblages around 4.5 Ma in both the Iceland and Norwegian Sea, including an assemblage turnover, decrease in cyst concentrations and broadly contemporaneous extinctions of four species. Following the disappearance of these taxa in Hole 642B (Fig. 2d) around 4.5 Ma, and a decrease in heterotrophic taxa, the ~~cysts of~~ cosmopolitan cysts of dinoflagellate species *Protoceratium reticulatum* increase in abundance and concentration. This is interpreted as a significant shift in the water mass characteristics of the Norwegian Sea likely due to increasing influence of warm North Atlantic water on the Norwegian Sea relative to the Iceland Sea, which is more influenced by the establishment of the EGC. However, when comparing the $U^{K'}_{37}$ SST records from Hole 642B and Site 907 (Herbert et al., 2016; De Schepper et al., 2015), the zonal SST gradient between the sites varied between 2°C and 6°C during the period 5.3 to 4.0 Ma (~~Fig. 4~~Fig. 3b). ~~The gradient remained stable, indicating that the eastern and western Nordic Seas were coupled.~~ This suggests an earlier establishment of the modern zonal differentiation of the Nordic Seas compared to the changes in dinoflagellate assemblages that took place at 4.5 Ma (Fig. 2d; De Schepper et al., 2015). The coupling remained intact through the cooling from 4.5 to 4.0 Ma. The $U^{K'}_{37}$ SST trends at ODP Hole 642B and Site 907 are roughly comparable in timing and amplitude, and the gradient between both sites is weakest (ca. 3 to 4°C; ~~Fig. 4~~Fig. 3b) when the Norwegian Sea was at its coolest between 4.3 and 4.0 Ma. Hence, these new data suggest that while cooling at ODP Site 907 may originate from the establishment of the EGC at ca. 4.5. Ma, no warming occurs in the NwAC until 4.0 Ma. This lack of warming, despite an increased Atlantic water influence from around 4.2 Ma onwards as suggested by the increase~~ing presence~~ of cysts of *P. reticulatum* (De Schepper et al., 2015), would imply that ~~the~~ northward heat transport by the North Atlantic Current was still relatively low.

The existence of a modern-like circulation, despite the potentially weakened heat transport, is supported by overflow at the Denmark Strait (Bohrmann et al., 1990) and enhanced ventilation of intermediate depths in the Nordic Seas between 4.5 and 4.4 Ma (Risebrobakken et al., 2016). Various studies have suggested that a shallow opening of the Central American Seaway before the L~~l~~ate Pliocene (Bartoli et al., 2005; Haug and Tiedemann, 1998; Kameo and Sato, 2000; Osborne et al., 2014; Steph et al., 2010) has in part been responsible for a weaker than modern northward heat transport ~~by the AMOC~~ at this time. A persistent shallow opening of the CAS is potentially responsible for reduced northward heat transport, as indicated by model comparisons between an open and a closed CAS (e.g. Maier-Reimer et al., 1990; Zhang et al., 2012). Alternatively, a reduction of the water depth over the GSR at approximately this time (Poore et al., 2006) could have resulted in lower SSTs in the Nordic Seas, in contrast to overall higher SSTs being the response to increased water depth over the GSR (Robinson et al., 2010; Hill, 2015). ~~depth between the North Atlantic and the Nordic Seas could have resulted in a weakening of North Atlantic water inflow (Poore et al., 2006; Robinson et al., 2010; Hill, 2015).~~ However, this may be inconsistent with the change towards more *P. reticulatum* in the dinoflagellate cyst assemblage, which is interpreted to show a stronger North Atlantic water mass influence on the Norwegian Sea (De Schepper et al., 2015).

### 45.3.4 Rapid warming followed by extended interval of high SSTs, 3.95 to 3.65 Ma

From 4.0 to 3.95 Ma, ODP Hole 642B records a dramatic increase in SSTs from around 10°C to 17°C over ca. 70 ka (0.14°C/ka), making it the longest and largest warming episode of the record. The warming was followed by a relatively stable warm period from 3.95 to 3.65 Ma (15 to 17°C). As high SSTs developed at Hole 642B the SSTs at ODP Site 907 decreased and remained at a Pliocene low until 3.55 Ma (Herbert et al., 2016; De Schepper et al., 2015). Hence, the zonal gradient in the Nordic Seas intensified during the 4.0 to 3.95 Ma transition, when the SST contrast between the Iceland Sea and the Norwegian Sea reached a sustained maximum of ~10°C, significantly larger than the Holocene difference of ~3°C (Fig. 4Fig. 3b). The high SSTs in the Norwegian Sea and the strong zonal temperature gradient within the Nordic Seas suggests that the surface circulation of the Nordic Seas was more vigorous during this time period. Strong inflow of warm Atlantic water is also indicated by enriched planktic $\delta^{13}C$ at Hole 642B, which is likely caused by enhanced ocean-atmosphere gas exchange in the upper water (Fig. 4Fig. 3e; Risebrobakken et al., 2016).

The warming of the Norwegian Sea at 4.0 Ma coincides with several tectonic shifts that could affect the climate development of the Nordic Seas region., namely aA threshold in the closure of the CAS has been suggested to take place at this time (Karas et al., 2017; Steph et al., 2010), and /or uplift of Greenland and northern Scandinavia took place (Knies et al., 2014a; Steph et al., 2010). Enhanced NADW production and a more vigorous AMOC have been noted suggested by Steph et al. (2010) towards 4.0 Ma based on benthic $\delta^{13}C$ in the low-latitude Atlantic. However, cConsistently low benthic $\delta^{13}C$ in the Norwegian Sea (Fig. 4Fig. 3f; Risebrobakken et al., 2016) indicates that bottom water ventilation at the Vøring Plateau did not increase., suggesting that the deep water formation during this time of vigorous surface circulation largely took place south of the Nordic Seas. Steph et al. (2010) link the change towards a stronger AMOC to the closure of the CAS. However, o This is iIn line with other studies, have shown where no response of benthic $\delta^{13}C$ in is seen at other Atlantic sites during this part of the Pliocene (Bell et al., 2015; Zhang et al., 2013), indicating that the changes may have been limited to specific water masses in the Caribbean region, and that increased heat transport to the Norwegian Sea was not linked to an intensification of the AMOC. masses masses in the Caribbean region(Bell et al., 2015; Zhang et al., 2013). If it is the case that no large-scale AMOC strengthening took place, regional changes in water mass transport may instead be responsible for the warming of the Norwegian Sea around 4.0 Ma. While the timing of ridge depth evolution is not very well constrained (Wright and Miller, 1996; Poore et al., 2006), it is possible that a threshold shift in Greenland-Scotland Ridge depth took place around 4.0 Ma, allowing for a more vigorous inflow of warm North Atlantic water into the Norwegian Sea from this point forward. The impact of the Greenland-Scotland ridge on Nordic Seas climate has been indicated my model experiments, which suggest that a deepening would lead to a slight warming of the Norwegian Sea and a cooling around Iceland (Hill, 2015). CloserMore detailed studiesy of the Greenland-Scotland Ridge system may shed more light on its effect on Nordic Seas climate development.

There are additional indicators for regional climate rearrangements in high northern latitudes at this time. Tectonic uplift took place around both Greenland and Scandinavia at 4.0 Ma (Japsen et al., 2006; Knies et al., 2014a), and may have been important for the enhanced regional glaciation on Greenland that has been noted to take took place at this time (Japsen et al., 2006; De Schepper et al., 2014; Solgaard et al., 2013). The period of consistently warm SSTs that occurred in the Norwegian Sea and North Atlantic between 4.0 Ma and 3.65 Ma may have triggered increased evaporation and hence precipitation, which can increase the Arctic freshwater supply and facilitate sea ice formation in the Arctic (Driscoll and Haug, 1998) if SSTs here are low enough. The Arctic sea ice cover extended towards the Fram Strait (ODP Site 910C) for the first time during the Pliocene at 4.0 Ma (Knies et al., 2014b), and the associated increased sea ice export would have further cooled the EGC and in consequence the eastern Nordic Seas (Herbert et al., 2016). In turn, a stronger zonal gradient in the Nordic Seas would have been enforced and shielded the growing Greenland ice cover from the warm NwAC (Bohrmann et al., 1990; Japsen et al., 2006; De Schepper et al., 2015; Solgaard et al., 2013). Uplift and increased precipitation may have enabled lateral ice sheet growth in the interior of Greenland from 4.0 Ma onward, which could take place without producing a notable IRD record (Ruddiman et al., 1980; Solgaard et al., 2013). Hence, the uplift of Greenland, in combination with enhanced supply of freshwater to the Arctic due to increased moisture transport and runoff, likely supported the cooling and the first appearance of winter sea ice in the Fram Strait at 4.0 Ma, as suggested by Knies et al. (2014b). The warming documented in the Norwegian Sea at 4.0 Ma (Hole 642B), in combination with the corresponding cooling in the northern Nordic Seas (Hole 910C; Knies et al., 2014b) and the Iceland Sea (Site 907; Herbert et al., 2016; De Schepper et al., 2015), indicates a strengthening of both the zonal and the meridional temperature gradient in the Nordic Seas. Risebrobakken et al. (2016) noted that the increased freshwater and sea ice flux in the EGC may have supported the warming in the NwAC by reinforcing the counter-flow of warm Atlantic water in the Norwegian Sea. A warm North Atlantic from 4.0 to 3.65 Ma is supported by $U^{K'}_{37}$ SST data from ODP Site 982 (Fig. 5Fig. 4;1) ( Lawrence et al., 2009), which lies within the pathway of modern-day North Atlantic inflow into the Nordic Seas (Fig. 1).. Hence, while the meridional temperature gradient between the Vøring Plateau (Hole 642B) and the Fram Strait (Hole 910C) was increased, the SST gradient between the North Atlantic (Site 982) and the Vøring Plateau was reduced, compared to the preceding interval.

### 45.3.5 Gradual cooling, 3.65 to 3.3 Ma

Sea surface temperatures decrease from an average of 16°C between 4.0 and 3.65 Ma to an average of 14°C between 3.65 and 3.45 Ma, before reaching a cold average of 11.5°C between 3.4 and 3.3 Ma (Fig. 2c). Instances of gradually increased $\%C_{37:4}$ accompany the SST decrease between 3.55 and 3.35 Ma (Fig. 2b). The influx of IRD increases around 3.55 Ma, after the beginning of the cooling trend. There does not appear to be a link between the cooling trend of the sea surface conditions and orbital forcing in this time period. Obliquity variability was relatively strong and remained so until well after the cool surface conditions were established (Fig. 3Fig. 5a, eb).

The surface cooling that we note in the Norwegian Sea from 3.65 Ma may reflect the global cooling that has been proposed to begin around 3.6 Ma by Mudelsee and Raymo (2005), which they link to a gradual overall increase of NHG. The observed cooling also corresponds to and supports a potential surface water density increase in the Norwegian Sea (Hole 642B), which was interpreted as potentially driven by regional cooling (~~Fig. 4~~Fig. 3e) (Panitz et al., 2016; Risebrobakken et al., 2016). The gradual increase in the magnitude and regularity of IRD concentration supports the idea of advancing glaciation around the Nordic Seas from 3.6 Ma. A somewhat enhanced overturning circulation, improving the ventilation of the intermediate water depths of the Nordic Seas at this time is indicated (Risebrobakken et al., 2016), and the warm SSTs at the North Atlantic ODP Site 982 may suggest ~~a vigorous AMOC and~~an enhanced northward heat transport (~~Fig. 5~~Fig. 4; Lawrence et al., 2009). If ~~overturning was~~ the northward heat transport was strong during the 3.65 to 3.3 Ma time period, the cooling we note in Norwegian Sea SSTs took place at a time when increased SSTs could be expected due to a potentially increased northward heat transport trough the NAC, a seemingly contradictory scenario.

The decrease in SSTs ~~that we note~~ could rather be explained by a decreased impact of the NAC on the NwAC. The SST gradient between ODP Hole 642B and ODP Site 907 (~~Fig. 4~~Fig. 3b) appears to be greatly reduced but variable (0 to 3°C) during the particularly cool phase at Hole 642B from 3.45 to 3.35 Ma. The high variability and increased SSTs at Site 907 (Herbert et al., 2016) may be indicative of a weakening of the circulation in the Nordic Seas, or a shift in the overall circulation pattern, with a largely weakened or reduced EGC and increased heat transport towards the Iceland Sea. Schreck et al. (2013) noted (nearly) monospecific dinoflagellate assemblages during the 3.45 to 3.35 Ma interval at ODP Site 907. A higher resolution investigation of ODP Site 907 identified high concentrations of an unspecified *Spiniferites* species between 3.7 and 3.3 Ma (~~SDS~~De Schepper, unpublished data). Fronval and Jansen (1996) report the only occurrence of foraminifera at Site 907 near 3.3 Ma, deviating from a generally carbonate barren record during the L~~l~~ate Pliocene and supporting the notion that conditions in the Iceland Sea were unusual at this time. A possible interpretation is that the influence of the Atlantic domain in the Nordic Seas was spread out laterally during this the 3.65 to 3.3 Ma period, weakening the overall influence at the Vøring Plateau but strengthening it in the Iceland Sea. It thus appears that regional water mass redistributions were more important for the sea surface development than a potential global cooling proposed by Mudelsee and Raymo (2005).

### ~~4~~5.~~3.~~6 The mid-Piacenzian warm period, 3.3 to 3.14 Ma

The records of sea surface conditions presented here, as well as other previously reported records from ODP Hole 642B (Jansen and Sjøholm, 1991; Risebrobakken et al., 2016), find no indication of the global cooling event that has been noted to take place during Marine Isotope Stage M2 (MIS M2, 3.312 to 3.264 Ma; Lisiecki and Raymo, 2005). This lack of recorded cooling may indicate the presence of a short-lived hiatus in the sediment sequence at ODP Hole 642B, or that the event had no particularly pronounced cooling impact on the Norwegian Sea. Cooling during MIS M2 had been noted in the North Atlantic by ~~(~~Lawrence et al., 2009) (~~Fig. 5~~Fig. 4) and by~~;~~ De Schepper et al. ~~,(~~2009, 2013) and an increase in IRD has been reported from the Iceland Sea (Jansen et al., 2000). In the Norwegian Sea we note a strong warming in the later part of MIS M2, in line with the corresponding decrease in global ice volume (Lisiecki and Raymo, 2005). The Norwegian Sea warming ~~had~~ has also been indicated by pollen records ~~from 642B~~stemming from the northern Norwegian landmass, which indicate vegetation adapted to warmer-than-present climate (Panitz et al., 2016).

During the period following 3.264 Ma the Norwegian Sea SSTs were 2 to 3°C warmer than during the Holocene (Fig. 2c) (Bachem et al., 2016). Global temperature was also 2 to 3°C warmer than present (e.g. Dowsett et al., 2016). Even though warm SSTs prevailed in the Norwegian Sea, variable conditions existed, following changes in radiative forcing and a vigorous subpolar gyre, as indicated by the similar pattern of cooling seen in Hole 642B and Site 982 (Bachem et al., 2016; Lawrence et al., 2009). The Iceland Sea record of ODP Site 907 (Herbert et al., 2016) does not have the necessary resolution for a direct comparison to the Norwegian Sea and North Atlantic records, although the SSTs at Site 907 appear to have been highly variable (Fig. 2c). The zonal gradient between the Iceland Sea and the Norwegian Sea was similar to the Holocene average during much of the 3.3 to 3.14 Ma period. This suggests a circulation that was similar to that of the Holocene in the Nordic Seas between 3.30 and 3.14 Ma, but that northward heat transport was likely stronger than between 3.45 and 3.35 Ma, but weaker than between 3.95 and 3.65 Ma.

## ~~5~~ 6 Conclusions

Several climate transitions took place in the Norwegian Sea throughout the Pliocene, indicating a variable climate instead of a steady long-term cooling trend. The average temperature of the Pliocene was 13.6°C, 2°C warmer than the regional Holocene average of 11.6°C, yet temperature changes of up to 7°C did take place. The E~~e~~arly Pliocene sea surface conditions between 5.32 and 4.64 Ma were highly variable (swings between 11°C and 15°C over a few 10 ka), which appears to be partially related to high-amplitude orbital variability. A zonal SST gradient comparable of that of the Holocene (3°C) already existed in the Nordic Seas during this time. The entire Nordic Seas cooled between 4.5 and 4.3 Ma, which is interpreted to reflect a strengthening of the EGC and the eastward extension of the Arctic Front, as well as reduced seasonality due to reduced amplitude of obliquity forcing. Low temperatures near or below the Holocene average persisted in the Norwegian Sea until 4.0 Ma. During the cool period from 4.3 to 4.0 Ma the zonal gradient in the Nordic Seas was at ~4°C, near its Holocene level. A distinct warming took place between 4.0 and 3.95 Ma, from 10°C to 17°C (0.14°C/ka), likely linked to increased northward heat transport due to enhanced overturning, and a return towards stronger seasonality. A steep increase in the zonal gradient of the Nordic Seas, leading to a contrast of up to 10°C (more than three times the Holocene gradient) set in after 4.0 Ma and lasted throughout the Norwegian Sea warm phase until 3.6 Ma, indicating a strongly increased northward heat transport. Norwegian Sea SSTs show cooling after 3.65 Ma, coinciding with global cooling and increasingly widespread glacial expansion. The Norwegian Sea cooled and the zonal gradient of the Nordic Seas decreased sharply, potentially due to a wider spread of Atlantic water. During the 3.264 to 3.14 Ma period, the Nordic Seas SSTs were higher than modern, although not as high as during the 3.95 to 3.65 Ma period. While glaciation around the Nordic Seas is indicated by the existence of IRD throughout the record (5.33 to 3.14 Ma), the relatively warm SST~~'~~s as well as the sporadic and small-scale nature of the IRD influx, imply that Scandinavia did not experience significant glaciation during this interval. ~~Hence,~~ T~~t~~he Nordic Seas underwent several large-scale transformations of its surface conditions and zonal gradients during the Pliocene, at least in part caused by regional tectonic shifts, which shows that ~~it~~ this region was highly dynamic and sensitive to changes in ~~regional~~ heat transport even before Northern Hemisphere ice sheets expanded. – The documented oceanographic changes in the Nordic Seas were likely important for the growth of small--scale Pliocene glaciers and the enhanced glacial ~~growth~~ expansion at high ~~Northern~~ northern latitudes since 3.65 Ma ~~, e.g.~~ through their~~its~~ influence on the Arctic fresh water regime.

## Data availability

The new data presented here will be available on the PANGAEA online data repository at: https://doi.pangaea.de/10.1594/PANGAEA.865217.

## Competing Interests

The authors declare that they have no conflict of interest.

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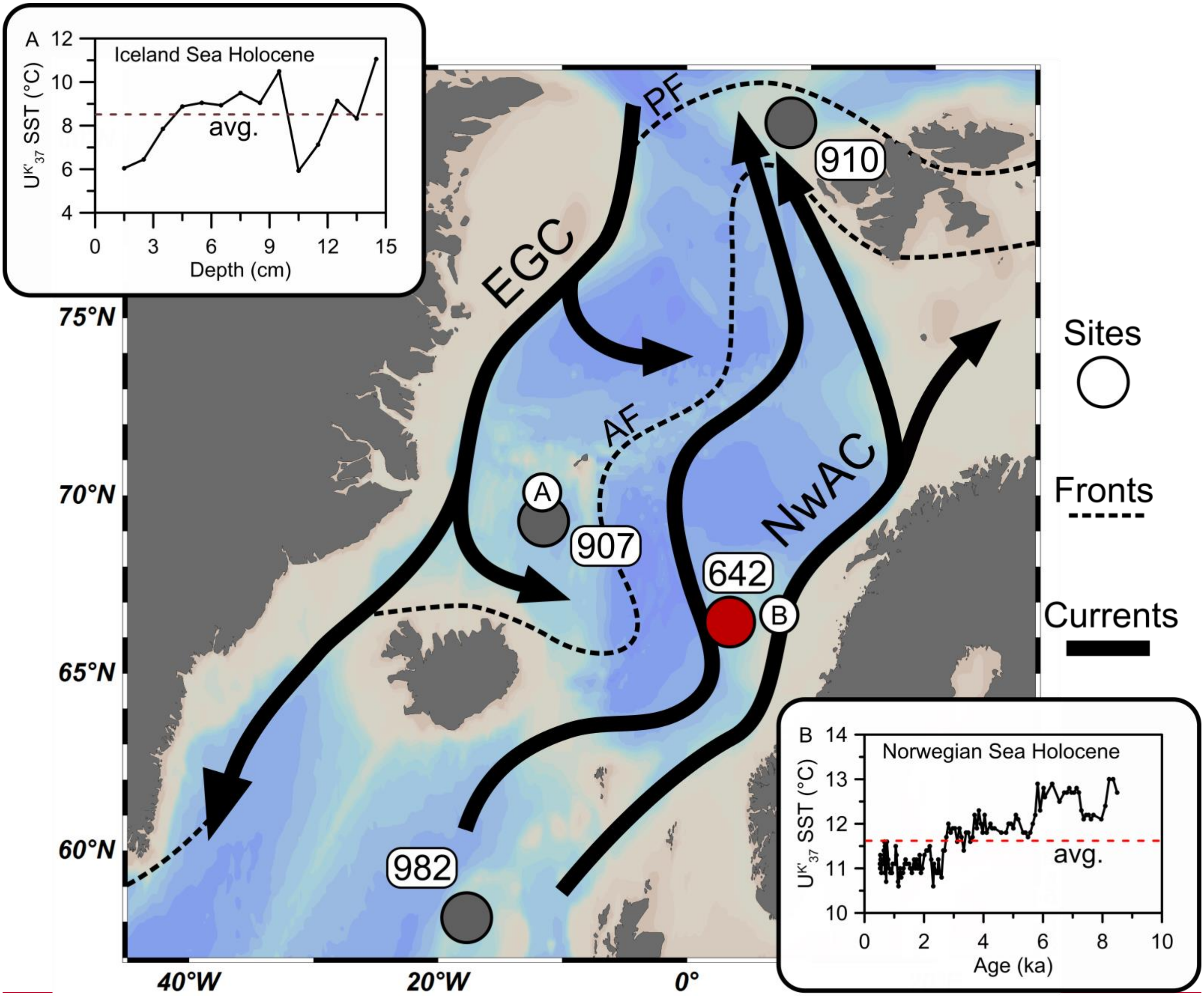
| Depth (cm) | Lab ID | Dated material | $^{14}C$ age | Calibrated age range (BP) (±1σ, ΔR=0±50) | Relative probability | Calendar age (median probability) yr BP 1950 | Reference |
|---|---|---|---|---|---|---|---|
| 5-5.5 | BETA459130 | *N. pachyderma* | 2010±30 | 1510-1660 | 1 | 1576 | This study |
| 10-10.5 | BETA459131 | *N. pachyderma* | 2830±30 | 2503-2685 | 1 | 2581 | This study |
| 15-15.5 | BETA459132 | *N. pachyderma* | 5630±30 | 5945-6104 | 1 | 6034 | This study |
| 20-20.5 | BETA459133 | *N. pachyderma* | 8310±30 | 8780-8970 | 1 | 8864 | This study |
| 42.5-43 | BETA432223 | *N. pachyderma* | 1700±60 | 19905-20143 | 1 | 20023 | Saint-Macary, 2016 |

**Table 1: AMS $^{14}C$ dates from GS15-198-62MUC-A, and calibrated calendar ages. All dates were calibrated using Calib 7.10 (Stuiver et al., 2017), the Marine13 calibration dataset, and a ΔR=0±50. *N. pachyderma* = *Neogloboquadrina pachyderma*. Median probability ages are used as tie points when calculating the age model, based on linear interpolation between these tie point.**




~~**Figure 1: Nordic Seas, showing simplified modern surface currents. NwAC: Norwegian Atlantic Current; EGC: East Greenland Current; AF: Arctic Front; PF: Polar Front. The study site, ODP Hole 642B, is marked by a red circle. Pliocene sites referred to in the text (ODP Sites 907, 910, and 982), are marked by grey circles. The two sites that provide Holocene SST averages for comparison are marked with small white circles. Holocene SST data are shown in inserts (A: GS15-198-62 MC-A, this study; B: MD95-2011, Calvo et al., 2002), with dashed lines indicating averages.**~~

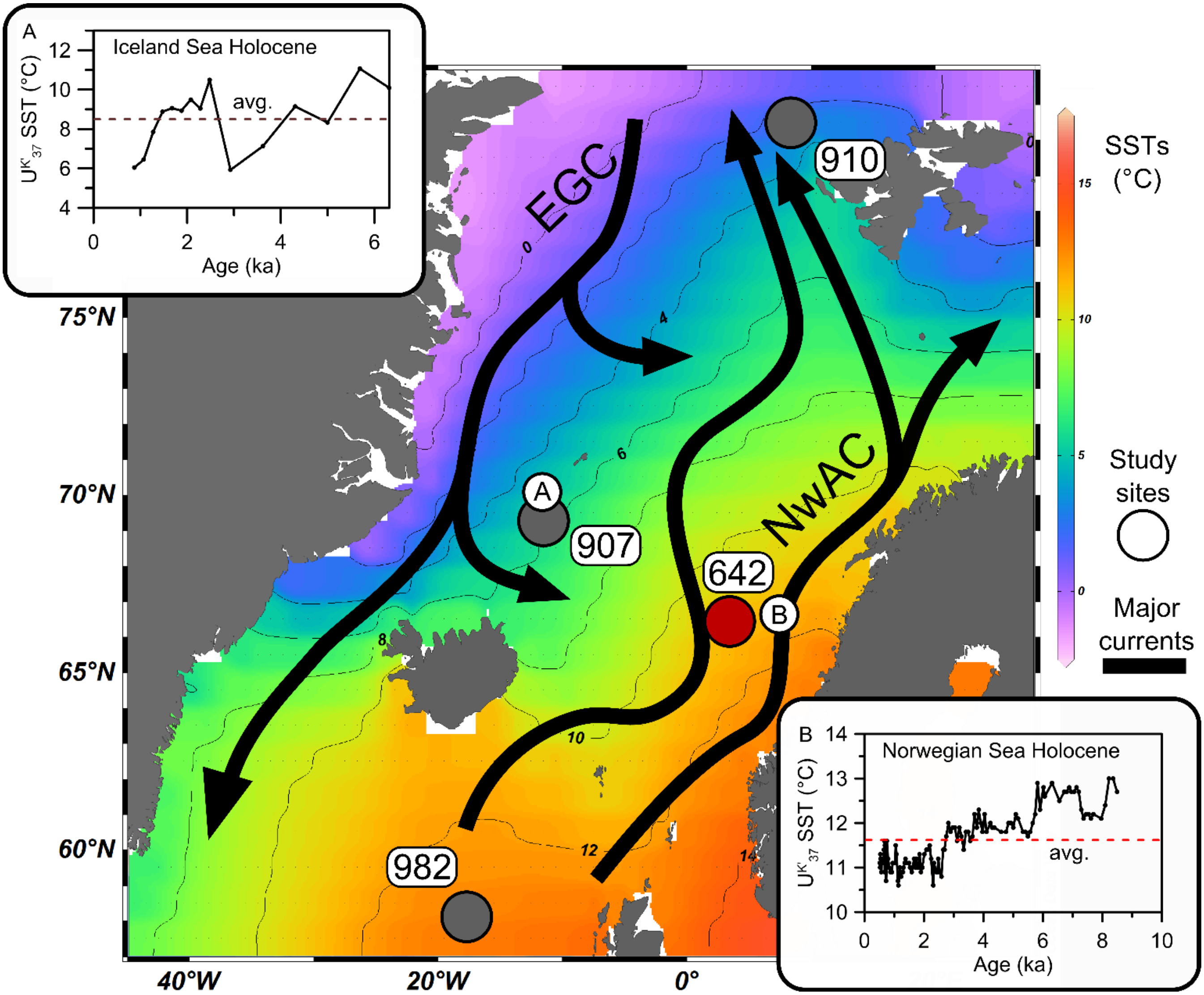
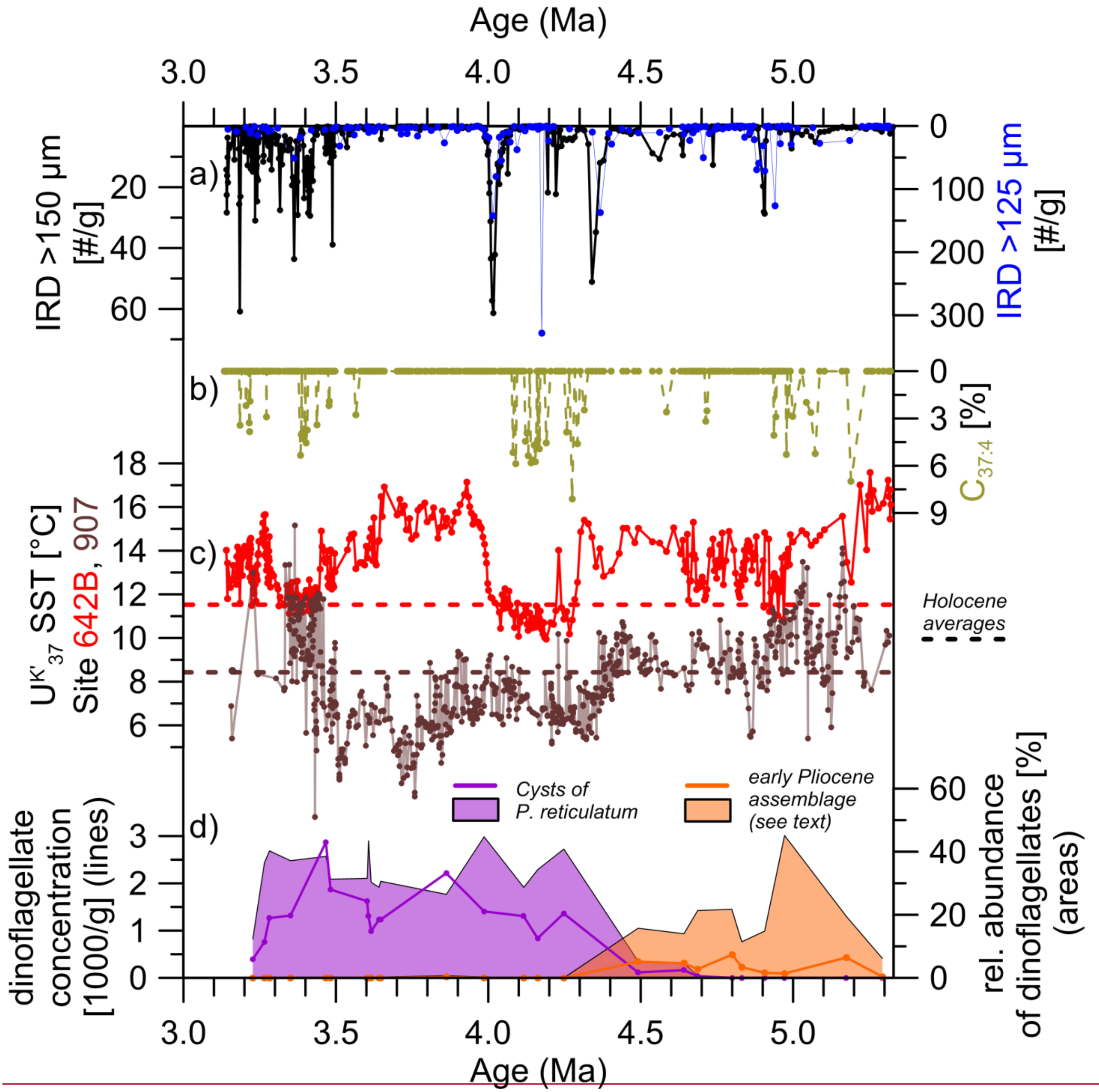



Figure 1: Nordic Seas, showing simplified modern surface currents and summer temperatures (JAS, World Ocean Atlas, Locarnini et al., 2013). NwAC: Norwegian Atlantic Current; EGC: East Greenland Current. The study site, ODP Hole 642B, is marked by a red circle. Pliocene sites referred to in the text (ODP Sites 907, 910 and 982), are marked by grey circles. The two sites that provide Holocene SST averages for comparison are marked with small white circles. Holocene SST data are shown in inserts (A: GS15-198-62 MC-A, this study, ages in Table 1; B: MD95-2011, Calvo et al., 2002), with dashed lines indicating averages.




~~**Figure 2: IRD >150 µm (this study) and >125 µm (Jansen and Sjøholm, 1991); b) %$C_{37:4}$; c) $U^{K'}_{37}$ SSTs (Müller et al., 1998 calibration). New data from ODP Hole 642B in red, data from ODP Site 907 in brown (Herbert et al., 2016). Dashed lines indicate Holocene average SSTs for the Norwegian Sea (red: Calvo et al., 2002) at 11.6°C, and for the new Iceland Sea site GS15-198-62 MC-A, at 8.5°C (brown: this study); d) concentrations and relative abundances of dinoflagellate cysts at ODP Hole 642B. Purple: cysts of *Protoceratium reticulatum*. Orange: grouping of the most abundant Early Pliocene extinct taxa, including *Reticulatosphaera***~~

~~*actinocoronata*, *Ataxiodinium* sp. A, *Batiacasphaera micropapillata* complex, and *Operculodinium tegillatum* (De Schepper et al., 2015).~~

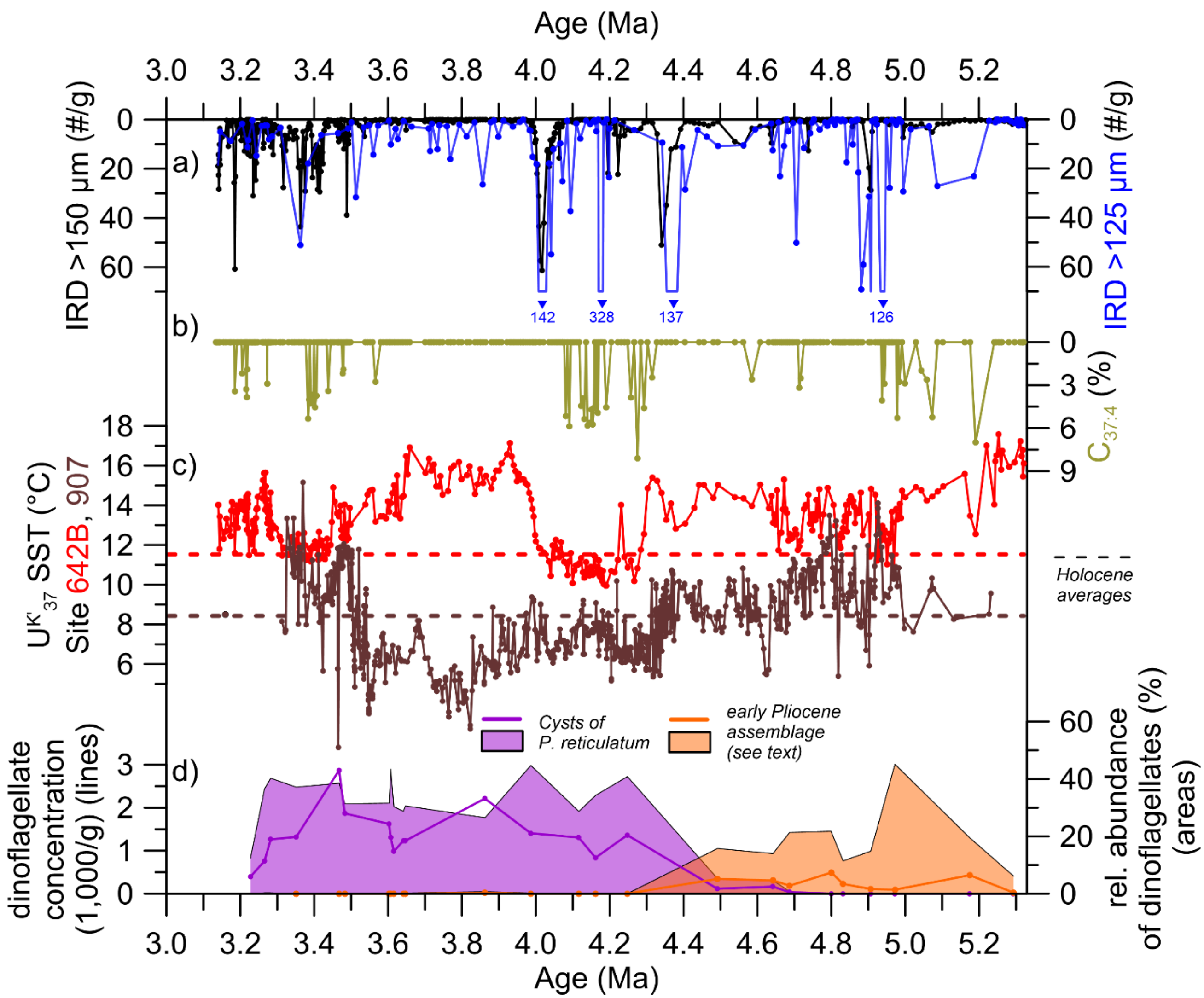
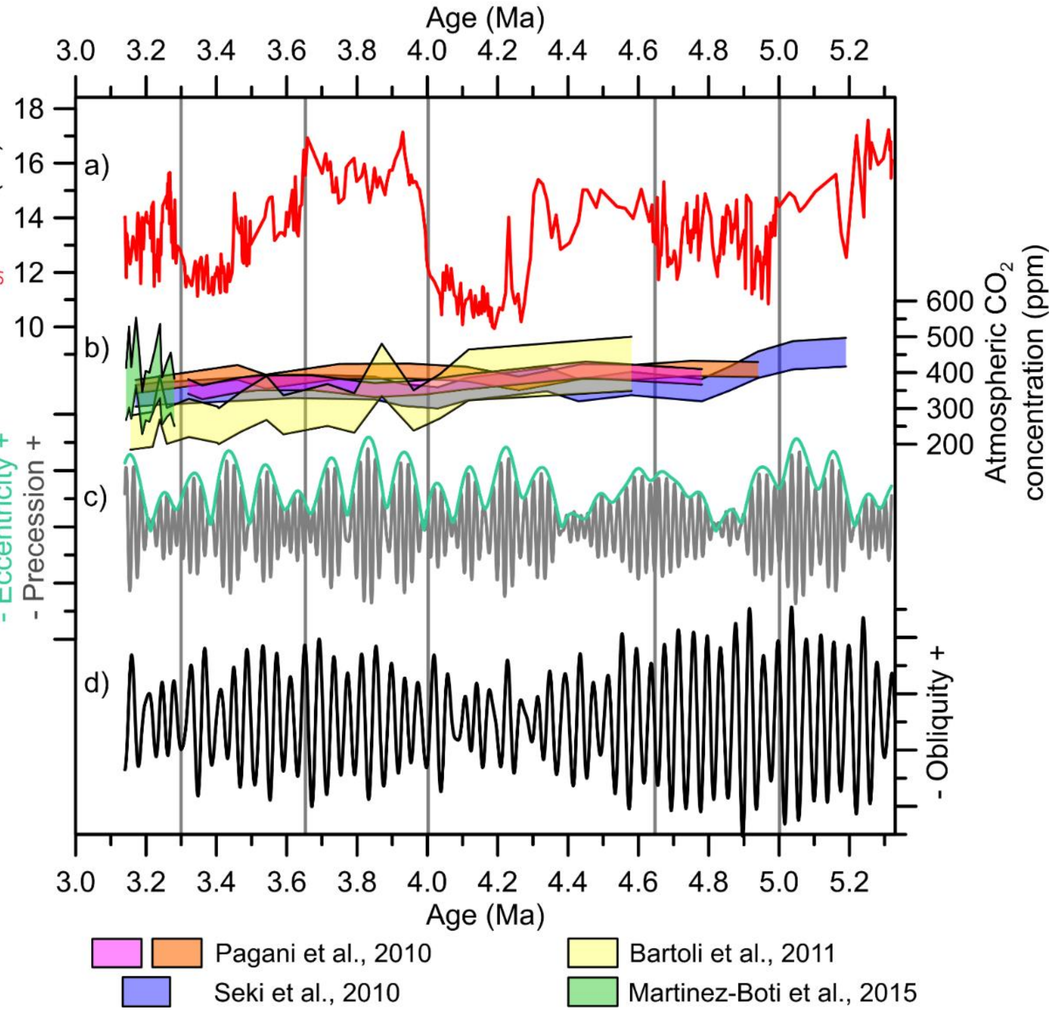



Figure 2: IRD >150 µm (black line, this study) and >125 µm (blue line, ~~Jansen and Sjøholm, 1991~~Jansen et al., 1990); b) %$C_{37:4}$; c) $U^{K'}_{37}$ SSTs (Müller et al., 1998 calibration). New data from ODP Hole 642B in red, data from ODP Site 907 in brown (Herbert et al., 2016; age model revised by Clotten et al., in review~~.~~). Dashed lines indicate Holocene average SSTs for the Norwegian Sea (red: Calvo et al., 2002) at 11.6°C, and for the new Iceland Sea site GS15-198-62 MC-A, at 8.5°C (brown: this study); d) concentrations and relative abundances of dinoflagellate cysts at ODP Hole 642B. Purple: cysts of *Protoceratium reticulatum*. Orange: grouping of the most abundant Early Pliocene extinct taxa, including *Reticulatosphaera actinocoronata*, *Ataxiodinium* sp. A, *Batiacasphaera micropapillata* complex, and *Operculodinium tegillatum* (De Schepper et al., 2015).


Age (Ma)
3.0 3.2 3.4 3.6 3.8 4.0 4.2 4.4 4.6 4.8 5.0 5.2
UK'37 SST (°C)
18 16 14 12 10
a)
b)
c)
d)
600 500 400 300 200
Atmospheric CO2 concentration (ppm)
- Eccentricity +
- Precession +
- Obliquity +
Pagani et al., 2010
Bartoli et al., 2011
Seki et al., 2010
Martinez-Boti et al., 2015

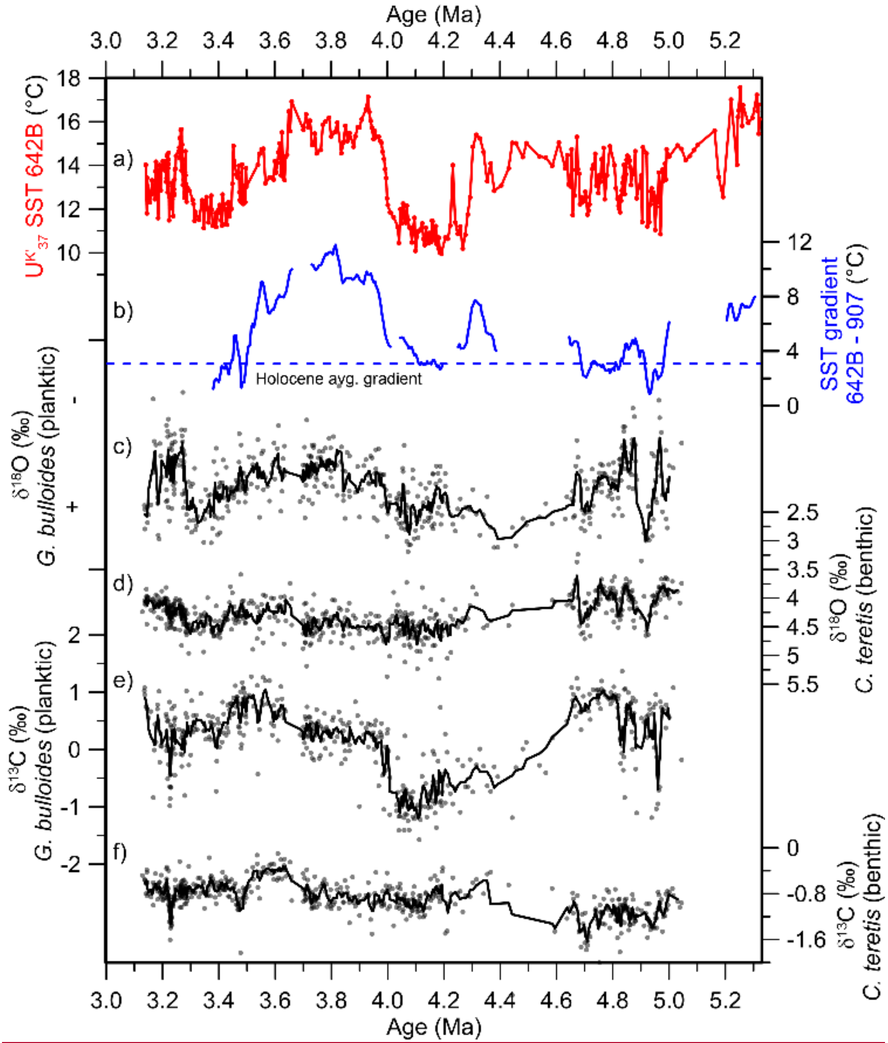



**Figure 33: a) $U^{K'}_{37}$ SSTs from Hole 642B; b) SST gradient between Hole 642B and Site 907 (Herbert et al., 2016; age model revised by Clotten et al., in reviewprep.), interpolated to 5 ka . Intervals where either record is above 10 ka resolution are not shown. The Holocene average gradient between the respective neighboring sites MD95-2011 and GS15-198-62 MC-A is marked by the dashed blue line; c) planktic $\delta^{18}O$ (*G. bulloides*). Scale not shown due to documented diagenetic impacts on absolute values (Risebrobakken et al., 2016); d) benthic $\delta^{18}O$ (*C. teretis*); e) planktic $\delta^{13}C$ (*G. bulloides*); f) benthic $\delta^{13}C$ (*C. teretis*). All data from ODP Hole 642B; c-f) from Risebrobakken et al. (2016). Grey dots represent raw isotope data; thick black lines indicate the 5-point running average of isotope data.**

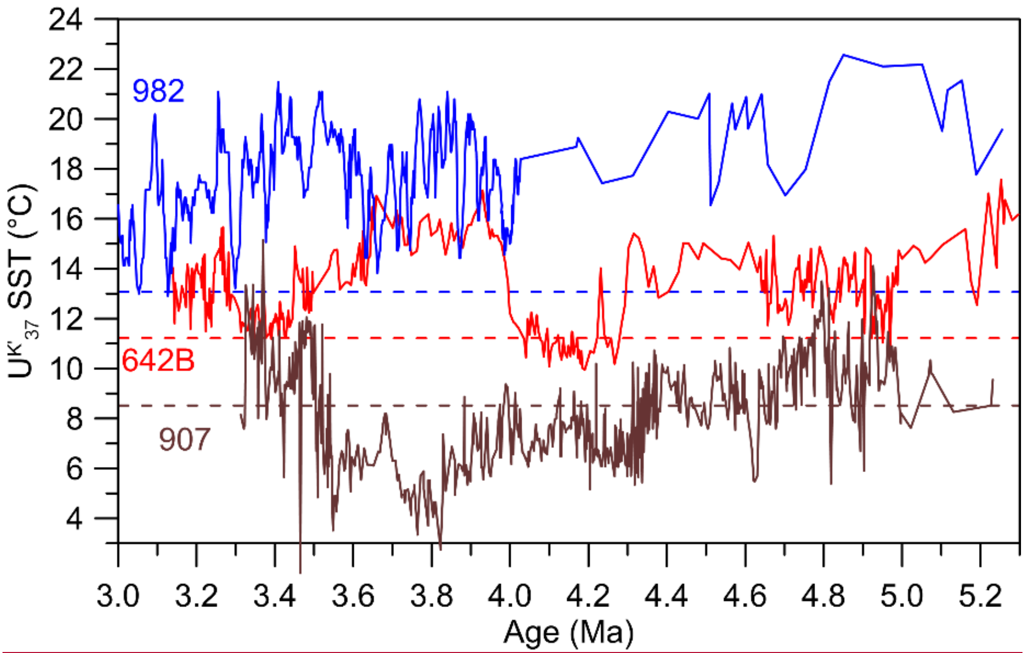



**Figure 4: Sea surface temperature records from ODP Site 982 (blue; 4-3 Ma: Lawrence et al., 2009; 5.3-4 Ma: Herbert et al., 2016), compared to SSTs from ODP Hole 642B (red, this study) and ODP Site 907 (brown, Herbert et al., 2016; age model revised by Clotten et al., in review). Comparable averages are indicated by respective dashed lines (982: core-top data, Lawrence et al., 2009; 642B: Holocene average, Calvo et al., 2002; 907: Holocene average, this study).**

~~**Figure 3: a) SSTs from ODP Hole 642B; b) examples of Pliocene atmospheric $CO_2$ concentration proxy data; c) precession and eccentricity envelope; d) obliquity (c and d from Laskar et al., 2004). Important climate transitions mentioned in the discussion are marked by vertical lines.**~~

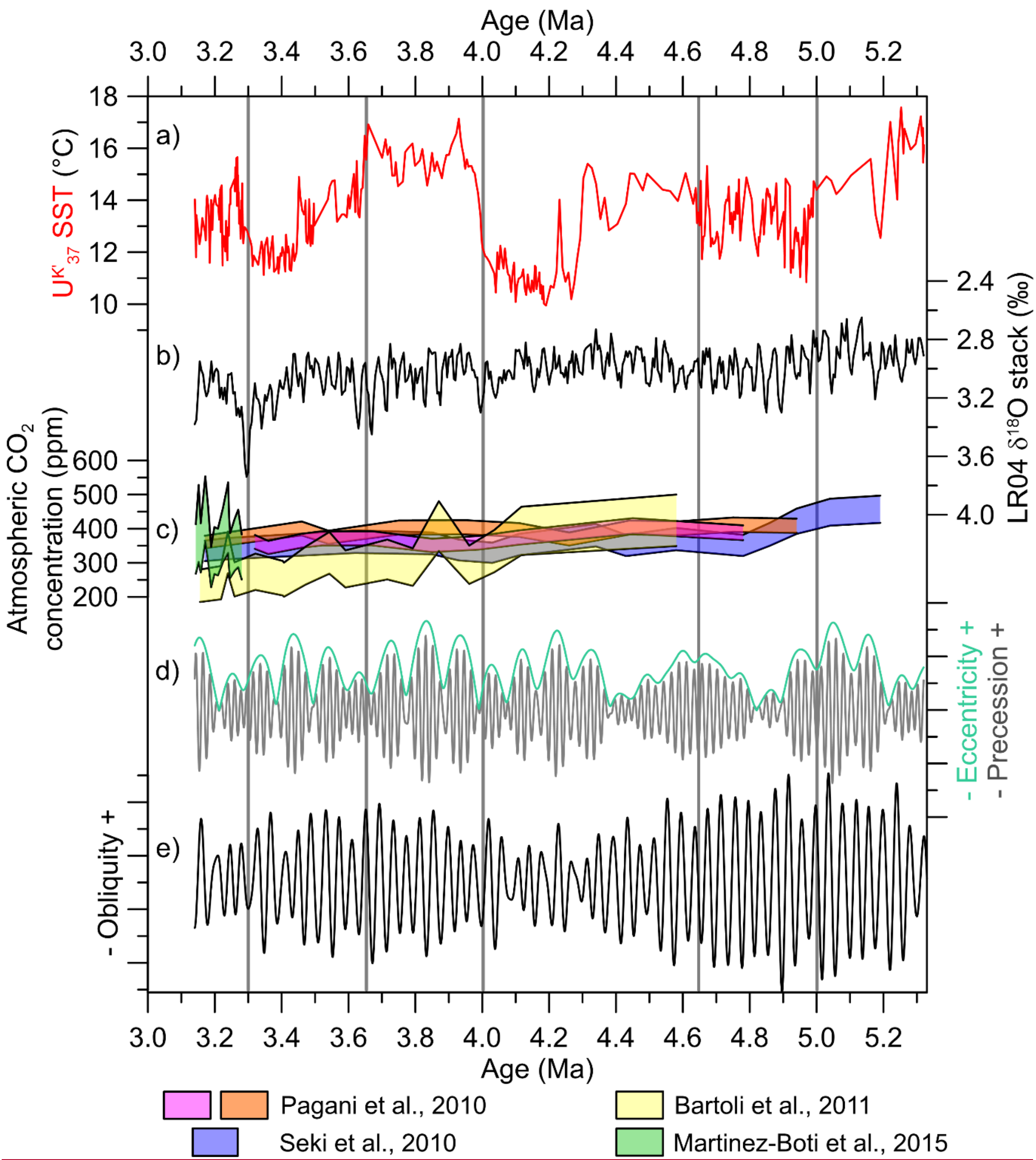


**Figure ~~3~~5: a) SSTs from ODP Hole 642B; b) benthic $\delta^{18}O$ isotope stack LR04 (Lisiecki and Raymo, 2005); c) examples of Pliocene atmospheric $CO_2$ concentration proxy data; d) precession and eccentricity envelope; e) obliquity (d and e from Laskar et al., 2004). ~~Important~~Local climate transitions at ODP Hole 642B discussed here are marked by vertical lines.**