Universiteit Utrecht

Editorial Board, Climate of the Past

To the editorial Board

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Department of Earth Sciences
Marine Palynology and
Paleoceanography

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Your reference	
Our reference	Climate of the Past manuscript
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Date	November 22, 2017
Subject	Submission of manuscript to Climate of the Past (cp-2017-153)

Dear David Thornalley,

We would like to thank you for the extra week time granted for resubmitting this manuscript. Please find enclosed a final and marked-up version of our manuscript, entitled "**Oligocene and Miocene TEX_{86}-derived seawater temperatures from offshore Wilkes Land (East Antarctica)**", as well as the rebuttals to the reviewers.

Firstly, as you may have noticed, we have changed the title to include Miocene for the reason we explain below.

We have significantly revised our manuscript, taking into account the comments of the reviewers. Notably, the so-called thought experiment that deduced Antarctic ice volume changes based on our sea surface temperature record was (properly) considered too far-fetched by all reviewers, and has therefore been removed. Instead, the discussion focuses on comparing our sea surface temperature record with existing sea surface temperature, bottom-water temperature and stable oxygen isotope records in a much more in a qualitative way. Trends seen in our temperature records are now interpreted in terms of paleoceanographic changes rather than focused exclusively on ice sheet stability.

As this manuscript is part of triple submission, with the other manuscripts also including data on the Miocene section of the study site (IODP Site U1356), we believed it was necessary to update this manuscript by including recently published Miocene TEX_{86}-based sea surface temperature data of Site U1356 (Sangiorgi et al., 2018, Nature Communications). As for the Oligocene data, the relation between TEX_{86} and the lithology was examined, and the reconstructed sea surface temperatures are discussed in relation to existing sea surface temperature, bottom-water temperature and stable oxygen isotope records.

As a final remark, Figure 5 was removed. Henk Brinkhuis was added as a co-author to this manuscript, due to his participation as co-chief to IODP Expedition 318 where the material comes from and his valuable contribution to this new version of the manuscript.

The manuscript contains 4 figures, 2 supplementary figures and 2 supplementary tables and about 10,000 words.

In anticipation of your reply,

Best regards, also on behalf of my co-authors,

Julian D. Hartman
Corresponding author

Point-by-point response to the reviewers

Reply to Referee #1

We would like to thank Referee #1 for his/her extensive and constructive review.

The major concern of R1, which is also that of R2, is that our attempt to quantitatively disentangle temperature and ice volume from the benthic δ18O record requires too many assumptions. We understand this concern and agree with the reviewers. We agree that the most important message of this paper is to provide the first long-term Oligocene SST record from close to the Antarctic margin, and we will place the focus on this particular aspect in the revised version of our manuscript.

In addition, we will discuss the TEX86-based temperature reconstructions, related uncertainties, and their oceanographic and climate implications in a qualitative way. We will also discuss multiple scenarios that might explain the differences and similarities between the TEX86-based temperature record, the benthic δ18O record and the Mg/Ca-based bottom temperature record, instead of focusing only on the link between temperature and ice volume. Below, we give a point-to-point response to the comments of R1.

ORIGINAL COMMENT:
1) Temperature and ice volume

In Section 4.2, the authors attempt to use TEX86 SST estimates to disentangle temperature and ice volume from the deep-sea delta18O signal. However, there are several caveats to this approach. These include: (1) a possible summer bias in TEX86 estimates, (2) uncertainties in the location of deep-water formation, (3) a "poor age model" (the authors words, not mine!) and (4) low sampling resolution (line 416 to 421). As such, I remain unconvinced by the discussion that follows. This is problematic given how much time the paper devotes to it.

Unless you can present additional lines of evidence which support your conclusions (e.g. GCM simulations c.f. Liu et al., 2009), these results are highly speculative.

REPLY:
We agree that our quantitative estimates of the ice volume effect in d18O records based on independent temperature reconstructions from our TEX86-based SST record involves many assumptions. Although we feel that we had objectively discussed these assumptions and associated speculation in our manuscript, the shared concerns of R1 and R2 on this matter indicate that we should revise this part of the discussion. In our revised manuscript, we will limit the discussion to a qualitative assessment of our new temperature record and its influence on the benthic foraminifer δ18O record. Irrespective of all the assumptions involved, we remain confident that our TEX86 record convincingly shows more profound temperature changes both on orbital and on long-term time scales than previously appreciated (e.g., Lear et al. 2004), in an area that is close to the region of deep-water formation (the Wilkes Land-Adélie Coast margin has been identified as a region of deep-water formation during the Eocene by Huck et al. 2017, Paleoceanography). This would imply that a larger portion of the

high-amplitude benthic δ18O can potentially be explained by southern high-latitude climate change and a smaller fraction by ice volume changes. However, we will refrain from quantifying the amount of variation in the benthic δ18O record that could be explained by our data. Instead, we will focus the discussion on how other aspects, such as the moving of the Southern Ocean polar fronts and the position of deep-water formation, could explain the differences and similarities between the benthic δ18O record, the TEX86-based temperature record, and the Mg/Ca-based bottom-water temperature record.

Numerical model simulations of adequate time interval (i.e. geographical boundary conditions of the Oligocene) and spatial resolution are currently not available, although we have initiated collaboration with modelers to produce such simulations in the near future. We choose to leave the model outcomes for a future paper, and solely focus on the data in this current manuscript.

ORIGINAL COMMENT:
In this paper, the authors show an intriguing temperature offset between two contrasting lithologies. They argue that the laminated carbonate-rich marls reflect glacial cycles, whereas the bioturbated carbonate-rich deposits reflect interglacial cycles. However, I have two concerns:

Firstly, this relies heavily upon Salabarnada et al. which is currently in review.

REPLY:
We are aware that it would have been difficult for reviewers to assess the veracity of papers that are still under review. This is also one of the reasons why we chose to submit our papers (Hartman et al., Bijl et al., and Salabarnada et al.) to Climate of the Past, as Copernicus enables all reviewers (in fact everybody) to access papers under review (and join in on those discussions) for the purpose of their own review.

Indeed, the lithological interpretations are not part of this paper and are entirely from Salabarnada et al. Crucially, the interpretation of the lithofacies as being representative of glacial versus interglacial deposits in Salabarnada et al. are based on the integration of the facies (characterized on the basis of sedimentological data, physical properties, and geochemical data) independently of our TEX86 results, and merely stem from bottom current and pelagic sedimentation variations. We want to point out that Salabarnada et al. already submitted replies to their reviews (see the reviews and rebuttals at https://www.clim-past-discuss.net/cp-2017-152/#discussion). The consistent offset between TEX86-based SSTs between the lithologies supports the independent interpretation of the lithofacies by Salabarnada et al. very nicely. This is to us additional support for a SST signal preserved in TEX86.

ORIGINAL COMMENT:
Secondly, there are other mechanisms which could account for this variability. These include: a) oxic degradation and differential degradation of core GDGTs and/or b) changes in the Thaumarchaeotal community (e.g. deep vs shallow ecotypes).

The latter is particularly important to consider as": : :the abundance of 'shallow' versus 'deep water' Thaumarchaeotal communities at deep water sites, like Site U1356, could be affected by the presence of sea ice and the relative influence of (proto-)Component Deep Water upwelling" (lines 220-222).

One way to assess this would be to compare GDGT-2/3 ratios for glacial and interglacial deposits (see Taylor et al., 2013 but also Kim et al., 2015; GCA). You may also want to revisit Littler et al. (2014; P3), as they observe a similar offset in TEX86 values between laminated and homogenous marls during the Cretaceous.

REPLY:
a) The effect of oxic degradation has been studied by Huguet et al. (2009, OG) on turbidites from the Madeira Abyssal Plain. Although differences between TEX86 values from unoxidized and oxidized sediments have been observed, these are not consistent and it seems therefore that differential degradation of isoprenoid GDGTs does not play a role (Huguet et al. 2009, OG). Instead, oxic degradation may lead to an increased relative influence of soil-derived isoprenoid GDGTs, which could bias the TEX86 in different ways depending on the composition of the soil-derived isoprenoid GDGTs (Huguet et al. 2009, OG). An increased relative contribution of soil-derived organic matter to marine sediments can be identified using the BIT Index (Hopmans et al., 2004; Weijers et al., 2006). Following this approach, we have discarded nine samples with a BIT Index above 0.3, a threshold at which the terrestrial contribution could potentially have affected TEX86 values. We acknowledge that this is currently not mentioned in the manuscript and we will add this discussion in a revised version of the manuscript.

b) GDGT2/3 values are available in Table S1 in the Supplementary Information. For the revised manuscript, we will add a figure displaying the GDGT2/3 ratios to facilitate easy comparison between glacial and interglacial lithologies. Although there is considerable variability in GDGT2/3 ratios throughout the record (which is why we refrain from using TEX86-L), it cannot explain the differences in TEX86 between glacial and interglacial sediments. Nor can it explain the long-term trends in our data.

ORIGINAL COMMENT:
Finally, you also have quite large variations in TEX86 values even within the same lithofacies (e.g _31 Myr ago). Is this a true climate signal? Or are there additional controls on the GDGT distribution?

REPLY:
Considering that we have excluded all known biases due to soil-derived input, methanogenic and methanotrophic input, and oxic degradation, and the fact that there is no relation between the TEX86 values and the GDGT2/3 ratio, we interpret the variation in TEX86 as a true temperature (climate) signal. We agree that there is indeed quite some variation within the bioturbated facies around 31 Ma, and will provide and discuss possible explanations for this variability in the revised version of the manuscript.

ORIGINAL COMMENT:
3) Summer Bias

The authors argue that TEX86 values are biased towards summer SST (lines 353-361). Although this observation has also been made for other high-latitude sites during the Oligocene (e.g. ODP Site 511), it is quite speculative and is based upon the assumption that ancient high-latitude GDGT export is similar to the modern. This is quite an assumption! Therefore, do you have any other evidence for a summer bias?

REPLY:
The potential summer bias in high latitude TEX86-based SST reconstructions has been discussed extensively in other papers (e.g., Sluijs et al., 2008; Bijl et al., 2009; 2010; 2013). Like in these warm past climates, we expect that primary productivity in the Oligocene Southern Ocean was in sync with seasonal availability of light irrespective of the presence of sea ice. Transport of isoGDGTs likely requires fecal pelleting to sink effectively to the sea floor, and therefore depends on the presence of larger zooplankton that feed on the phytoplankton. This means that, like today, TEX86 temperature reconstructions are likely skewed towards the season with highest primary productivity, i.e. the summer. We will explain this more clearly in a new version of the manuscript.

ORIGINAL COMMENT:
4) Comparison with CO2 records

You observe significant temperature fluctuations in your record (up to 10 _C). This may be partly related to glacial/interglacial variability. However, is there also a potential role for CO2? (see Zhang et al. (2011) and Anagnostou et al. (2016) for recent Oligocene CO2 estimates). It might be worth showing these CO2 records in Figure 4 too.

REPLY:
We agree with the reviewer that atmospheric CO2 concentrations were likely the driving factor of Oligocene glacial-interglacial variability (DeConto et al. 2008; Liebrand et al. 2017). However, locally, surface water temperature variability can respond very sensitively to glacial-interglacial climate change and in a non-linear way, e.g., via the migration of ocean fronts. The discussion about the forcing mechanism for Oligocene high-latitude glacial-interglacial climate variability lies beyond the scope of this paper. Moreover, the resolution of the existing CO2 reconstructions for the Oligocene (Zhang et al. 2013) (as well as those for the Eocene (Anagnostou et al. 2016)) does not capture the glacial-interglacial variability seen in our record. We will therefore refrain from adding a CO2 reconstruction to Figure 4, as it would suggest a correlation between the two, which we cannot say based on our results.

ORIGINAL COMMENT:
5) Branched GDGTs:

Although the authors have analysed branched GDGT (see Supp. Table), MBT/CBT values were not reported. However, this could provide important insights into continental air temperatures during the Oligocene and would be an interesting addition to this paper.

For example, how do MBT'/CBT values compare to TEX86 estimates? Do they exhibit the same temporal trends? Are they offset? Do they max out? etc etc.

REPLY:
Although we agree that data on Oligocene air temperatures would be a great addition to our understanding of Oligocene Antarctic climate evolution, we fear that branched GDGT (brGDGT) data obtained from Site U1356 are unable to provide reliable information on this front. The reason for this is

the very low absolute and relative abundances of soil-derived brGDGTs (BIT<0.3), which is probably caused by the too large distance to shore and/or limited soil development and subsequent transport from the land. In addition, a substantial portion of the samples analyzed has #rings-tetra values higher than 0.4 (see Table S1), which indicates that temperature estimates for these samples are likely affected by a contribution of *in situ* produced brGDGTs (Sinninghe Damsté, 2016, GCA). All of the above makes it difficult to infer a reliable long-term atmospheric temperature trend at this stage.

ORIGINAL COMMENT:
6) Calibrations

This study uses the linear calibration of Kim et al. (2010). However, it is important to note that Kim et al. (2010) plots SST on the y-axis (see Kim et al. 2010; Fig.5). As such, this calibration will suffer from a regression dissolution bias and should not be used.

REPLY:
Referee #1 is correct in stating that the calibration of Kim et al. (2010) suffers from a regression dilution bias caused by the uncertainty in the measured TEX86 values plotted on the x-axis, and we shall add this potential complication in the methods section. This bias causes flattening of the slope (Hutcheon et al. 2010, BMJ) and therefore affects TEX86-based temperature reconstructions at the lower and upper end of the calibration range. However, because TEX86 in our record lies around the middle of the total TEX86 range used for the linear calibration of Kim et al. (2010), reconstructed temperature values for Site U1356 will not be severely biased.

Indeed, the BAYSPAR method is the only TEX86 calibration that is not affected by the regression dilution. However, by applying the BAYSPAR method, only core tops within a selection of 20°x20° grid boxes are used, thereby excluding all of the low-temperature Southern Ocean core-top calibration values (Fig. 3). Considering that Site U1356A is a high-latitude Southern Ocean site, we did not want to only use BAYSPAR and, therefore, plotted the linear calibration of Kim et al. (2010) for comparison. Although this linear calibration shows large scatter at the lower temperature end, it has been shown that all Southern Ocean core-top values in the Kim et al. (2010) dataset fall within the standard error (±5.2°C) of the linear calibration of Kim et al. (2010) (Ho et al. 2014, GCA). In addition, the fact that the temperature reconstruction based on the Kim et al. (2010) calibration compares very well with the BAYSPAR-based temperature record (Fig. 3) indicates that the effect of regression dilution bias is, in our case, relatively minimal.

In the revised manuscript we will clarify our choice to use both the BAYSPAR and the Kim et al. (2010) linear calibration.

ORIGINAL COMMENT:
This paper also flips between different calibrations and there needs to be some consistency in the text and figures. For example, in Figure 3 you calculate SSTs at IODP 1356 with TEX86 (Kim 2010) and BAYSPAR (T&T 2015). However, ODP Site 511 is only shown using TEX86 (Kim 2010). Why not also recalculate with BAYSPAR?

REPLY:
We agree that there are some inconsistencies in the use of calibrations in the text and figures. We shall recalculate the temperatures of ODP Site 511 using BAYSPAR and add them to Figure 3.

ORIGINAL COMMENT:
Similarly, you only use only BAYSPAR in Figure 4, despite the manuscript stating that Kim et al. (2010) was the preferred calibration (line 241).

REPLY:
To clarify, we do not state that we prefer the linear calibration of Kim et al. (2010) over the BAYSPAR calibration. This is why we also apply the BAYSPAR calibration. The offset between these two calibrations is, however, only 0.5°C, well within the calibration error of both regressions. Because of the small temperature difference between the two calibrations it is only for convenience that we showed only one calibration in Figure 4. In the revised manuscript we will plot both reconstructions in Figure 4.

ORIGINAL COMMENT:
Minor comments:

There are a few other TEX86 datasets which might be of interest to the authors;

a. Wade et al, (2012) -> TEX86 values span the earliest Oligocene (ca. 34-32 Ma). b. Zhang et al., (2011) -> TEX86 values span most of the Oligocene.

REPLY:
TEX86 data of Wade et al. (2012), and Zhang et al. (2013, not 2011) clearly show that the early Oligocene did experience a latitudinal temperature gradient. Although a valid observation in itself, these low-latitude regions are not the focus of our study. Our study focusses on near-Antarctic SST estimates and trends and how these relate to our current knowledge of the Oligocene Antarctic ice-sheet dynamics.

ORIGINAL COMMENT:
66: state CO2 estimates for the Oligocene here

REPLY:
We will state CO2 estimates for the Oligocene

ORIGINAL COMMENT:
93: specifically, ISOPRENOIDAL glycerol dialkyl glycerol tetraethers

REPLY:
We will insert ‘isoprenoidal’

ORIGINAL COMMENT:
94: Careful of the wording here. If you have GDGTs, you will likely have other fossil organics preserved. Do you mean that these are the only fossil "paleothermometers” which are preserved?

REPLY:
We mean specifically fossil paleothermometers.

ORIGINAL COMMENT:
101-106: this should probably go into the discussion.

REPLY:
We agree with the reviewer that this should not be part of the introduction. This section will be transferred to either the methods section 2.6 on TEX86 calibrations or the discussion of the revised manuscript.

ORIGINAL COMMENT:
102: BAYSPAR is not strictly a local/ regional calibration. It searches the global coretop dataset for TEX86 values which are similar to the measured value and draws regression parameters from these modern locations.

REPLY:
We agree that BAYSPAR is not strictly a local/regional calibration. By selecting only TEX86 core-top values similar to the ones measured in Oligocene samples at Site U1356 BAYSPAR constructs a calibration based on multiple modern-day analogue sites and therefore is not regional. We shall therefore be more careful using the word 'regional'.

ORIGINAL COMMENT:
141: space needed between oceanography and are

REPLY:
A space will be added

ORIGINAL COMMENT:
140: should this read "Palaeoceanographic setting"?

REPLY:
Paleoceanographic setting would be a better heading.

ORIGINAL COMMENT:
194: they are not always minor components. For example, in arid and/or alkaline settings they can be the major components (e.g. Huang et al., 2014)

REPLY:
Indeed, isoGDGTs are major components in arid/alkaline soils when compared to brGDGTs. However, compared to in marine sediments, the concentration of isoGDGTs in soils is always low. We shall therefore not alter this statement.

ORIGINAL COMMENT:
202: why can #ringtetra discriminate between marine and soil-derived GDGTs?

REPLY:
This information is not explicitly given in the manuscript and we shall include this in the revised version. To answer the question, #rings-tetra can discriminate between marine and soil-derived branched GDGTs as the composition of soil-derived GDGTs typically show high amounts of the acyclic tetramethylated GDGT-Ia, while a dominance of cyclic tetramethylated (Ib, Ic) (and also pentamethylated) brGDGTs has been attributed to *in situ* production within the sediments (see Sinninghe Damsté 2016).

ORIGINAL COMMENT:
208-220: it has been shown that TEX86-L does not work (e.g. Taylor et al., 2013; Hernandez-Sanchez, 2014) and I think that this discussion can be shortened significantly.

REPLY:
Agreed. A less detailed discussion is sufficient by stating earlier that TEX86L does not work due to its sensitivity to changes in the GDGT2/3 ratio as shown by Hernandez-Sanchez et al. (2014).

ORIGINAL COMMENT:
209: these are 'assumed' to originate from Thaumarchaeota. But they can have many sources!

REPLY:
We shall change the sentence to "In marine sediments these lipids are assumed to originate mostly from cell membranes of marine Thaumarchaeota, because they are one of the dominant prokaryotes in today's ocean and occur throughout the entire water column".

ORIGINAL COMMENT:
221: Do you have any constraints on water depth? If the site is less than 100m depth, then the presence of "subsurface" archaea is likely to be minimal. However, if the site is >1000m, then subsurface archaea might be an important contribution to the sedimentary GDGT pool.

REPLY:
Today the water depth of Site U1356 is 3992 m (see material & methods section). We have no quantitative constraints on water depth during the Oligocene, but the sediments, characterized by hemipelagic deposits reworked by bottom currents and distal gravity flows, as well as biota suggest a deep-water setting in the Oligocene (Escutia et al., 2014 Develop. Mar. Geol.). It is therefore certainly not a shallow (<1000 m depth) site. Regardless, it is more likely that GDGTs derived from shallower waters (<1000 m depth) are more effectively transported to the sediments through a.o. fecal pelleting (Schouten et al., 2013 and references cited therein). If deep archaeal communities would have contributed to the sedimentary GDGT pool, this would result in a higher GDGT2/3 ratio for these samples, which will have only a minor effect on the TEX86 (i.e. TEX86H) index (Hernández-Sánchez et al. 2014).

ORIGINAL COMMENT:
280: The Methane Index does not flag methanogens. Rather, it can identify anaerobic methanotrophs (i.e. ANME).

REPLY:
In line 280 proxies for identifying methanotrophs have mistakenly been lumped together with those identifying methanogens. We shall correct for this.

ORIGINAL COMMENT:
286: What are “non-temperature related influences on TEX86”? It might be useful to go into a little more detail here...

REPLY:
We will elaborate more on ‘non-temperature related influences on TEX86’, such as archaeal growth rates or an input from methanogenic Euryarchaeota (Zhang et al., 2016 Paleoceanography), in the revised manuscript.

ORIGINAL COMMENT:
283-284: You state that 8 had high BIT values, but only 5 were discarded? Why?

REPLY:
We meant to say that in addition to the eight samples with high BIT values, another 5 were discarded based on high GDGT-0/Cren or Methane Index values. As all samples with too high BIT values also had high GDGT-0/Cren or Methane Index values, a total of 13 samples showed indications of input from methanogens or methanotrophs. We will clarify this in the revised version.

ORIGINAL COMMENT:
317: To be clear, BAYSPAR is based upon “581 coretops, including the 426 sites from the Kim et al. (2010) calibration study and an additional 155 sites from regional coretop TEX86 studies (Leider et al., 2010; Shintani et al., 2010; Ho et al., 2011; Wei et al., 2011; Chazen, 2011; Shevenell et al., 2011; Fallet et al., 2012; Jia et al., 2012; Hu et al., 2012)”. See Tierney and Tingley (2015) for more details.

REPLY:
We shall mention the additional 155 sites aside from the Kim et al. (2010) calibration set.

ORIGINAL COMMENT:
319: Can you explain where the 3.5°C error bars come from. I thought that BAYSPAR gave you 90% uncertainty levels rather than a definitive calibration error.

REPLY:
Referee #1 is correct in stating that the BAYSPAR program gives you 90% confidence levels for each sample. Assuming that the error is normally distributed around the mean, the lower and upper 90% confidence interval boundary can be calculated as the mean plus or minus 1.645 times the standard error. As for each sample the mean, upper and lower confidence interval are known, the standard error can be calculated. On average the calculated standard error for all of the samples is ±4.2°C. The ±3.5°C standard error was miscalculated based on BAYSPAR giving the 95% confidence levels. We shall make this calculation in the methods section and correct this error.

ORIGINAL COMMENT:
331: What was the paleolatitude of the Wilkes Land section during the Oligocene?

REPLY:
We shall add the paleolatitude of Site U1356 to the manuscript, which is 58.86°S.

ORIGINAL COMMENT:
Line 404: how exactly does this resampling work? It is not clear from the text.

REPLY:
Resampling is done by predicting the $\delta18O$ value from a LOESS fit through the glacial and interglacial $\delta18O$ values. We shall explain this in the text.

ORIGINAL COMMENT:
Figure 5: Most of the data in Figure 5 is already in Figure 4. As such, I would recommend removing it.

REPLY:
We removed this figure.

Reply to anonymous Referee #2

Firstly, we would like to thank Referee #2 for his/her thorough feedback on the manuscript.

We recognize that the major concerns of R2 are the same as those of R1, for which we have written a more detailed reply letter.

ORIGINAL COMMENT:
In this paper Hartman et al., present Southern Ocean TEX86-derived temperature estimates from the Oligocene. They then use the TEX86-derived temperature reconstruction to de-convolve a δ18O of benthic foraminifera from an equatorial Pacific site into the δ18O of seawater component to infer relative stability of the Antarctic ice sheet during the Oligocene. I think the TEX86 record is a useful contribution to our understanding of temperature conditions around Antarctica during the Oligocene. However, I found the "thought experiment" inferring Antarctic ice volume stability (lines 419-420), particularly given the limitations of TEX86, unconvincing. The authors are very mindful about the limitations of this "thought experiment" but inferring ice volume stability feels over-reaching. I think a revised manuscript should focus on the regional oceanography and polar frontal systems. I also found it difficult to comprehensively review this manuscript because it references two submitted articles Salabarnada et al., and Bijl et al.,) related to the lithology and surface water conditions.

REPLY:
Similarly to our reply to R1, we agree with R2 and will focus on the relation between temperature and δ18O in a more qualitative way, and redirect our discussion more towards the nature of the high variability in the SSTs in a revised version of our manuscript. In addition, we agree with Referee #2 that the discussion is too much focused on the one scenario that links the TEX86 variability to the δ18O variability, while the discussion on the role of oceanography (polar front shifts) and its link to temperature changes is limited. Indeed, the role of oceanography is also very important for the stability of the cryosphere (Sangiorgi et al. 2018, Nature Comm.) and it is therefore highly interesting to analyze our temperature data in light of possible oceanographic changes. In the revised manuscript we will therefore explore scenarios that involve the potential role of shifting polar frontal systems over Site U1356 to explain the TEX86 variability.

We are sorry that Referee #2 felt unable to comprehensively review this manuscript because it refers to two submitted papers (Salabarnada et al. and Bijl et al.), both in review in CP. By submitting the three manuscripts back-to-back in Copernicus journals, we hoped to enable all reviewers to openly access them for the purpose of their own review. We understand that submitting 3 back-to-back papers implies that the reviewers should read and evaluate all three papers to comment on one of the them. Salabarnada et al. submitted their rebuttals at at https://www.clim-past-discuss.net/cp-2017-152/#discussion and the reviews for Bijl et al. can be found here (https://www.clim-past-discuss.net/cp-2017-148/#discussion). We believe that none of these reviews suggest a major reconsideration of our conclusions.

ORIGINAL COMMENT:
There are many fundamental assumptions the authors make and explore within the manuscript with

respect to relative contribution of temperature and ice volume in the δ18O of benthic foraminifera from Site 1218:

1) Temperature bias in TEX86 is to summer and deep water production (in the modern) is to winter. The authors note this throughout the manuscript but this is a difficult temperature disconnect to constrain. What is the seasonal range in temperatures from summer to winter today? The winter temperatures during deep water formation are constrained because seawater freezes at -2C. Summer temperatures, particularly in a warmer world, could vary by a lot. In particular, the TEX86-derived temperatures are nearly twice that of the Mg/Ca bottom water temperature record.

REPLY:
We agree with the reviewer that this temperature disconnect is difficult to quantify for the Oligocene, based on our data. In general, quantification of temperature disconnect for past periods before monitoring became available is always difficult and has at best to rely on proxies (and their uncertainties). Because of this, we do agree we should refrain from quantifying the temperature signal in δ18O using our TEX86 results. However, we would like to point out that the temperature at the locus of deep-water formation could have changed profoundly in the past. Deep-sea δ18O changed considerably over the ice-free Eocene (Zachos et al., 2008), which can only result from changes in deep-water temperature in the absence of ice sheets. Although on Oligocene glacial interglacial time scales we expect SST changes to be in part affected by the migration of polar frontal systems, we cannot rule out that winter temperatures at the locus of deep water formation changed as well. After all, the locus of deep water formation is to some extent predefined by geographic boundaries, next to the physical properties of the water that cause the water to sink. Therefore, the possibility that a significant part of the benthic foraminifer δ18O variation of Site 1218 is related to glacial-interglacial winter temperature variability remains. We shall focus the discussion more towards this point in a revised version of our manuscript.

ORIGINAL COMMENT:
2) No subsurface temperature bias in TEX86. Given that the temperatures vary by >10C and this assumption relies on a submitted manuscript (Salabarnada et al.,), I found this assumption difficult to evaluate. My main concern is that “interglacial” and “glacial” temperatures are related to lithology. The packaging and flux of TEX86 to the deep ocean is likely very different during these times: “interglacial” temperatures are during bioturbated carbonate-rich periods and “glacial” are during laminated silty periods. Also, are there post-depositional processes that might influence TEX86 estimates due to the change in lithology?

It seems given the uncertainty and variability in the temperature reconstructions, all calibrations should be discussed, including the subsurface ones. The BAYSPAR calibration itself (Tierney and Tingley, 2015), which is discussed in some detail, uses regional factors such as the vertical temperature gradient and related subsurface TEX86 influence to reconstruct temperature.

REPLY:
The sedimentation of Site U1356 during both glacial and interglacial periods is characteristic for a deep-

water distal setting, dominated by fine-grained turbidite overbank and hemipelagic depositions, that are reworked by bottom currents of different intensities (stronger during the interglacials). There is therefore lithologic variation between glacial and interglacial time periods, but we believe the processes responsible for the lithologic variability are not the ones that typically change GDGTs. Post-depositional processes, such as oxic degradation, do not affect the ratio between the various isoGDGTs (Huguet et al. 2009, OG). To investigate if there is any relation between lithology and archaeal community changes, we checked if there is any correlation between lithology and GDGT2/3 ratio, which can identify potential contributions of subsurface GDGTs. However, no relation between the lithological facies and the GDGT2/3 ratio has been found. We agree that this should be more adequately discussed, and will change this in the revised manuscript.

As Referee #2 mentions, there is significant variability in the temperature reconstructions across the various calibrations to (sub)surface temperature (Figure S2). However, in our materials & methods section we thoroughly discuss why most of these calibrations cannot be applied at Site U1356.

ORIGINAL COMMENT:
3) The authors mostly dismiss the Lear et al., 2004 Mg/Ca bottom water temperature record. This is odd because the Mg/Ca record is from the same site as the δ18O of benthic foraminifera (Site 1218) so it should be discussed in some length. The authors note changes in Mg/Ca of seawater and carbonate ion may influence the Mg/Ca-based temperature reconstruction. There are many uncertainties about the Mg/Ca paleotemperature sensitivity to changes in Mg/Ca of seawater (Evans et al., 2016 and for a nice discussion see Lear et al., 2015 for ice volume estimates for the Miocene to present) but the relative direction in bottom water temperatures shouldn't be an issue. The fact that the TEX86 and Mg/Ca-derived temperature estimates have different trends can't be explained by Mg/Ca of seawater changes. Additionally, the benthic foraminifera used in the Lear et al., 2004 study are an infaunal species, largely insulated from longterm changes in in carbonate ion (Lear et al., 2015, Ford et al., 2016).

REPLY:
We agree with Referee #2 that we too easily dismissed the Lear et al. (2004) Mg/Ca bottom water temperature record. We thank Referee #2 for pointing out to us that the benthic foraminifera *Oridorsalis umbonatus* used for reconstructing the Mg/Ca record of Site 1218 is infaunal and therefore to some extent, but not completely insulated from long-term changes in carbonate ion concentrations, and also for citing Lear et al. (2015), which states that this species is insensitive to changes in the Mg/Ca ratio of the seawater. We shall revise the discussion of the Lear et al. (2004) benthic Mg/Ca record in the revised manuscript. Instead of focusing mostly on the relation between our TEX86 record and the benthic δ18O record of Site 1218, we shall discuss several scenarios that will try to explain the differences and similarities between the long-term trends and the variability of our TEX86-based surface water temperature record, the Mg/Ca-based bottom-water temperature record of Lear et al. (2004), and the δ18O record more extensively.

ORIGINAL COMMENT:
4) Given the changes in lithology and the offset between the glacial and interglacial LOESS curves is constant, I'm not sure resampling the "glacial (values above average _18O) and interglacial (values

below average δ18O) δ18O trends at Site 1218" (lines 403-405 is the best approach. In fact, I think much of the discussion in the section "4.3 sea surface temperature variability at glacial and interglacial time scales" is poorly supported given the uncertainty in the age model, lithology, and TEX86-based temperature estimates. A more thoughtful approach would a comparison figure of mean δ18O of seawater estimates from 1) LOESS TEX86 and a LOESS δ18O of benthic foraminifera and 2) the high-resolution Mg/Ca and δ18O of benthic foraminifera.

REPLY:
Alternations between laminated and bioturbated carbonate-rich sediments allow us to identify orbital glacial-interglacial cyclicity. Although we cannot identify each orbital cycle within our record due to core gaps, the age model of U1356 is definitely robust enough for reconstructing long-term trends in the SST reconstructions. If we would not distinguish between TEX86-derived temperatures from glacial lithologies and those obtained from the interglacial lithologies, the temperature trend would flatten out due to the larger internal temperature variation. In addition, we would like to remind R2 that our TEX86 record is of relatively low resolution, and sample location is guided (in part) by avoiding sediments that are known not to be in situ (i.e., distal mass transport deposits). For this reason, samples are in places predominantly obtained from glacial sediments, while in other places they are predominantly obtained from interglacial sediments. Running a LOESS curve through the entire dataset could therefore potentially establish non-existing trends due to our irregularly-spaced sample distribution. In order to resolve this uneven distribution of samples from the two different lithologies, we apply a LOESS curve on the (independently separated) glacial and interglacial data(sub)sets. We are confident that this better reflects the actual temperature trends, because both the glacial and interglacial LOESS curve show the same long-term trend despite the fact that they are based on separate data(sub)sets. Since it would be an uneven comparison to compare these to the mean of δ18O, we have chosen to compare glacial SSTs to the above-average δ18O and the interglacial to the below-average δ18O.

Secondly, Referee #2 suggests comparing δ18O of the seawater calculated by using TEX86-based temperatures versus δ18O of the seawater calculated by using Mg/Ca-based temperatures. Upon reviewing our initial approach, and supported by the comments of both R1 and R2, we will no longer quantify δ18Osw changes from our TEX86 record. Since we will discuss matches and mismatches between the trends of the δ18O record and the TEX86-based temperature record more qualitatively in the revised manuscript, resampling of the benthic δ18O record is no longer valid.

ORIGINAL COMMENT:
5) The Site 1218 δ18O of benthic foraminifera is used because it covers the entire record. However, are the trends in δ18O of seawater different when the other high resolution Site 1264 δ18O of benthic foraminifera is used? Any one location can be influenced by changes in hydrography.

REPLY:
The long-term (million-year) trend of Site 1264 is very similar to that of Site 1218 (Liebrand et al. 2017, PNAS) and there is therefore no difference in the reconstructed δ18O of the seawater. In fact, globally all Oligocene δ18O records follow the same trend, except for the δ18O record of Maud Rise (Hauptvogel et al. 2017, Paleoceanography), which we believe is indeed influenced by changes in hydrography.

ORIGINAL COMMENT:
Minor comments: The authors should include changes in paleolatitude and whether that might influence the temperature record. Are there large changes in sedimentation rate that might influence preservation and/or these records?

REPLY:
We shall include the paleolatitudes of Site U1356. Site U1356 shifted from 58.86°S at 30 Ma to 59.43°S at 22 Ma (using van Hinsbergen et al. 2015, PloS One). We believe that this shift to higher latitudes could be at least partly responsible for the increased glacial-interglacial temperature variability in the late Oligocene. We acknowledge that this is not part of the manuscript in its current state and we will include this discussion in the revised manuscript in the part that focusses more on the potential role of Southern Ocean fronts.

Changes in sedimentation rate in general will not affect the temperature reconstruction, as the TEX86 (i.e. the relative abundance of GDGTs) relatively unaffected by oxic degradation (Kim et al., 2009, GCA) and if so, this would result in substantially elevated BIT indices something we do not observe (Huguet et al. 2009, OG). Changes in sedimentation rate at Site U1356 are mainly determined by the deposition of mass transport deposits. These could contain allochthonous GDGTs, which is why samples from this type of deposits were not used for reconstructing the sea surface temperature record.

Response to Stephen Gallagher (referee)

We thank Stephen Gallagher for reviewing our manuscript and for acknowledging the value of our dataset. His annotations to our manuscript showed us that some sections lack clarity. In particular the last part of section 4.2, which involves the "thought experiment", and section 4.3 that discusses the reconstructed temperature variability. Also, considering the comments of Referees #1 and #2, we have decided to significantly restructure those sections, placing more emphasis on the role of paleoceanography (polar fronts), and to refrain from quantifying ice volume changes. In the revised manuscript we will discuss several scenarios that can explain the differences and similarities between our TEX86-based temperature record, the benthic δ18O records and the Mg/Ca-based bottom-water temperature record. We believe that this approach will improve the structure and clarity of the manuscript.

ORIGINAL COMMENT:
This is very good new organic proxy dataset from offshore Wilkes Land. The authors present a near field palaeotemperature record that although is much lower in resolution compared to other proxy datasets it sheds light for the first time consideration of the long term sea surface temperature evolution of this Wilkes Land margin.

I have made extensive comments and suggestions in the attached annotated text to this paper.

REPLY:
All comments and suggestions in the annotated text were clear, mostly they were related to the choice of words or to incorrect English and suggestions will be included in a revised manuscript. The reviewer's major comments are addressed below.

Comment: In the annotated manuscript, in line 238, the reviewer asks for clarification on why TEX86 would not have been influenced by subsurface temperatures in the absence of low-salinity waters due to sea ice melt.

Answer: It has been shown that the sea-ice influenced, low-salinity surface waters of today's Southern Ocean contain virtually no Thaumarchaeota in the top layer of the water column (0-45 meter below sea level (mbsl), Kalanetra et al. 2009 Environ. Microbiol.). Instead, the GDGTs are derived from Thaumarchaeota living in the deeper water column (45-105 mbsl, Kalanetra et al., 2009 Environ. Microbiol.) and, therefore, TEX86 does not represent a true surface water signal (see also Kim et al., 2012 Geophys. Res. Let.). Dinoflagellate cysts in the same sediments suggest that oceanographic conditions were similar to today's Subtropical Front and that no sea ice was present. Hence, we conclude that TEX86 at Site U1356 does reflect a surface water temperature. We will clarify this in a new version.

Comment: In line 251 Stephen Gallagher has placed a question mark at the word 'prior' in the sentence "The prior for site U1356 is obtained from recent clumped isotope measurements (Δ47) on planktonic foraminifers from Maud Rise (ODP Site 689) (Petersen and Schrag, 2015), which show early Oligocene temperatures of 12°C."

Answer: the BAYSPAR method is based on Bayesian inference and therefore requires a prior distribution of temperature (i.e. the prior) in order to predict sea surface temperatures from the observed TEX86 values. In general, the prior is our initial belief or scientific understanding of the unknown quantities to be estimated, in this case sea surface temperature (Tierney & Tingley, 2014). As for deep time temperature reconstruction this prior cannot be based on modern-day annual mean sea surface temperatures, the BAYSPAR method requires a user-specified mean and variance for this prior (Tierney & Tingley, 2014). Therefore, we use previous estimates of southern high-latitude early Oligocene seawater temperatures (12°C based on Δ47) as a prior for our TEX86-based sea surface temperature reconstruction. We will better explain this in the revised manuscript.

ORIGINAL COMMENT:
I would like to add the following to the discussion: Reference to EAIS volume changes in line 70 page 3: As I iterated in my review of the Bjil et al submission to this volume: I appreciate the utility of using isotopes to interpret Antarctic Ice Sheet variability as summarise by Liebrand et al (2017) (www.pnas.org/cgi/doi/10.1073/pnas.1615440114) and this approach is used extensively when discussing the Cenozoic greenhouse icehouse transition. However, there are other sections that have been interpreted using backstripping and stratigraphic data in the Gippsland and New Jersey margins that reflect glacio-eustasy in the Oligocene and relative ice volume (Gallagher et al., 2013), it would be useful to consider the significance of these near field and far field sections in any section reviewing ice volume variability. This paper also considers the apparent instability of the EAIS during the Oligocene and presents a sea level curve with Oi events (Figure 6 in Gallagher et al; at slightly higher resolution that the present study) that bears striking similarity to the temperature curve presented in this paper (Figure 4 in this submission).

Gallagher, S. J., G. Villa, R. N. Drysdale, B. S. Wade, H. Scher, Q. Li, M. W. Wallace, and G. R. Holdgate (2013), A near-field sea level record of East Antarctic Ice Sheet instability from 32 to 27 Myr, Paleoceanography, 28, doi: 10.1029/2012PA002326.

REPLY:
We agree that the sea level curve reconstructed in this paper shows the same long-term trends as our temperature record. In our new version of the manuscript, we will sketch several scenarios to explain the differences and similarities between our TEX86 record and the benthic δ18O record in a more qualitative way. As this will likely involve ice volume changes and therefore global sea level changes, the paper by Gallagher et al. (2013) will be a nice addition to this discussion, providing a framework for our theories.

ORIGINAL COMMENT:
More specific comments are below:

Line 95: The core recovery in the Wilkes Land section is certainly not “complete”

REPLY:
The reviewer is correct in this and we will revise the sentences where we give the impression that Hole U1356A is without hiatuses.

ORIGINAL COMMENT:
Line 145 page 5: These are modelled plate tectonic reconstructions.

REPLY:
We will correct this. Indeed tectonic reconstructions show that Australia and South America were closer to Antarctica. We meant to say that numerical modeling of ocean currents shows that the strength of the circum-polar current was limited by these narrow gateways (Hill et al. 2013).

ORIGINAL COMMENT:
Line 160 reference to Bijl et al paper in Jl Micro to be cited?

REPLY:
We will cite Bijl et al. (2018, J. Micropal.) at the end of this line to refer to the position of *M. escutiana*.

ORIGINAL COMMENT:
Line 315 I agree to a certain extent about the lack of identification of Oi events due the gaps in the record (not unexpected during glacials near Antarctica), however, Oi2 is not near 32 Ma (Figure 4) it is actually near 30 Ma and it is possible there is core of this event in the section (see possible correction of Figure 4).

REPLY:
We will correct for this mistake and place Oi-2 near 30 Ma in Figure 4. Although it might be possible that Oi-2 is recorded in U1356A, age model limitations prevent us to be certain.

ORIGINAL COMMENT
Pages 13 and 14: This section is very interesting yet requires significant clarification, I have suggested ways to enhance the message and tone down the “speculation” in this section hopefully these suggestions help.

REPLY:
We will reduce the speculation by refraining from a quantitative comparison between TEX86 and benthic δ18O.

ORIGINAL COMMENT:
In conclusion, once the text has been clarified and the suggestions considered this will be another useful addition to the relatively sparsely documented Antarctic (palaeo)climate and oceanographic records.

REPLY:
We thank the reviewer for these positive comments.

List of all relevant changes made:

- The title was changed to include the Miocene data of Sangiorgi et al. (2018) (see below).
- Henk Brinkhuis has been added as a co-author to this manuscript, due to his participation as co-chief to IODP Expedition 318 where the material comes from and his valuable contribution to this new version of the manuscript.
- Because of the movement of the Earth Sciences department of Utrecht University, the address was changed.
- The corresponding email address has been changed.
- Section 2.6, which discusses the TEX_{86} calibrations has been rewritten for a large part in order to shorten the discussion on TEX_{86}^{L}, as proposed by Referee #1, and to improve our argumentation for the use of the BAYSPAR calibration and the linear calibration of Kim et al. (2010). Both these calibrations have also been consistently applied to all TEX_{86} data (incl. published data) and plotted in all figures, as was suggested by Referee #1.
- GDGT-2/GDGT-3 ratios have been added to Figure 2 and are discussed in the text. A correlation of the GDGT-2/GDGT-3 ratios to lithology, which may have implications for the interpretation of our dataset as Referee #1 and Referee #2 suggested, has now been excluded.
- Data of the mid-Miocene section published by Sangiorgi et al. (2018, Nat. Comm.) has been added to the record for consistency between the three different papers that are jointly submitted. The same analytical procedures as for the Oligocene data have been applied to this data. Of particular importance is the relation of reconstructed Miocene SSTs to the lithology, which has not been discussed by Sangiorgi et al. (2018). The lithology for the Miocene (based on Salabarnada et al., submitted this volume) has been added to Figures 2 and 4.
- For comparison, Miocene sea surface temperature estimates from other Sites (ODP Site 1171 and ANDRILL-2A) have been added, as well as bottom-water temperature estimates based on Mg/Ca records from ODP Site 1171 and ODP Site 747.
- In the previous manuscript only the high-resolution benthic $\delta^{18}O$ records of Site 1218 and Site 1264 were included in the discussion as well as Figure 4. To extend the benthic $\delta^{18}O$ record into the Miocene and to show that the records of Site 1218 and 1264 follow the global benthic $\delta^{18}O$ trend (questioned by Referee #2) other records have now been included and normalized to Site 1264 to get a good representation of the global average trend (LOESS curve). The benthic $\delta^{18}O$ record is not resampled as in the previous manuscript as a quantitative approach for the comparison between reconstructed SST long-term trends and benthic $\delta^{18}O$ long-term trends has been abandoned.
- The discussion is thoroughly revised based on the suggestions of the reviewers. In the discussion our reconstructed sea surface temperature record is compared to the $\delta^{18}O$ record in a more qualitative way. Notably, the so-called thought experiment that deduced ice volume from based on our sea surface temperature record was considered too far-fetched by all reviewers, and has therefore been removed. Several scenarios are discusses to explain the differences and similarities between trends observed in the sea surface temperature, $\delta^{18}O$ and Mg/Ca-based bottom water temperature records, instead of focusing on the transport of a sea surface temperature signal to the deeper waters only. Included in this discussion are now also

paleogeographic changes, shifts of Antarctic frontal zones (as proposed by Referee #2) and the effect of the Antarctic ice sheet on sea surface temperature.

- Figure 5 was removed, as suggested by Referee #1.

Oligocene and Miocene TEX_{86}-derived seawater temperatures from offshore Wilkes Land (East Antarctica)

Keywords:
TEX_{86}
Oligocene
Wilkes Land
sea surface temperature
Antarctic ice sheet

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Abstract. The volume of the Antarctic continental ice sheet(s) varied substantially during the Oligocene and Miocene (~34-5 Ma) from smaller to substantially larger than today, both on million-year and on orbital timescales. However, reproduction through physical modeling of a dynamic response of the ice sheets to climate forcing remains problematic, suggesting the existence of complex feedbacks between cryosphere, the ocean and the atmosphere systems. There is therefore an urgent need to improve the models for better predictions of these systems, including resulting potential future sea level change. To assess the interactions between cryosphere, ocean and atmosphere, knowledge of ancient sea surface conditions close to the Antarctic margin is essential. Here, we present a new TEX_{86}-based sea surface water paleotemperature record measured on Oligocene sediments from Integrated Ocean Drilling Program (IODP) Site U1356, offshore Wilkes Land, East Antarctica. The new data is presented along with previously published Miocene temperatures from the same site. Together the data covers the interval between ~34 to ~11 Ma and encompasses 2 hiatuses. This record allows us to accurately reconstruct the magnitude of sea surface temperature (SST) variability and trends on both million-year and on glacial-interglacial timescales. On average, TEX_{86} values indicate SSTs ranging between 10 and 21°C during the Oligocene and Miocene, which is on the upper end of the few existing reconstructions from other high-latitude Southern Ocean Sites. SST maxima occur around 30.5, 25 and 17 Ma. Our record suggests generally warm to temperate ocean offshore Wilkes Land. Based on lithological alternations detected in the sedimentary record, which are assigned to glacial-interglacial deposits, a SST variability of 1.5–3.1°C at glacial-interglacial timescales can be established. This variability is slightly larger than that of deep-sea temperatures recorded in Mg/Ca data. Our reconstructed Oligocene temperature variability has implications for Oligocene ice-volume estimates based on benthic $\delta^{18}O$ records. If the long-term and orbital-scale SST variability at Site U1356 mirrors that of the nearby region of deep-water formation, we argue that a substantial portion of the variability and trends contained in long-term $\delta^{18}O$ records can be explained by variability in Southern high-latitude temperature and that the Antarctic ice volume may have been less dynamic than previously thought. Importantly, our temperature record suggests that Oligocene-Miocene Antarctic ice sheets were generally of smaller size compared to today. ~~Today, the temperature of the surface waters near the Antarctic coast is a determining factor in the formation of Antarctic Bottom Water (AABW) through sea-ice production, sea-ice extent, and the extent of the ice shelf. For the Oligocene, deep-sea benthic foraminiferal oxygen isotope ($\delta^{18}O$) reconstructions suggest that the volume of the Antarctic continental ice sheet(s) varied substantially both on million-year and on orbital timescales after its inception in the early Oligocene, and even reached larger than modern-day volumes. Replication of such dynamicity through physical modeling remains problematic, suggesting the existence of complex feedbacks between the cryosphere, the ocean and the atmosphere. To assess the relation between cryosphere, ocean and atmosphere, knowledge of sea surface conditions close to the Antarctic margin is essential. We present a TEX_{86}-based surface water paleotemperature record measured on Oligocene sediments from Integrated Ocean Drilling Program (IODP) Site U1356, offshore Wilkes Land, Antarctica. This record allows us to reconstruct the magnitude of seawater temperature variability and trends on both million-year and on glacial-interglacial timescales. TEX_{86} index values suggest surface temperatures between 10 and 21°C during the Oligocene, which is on the upper end of the few available reconstructions. Sea surface temperature (SST) maxima occur around 30.5 and 25 Ma, irrespective of the calibration equation chosen. Based on glacial-interglacial lithological alternations we have~~

~~established that SST variability between glacial intervals and their successive interglacials ranged between 1.8–3.2°C. As benthic foraminiferal $\delta^{18}O$ data incorporate both an ice-volume and a temperature component, our reconstructed Oligocene temperature variability could have implications for current Oligocene ice-volume estimates. If the long-term ad orbital SST variability is representative of that of the nearby region of deep-water formation, we can assess the impact of this temperature record on the volume and dynamics of the Antarctic ice sheet(s) by comparing it with the $\delta^{18}O$ trends and variability. From this comparison, we argue that a significant portion of the variability and trends contained in long-term $\delta^{18}O$ records can be explained by variability in Southern high-latitude temperature. If indeed a large part of the $\delta^{18}O$ variability is due to large glacial-interglacial bottom-water temperature shifts, the Oligocene Antarctic ice volume was less sensitive to climate change than previously assumed.~~

1 Introduction

~~Physical~~ Numerical paleoclimate models predict that with the current rate of ice volume loss (up to ~~97.8~~109±56 Gt/yr, ~~Pritchard et al. 2012~~The IMBRIE Team, 2018) several sectors of the West Antarctic marine-based ice sheet will ~~collapse~~ disappear within the coming few centuries (e.g., Joughin et al. 2014; The IMBRIE Team, 2018) favored by ocean warming-induced collapse. Observations show that glaciers on East Antarctica are also vulnerable to basal melt through warming of the ocean waters when they are grounded below sea level (Greenbaum et al., 2015; Miles et al., 2016; Shen et al., 2018; The IMBRIE Team, 2018), making the East Antarctic ice sheet (EAIS) not as stable as previously thought (Mcmillan et al., 2014). Recent numerical modelling studies ~~are more in line with~~have improved on reproducing the observed ice-sheet volume ~~measurements~~decrease, ~~because~~ as they incorporate positive feedbacks (e.g., bedrock topography) to global warming and more complicated physics (e.g., hydrofracturing and ice-cliff failure) into these models (Austermann et al., 2015; Deconto and Pollard, 2016; Fogwill et al., 2014; Golledge et al., 2017; Pollard et al., 2015).~~,~~ ~~and~~ They indeed show that sensitivity to global warming is particularly high where the ice sheet is grounded below sea level (Fretwell et al., 2013), such as in the Wilkes Land basin (Golledge et al., 2017; Shen et al., 2018).

Both on glacial-interglacial (Parrenin et al., 2013) and longer term Cenozoic timescales (Pagani et al., 2011; Zachos et al., 2008), Antarctic ice-volume changes have been mostly linked to changes in atmospheric CO_2 concentrations ($p\mathrm{CO_2}$, see e.g., Foster & Rohling 2013; Crampton et al. 2016), modulated by astronomically forced changes in ~~solar~~ insolation (e.g., ~~Pälike et al., 2006;~~ Holbourn et al., 2013; Liebrand et al., 2017; Miller et al., 2017; Pälike et al., 2006b; Westerhold et al., 2005). Foster & Rohling (2013) compiled ~~past~~ $p\mathrm{CO_2}$ proxy data and associated sea level reconstructions for the last 40 million years (Myr). These data suggest that if the past is projected to the future all ice on West Antarctica and Greenland ~~could~~ may be lost under current and near future atmospheric CO_2 conditions (400-450 ppmv) in equilibrium state. Projections of $p\mathrm{CO_2}$ for ~~the~~ future emission scenarios of the latest IPCC Report (2014) show a range ~~between~~ from 500 ~~and~~ to 1000 ppmv for the year 2100, which could ~~imply~~ lead to additional ice-sheet volume loss ~~of~~from East Antarctica ~~a ice-sheet volume~~. This range in atmospheric $p\mathrm{CO_2}$ is similar to that reconstructed for the warmest intervals of the Oligocene and Miocene epochs (full range: 200–1000 ppmv; e.g., Zhang et al. 2013).~~,~~ Given that observations clearly link the recent instability of marine-based ice sheets to ocean warming, it becomes important ~~highlighting the importance~~ to better constrain near-field sea surface temperatures (SSTs) from the ~~Oligocene~~ Antarctic margin during the Oligocene and Miocene to improve our understanding of past ice sheet dynamics and the projections for the future.

EAIS volume changes have been suggested for the Oligocene and Miocene based on a number of deep-sea $\delta^{18}O$ records, which reflect a combination of bottom-water temperature and ice volume (e.g., Liebrand et al., 2017; Miller et al., 2013; Pekar et al., 2006; Pekar and Christie-Blick, 2008; Shevenell et al., 2004; Westerhold et al., 2005), ~~which reflect a combination of bottom-water temperature and ice volume~~ as well as sedimentary paleosealevel reconstructions (John et al., 2011; Gallagher et al., 2013; Stap et al., 2017). These records show long-term (1-3 Myr) trends punctuated by strong but transient glaciation events (Oi- and Mi-events) (Hauptvogel et al., 2017; Miller et al., 2017; Liebrand et al., 2017, 2016; Pälike et al., 2006b; Westerhold et al., 2005).~~:~~ Following the onset of the Oligocene, marked by the Oi-1 glaciation event, the long-term trend shows a shift towards lighter $\delta^{18}O$ ~~after the Oi-1~~

~~event~~ values and a steady increase towards 27 Ma, then a decrease to 24 Ma and a final increase leading into the Miocene, marked by the Mi-1 glaciation event (Beddow et al., 2016; Cramer et al., 2009; Liebrand et al., 2016; Zachos, 2001). Miocene benthic $\delta^{18}O$ long-term trends show a sudden increase at 16.9 Ma, which marks the onset of the Miocene Climatic Optimum (MCO), a plateau phase, and a subsequent stepwise decrease known as the mid-Miocene Climatic Transition (MCT) (Holbourn et al., 2015, 2013, 2007; Shevenell et al., 2004; Westerhold et al., 2005)~~The high-resolution records show that these trends are punctuated by strong but transient glaciation events (Hauptvogel et al., 2017; Liebrand et al., 2017, 2016; Pälike et al., 2006)~~. The Oligocene and Miocene~~se~~ glaciations are paced by periods of strong 110-kyr eccentricity fluctuations of up to 1‰ (Liebrand et al., 2017, 2016, 2011). ~~Either t~~These $\delta^{18}O$ fluctuations may be~~are~~ mostly resulting from the waxing and waning of the EAIS, in which case the ice sheet ~~must have been~~was highly dynamic, or they mostly reflect large changes in deep-sea temperature, in which case large SST fluctuations in the region of deep-water formation ~~must~~ were to be expected. Considering the former, fluctuations between 50% and 125% of the present-day EAIS have been suggested for the Oligocene (DeConto et al., 2008; Pekar et al., 2006; Pekar and Christie-Blick, 2008), but this amount of variability has not yet been entirely reproduced by numerical modeling studies (DeConto et al., 2008; Gasson et al., 2016; Pollard et al., 2015). Considering the latter, several studies have suggested that during the Oligocene the southern high latitudes were the prevalent source for cold deep-water formation (Katz et al. 2011; Goldner et al. 2014; Borelli & Katz 2015). Hence, deep-water temperature records from the southern high-latitudes, particularly those capturing temperature changes on million-year as well as orbital timescales, may provide information on the relative contribution of deep-sea temperature variability ~~in~~ to the $\delta^{18}O$ records~~, and as such should reflect the sensitivity of Antarctic ice sheets to CO_2 concentrations~~. However, reconstructions of deep-water temperature based on $\delta^{18}O$ and Mg/Ca ratios of benthic foraminifera are hampered by the poor preservation of carbonates on the high-latitude Southern Ocean floor, and rely on critical assumptions on past composition of seawater chemistry. ~~Assuming~~ Therefore, one needs to assume that the deep-sea temperature trend captured in the Oligocene and Miocene $\delta^{18}O$ records is related to surface water temperature in the Southern Ocean similarly to today (Baines, 2009; Jacobs, 1991) and in the Eocene (Bijl et al., 2009).~~,~~ Based on this assumption, ~~ice-proximal~~ Southern Ocean SSTs would potentially gauge ~~the Oligocene~~ deep-sea temperature variability. Only few ~~early~~ Oligocene SST estimates are available for the Southern Ocean and they relate to the early Oligocene (Petersen and Schrag, 2015; Plancq et al., 2014). Few Southern Ocean SST records are available for the early and mid-Miocene (14–17 Ma) (Kuhnert et al., 2009; Majewski & Bohaty, 2010; Shevenell et al., 2004) and only two (Levy et al., 2016; Sangiorgi et al., 2018) are derived from south of the Polar Front (PF). Obstacles for reconstructing Oligocene and Miocene SST in the Southern Ocean are the paucity of stratigraphically well-calibrated sedimentary archives, as well as suitable indicator fossils/compounds within these sediments that can be used to reconstruct SST. ~~In this study we use the ratio between several glycerol dialkyl glycerol tetraethers (GDGTs), the TEX_{86} SST proxy. These resistant organic compounds are often the only fossil remains that preserve, because biogenic carbonate and silica dissolve under the corrosive bottom-water conditions of the high-latitude Southern Ocean.~~

In 2010, the Integrated Ocean Drilling Program (IODP) ~~drilled~~ cored a sedimentary archive at the boundary of the continental rise and the abyssal plain offshore Wilkes Land ~~that does contain~~with a well-dated ~~and complete~~

Oligocene and Miocene sequence: IODP Site U1356 (Fig. 1), suitable for paleoclimatological analysis. In this study we use the now well-established ratio between several isoprenoidal glycerol dialkyl glycerol tetraethers (GDGTs), the so-called TEX_{86} proxy (Schouten et al., 2013, 2002), to reconstruct SSTs at this high-latitude Southern Ocean site. We ~~here reconstruct~~ present new ~~the first~~ SST data ~~record from high Southern Ocean latitude~~ based on TEX_{86}, covering almost the entire Oligocene, ~~and~~along with published TEX_{86} values for the mid-Miocene section (Sangiorgi et al., 2018). ~~compare it with the few existing early Oligocene SWT data from other high latitude Southern Ocean sites (ODP Sites 511 and 689) and with deep-water $\delta^{18}O$ records from lower latitudes. Although the TEX_{86}-SST relation shows scatter in the low-temperature (<5°C) domain (Kim et al., 2010, 2008), more regional modern-analogue calibration methods exist today to overcome some of the scatter (Tierney and Tingley, 2015, 2014). Still, TEX_{86} is known to overestimate temperatures at high latitudes due to multiple possible biases (Ho et al., 2014; Ho and Laepple, 2016; Schouten et al., 2013). However, there is general consensus that TEX_{86} is able to capture decadal and longer-term temperature trends (Ho and Laepple, 2016; Richey and Tierney, 2016), which is why our main focus lies on relative SST changes.~~

~~The Wilkes Land region is one of the regions of East Antarctica sensitive to warming, because most of the bedrock lies below sea level today (Fretwell et al., 2013; Golledge et al., 2017) and Site U1356 may therefore have recorded past dynamics of the East Antarctic ice sheet. However, during the Oligocene the ice sheet was likely not marine-based (Wilson et al., 2012). Still, d~~Detailed lithological logging of both the Oligocene and Miocene sections of Site U1356 allows for the distinction of glacial and interglacial deposits (Salabarnada et al., submitted this volume). This enables us to assess long-term evolution of SS~~W~~Ts in proximity of the ice-sheet as well as the temperature differences between glacials and interglacials on orbital time scales, which have implications on the dynamics of the ~~Oligocene~~ Antarctic ice-sheet and its sensitivity to climate change. We compare our record with the few existing early Oligocene and mid-Miocene SST data from other high latitude Southern Ocean sites as well as with deep-water $\delta^{18}O$ and Mg/Ca-based bottom water temperature (BWT) records from lower latitudes (Billups & Schrag 2002; Lear et al., 2004; Shevenell et al., 2004), and discuss the implications of our findings.

2 Materials & Methods

2.1 Site description

Integrated Ocean Drilling Program (IODP) Expedition 318 Site U1356 was ~~drilled~~ cored about 300 kilometers off the Wilkes Land coast (63°54.61'S, 135°59.94'E) at the boundary between the continental rise and the abyssal plain at a water depth of 3992 m (Escutia et al. 2011, see Fig. 1). Today, this site is ~~positioned~~ south of the Antarctic Polar Front (PF) and is ~~thus~~ under the influence of by Antarctic Bottom Waters (AABW), Lower Component Deep Water (LCDW), Upper Component Deep Water (UCDW), and Antarctic Surface Water (AASW) (Orsi et al., 1995).

2.2 Sedimentology

At present, IODP Site U1356 receives sediments transported from the shelf and the slope as well as *in situ* pelagic component. Although we have no quantitative constraints on the water depth during the Oligocene and Miocene, the sediments as well as the biota suggest a deep-water setting at Site U1356 during these times (Houben et al., 2013; Escutia et al., 2014). Sedimentary Units of Hole U1356A have been defined in the shipboard report (Escutia et al., 2011). Detailed logging of the sediments recovered in Hole U1356A has revealed that the Oligocene and Miocene sedimentary record (between ~~431.74~~95.40 and 894.80 meters below sea floor, mbsf) consists mostly of alternations of (diatomaceous) laminated and bioturbated sediments, ~~mass transport deposits (MTDs)~~gravity flow deposits, and carbonate beds (Salabarnada et al., submitted this volume; Sangiorgi et al., 2018~~Salabarnada et al., submitted this volume~~) (Fig. 2). Gravity flow deposits include Mass Transport Deposits (MTDs) formed by the slump and debris flow sediments of the Miocene, Oligocene and Eocene-Oligocene Transition (EOT), and the late Oligocene-Miocene turbidite type facies as defined by Salabarnada et al. (submitted this volume). Samples from the ~~mass-waste beds~~MTDs ~~seem to~~ contain the largest contribution of reworked older material transported from the continental shelf (Bijl et al., submitted this volume), while in the other lithologies, this component is much more reduced or absent ~~altogether~~.

Between 593.4 and 795.1 ~~meters below sea floor~~mbsf, there are clear alternations between greenish~~,~~ carbonate-poor laminated and grey bioturbated deposits with some carbonate-rich bioturbated intervals~~deposit~~. These deposits ~~have been~~are interpreted as contourite deposits recording glacial-interglacial environmental variability (Salabarnada et al., submitted this volume). Above 600 mbsf, ~~these alternations are less clear, and the~~ sediments mostly consist of MTDs with low to abundant clasts (Fig. 2). However, between the MTDs greenish or grey laminated deposits and greenish or grey bioturbated deposits are preserved. Near the bottom of Unit III as defined in the shipboard report (around 433 mbsf and below), a different depositional setting is represented with alternations between pelagic clays and (ripple) cross-laminated sandstone beds (Escutia et al., 2011). These sandy (ripple) cross-laminated beds are interpreted as turbidite deposits (Salabarnada et al., submitted this volume). Above these turbidite deposits, there are diatomaceous silty clays that are characterized by an alternation of green laminated and grey homogeneous (bioturbated) silty clays. Apart from their diatom content, these deposits are very similar to the Oligocene alternations between carbonate-poor laminated and carbonate-containing bioturbated deposits, and are therefore interpreted likewise (Salabarnada et al., submitted this volume). Upcore within the Miocene section, the alternations between laminated and homogeneous diatomaceous silty clays become more frequent. In the upper Miocene sections (95.4–110 mbsf) laminations become less clear as the sediments become less consolidated, however green and grey alternations can still be distinguished. The more diatomaceous green deposits are interpreted as interglacial stages. Samples analyzed for TEX_{86} ~~a~~were chosen from all the ~~7~~ different lithologies (Fig. 2). In particular the (diatomaceous) ~~carbonate-poor~~ laminated and ~~(carbonate-rich)~~ bioturbated deposits ~~have been~~were sampled, so we can test whether the glacial-interglacial variability inferred from the lithology is reflected in our TEX_{86} data.

2.3 ~~O~~Oligocene and Miocene paleoceanographic setting

The ~~details of the~~ Oligocene and Miocene Southern Ocean paleoceanographic configuration~~y~~ ~~are~~ is still obscure and controversial~~not fully understood~~. Some studies suggest that most Southern Ocean surface and deep water masses were already in place by ~~the~~ Eocene-Oligocene b~~B~~oundary times ~~times~~ (Katz et al., 2011). Neodymium isotopes on opposite sides of Tasmania suggest that an eastward flowing deep-water current was present since 30 Ma (Scher et al., 2015). A westward flowing Antarctic Circumpolar Counter Current (ACCC) was already established during the ~~late~~ middle Eocene (49 Ma; Bijl et al. 2013) (Fig. 1). ~~Opening of the~~ Tasmanian gateway opening also allowed the proto-Leeuwin current (PLC) flowing along southern Australia continue eastward (Carter et al., 2004; Stickley et al., 2004) (Fig. 1). ~~Despite these reconstructions, numerical modeling studies showed that both~~However ~~Australia and South America were substantially closer to Antarctica (Fig. 1) than today~~, numerical modeling studies show that ~~which must have limited~~ throughflow of the Antarctic Circumpolar Current (ACC) was still limited during the Oligocene (Hill et al., 2013), because Australia and South America were substantially closer to Antarctica (Fig. 1) than today (Markwick 2007). Moreover, tectonic reconstructions and stratigraphy of formations on Tierra del Fuego suggest that following open conditions in the middle and late Eocene, the seaways at Drake Passage underwent ~~temporal closure~~uplift ~~from~~ starting at 29 Ma ~~onwards~~ and definitive closure around 22 Ma ~~following open conditions in the middle and late Eocene~~ (Lagabrielle et al., 2009). Evidence for active spreading and transgressional deposits in the Tierra del Fuego area record the widening of Drake Passage from 15 Ma onwards. The timing of the Drake Passage opening, which allowed for significant ACC throughflow, is still heavily debated (Lawver & Gahagan 2003; Livermore et al., 2004; Scher & Martin 2006; 2008; Barker et al., 2007; Maldonado et al., 2014; Dalziel 2014). Contourite deposits suggest that strong Antarctic bottom water currents first appeared in the early Miocene (21.3 Ma) and that Weddell Sea Deep Water was able to flow westwards into the Scotia Basin since the middle Miocene (~12.1 Ma) (Maldonado et al., 2003; 2005). It has been suggested that the closure and the reopening of Drake Passage are responsible for the warmer late Oligocene and the Miocene Climatic Optimum (MCO), and the subsequent cooling during the Miocene Climate Transition (MCT), respectively, as inferred from the benthic $\delta^{18}O$ records (Lagabrielle et al., 2009). If the throughflow at the Drake Passage was ~~indeed~~ limited in the late Oligocene and early Miocene~~(Lagabrielle et al., 2009)~~, ~~the model study of Hill et al. (2013) suggests that~~ the Antarctic Circumpolar Counter Current (ACCC) was more dominant than the ACC during these times according to the model study of Hill et al. (2013).

Antarctica ~~itself~~ was positioned more eastward during the Oligocene and Miocene relative to today (~~foremost~~ due to true polar wander; van Hinsbergen et al., 2015), ~~leading to a relative northward position of~~and Site U1356 was more to the north during the Oligocene and Miocene compared to today (58.5°S at 34 Ma to 61.2°S at 10 Ma). Reconstructions of the position of the PF based on the distribution of calcareous and siliceous microfossils, place the PF at 60°S during the early Oligocene (Scher et al., 2015), which means that Site U1356 may have crossed the PF between 34 and 10 Ma. The more northerly position of Site U1356 may have facilitated the influence of warmer waters during the mid-Miocene at Site U1356 (Sangiorgi et al., 2018), and therefore ~~Because of this,~~ bottom-water formation ~~did likely not occur at~~ may have been absent or limited at Site U1356~~A~~. ~~b~~Bottom-water formation is expected in more southerly positioned shallow basins~~, and~~ where glaciers extended onto the Antarctic shelf, such as the nearby Ross Sea (Sorlien et al., 2007). However, neodymium isotopes obtained from Site U1356 suggest that bottom water formed offshore the Adélie and Wilkes Land coast during the Early Eocene, which seems in contrast with the globally high temperature of that time (Huck et al., 2017). Modeling studies have, however, suggested that density contrasts created by seasonal changes in SST and salinity (with or without sea ice) may have induced deep-water formation and downwelling around Antarctica (Goldner et al., 2014; Lunt et al., 2010). ~~Instead, bottom-water formation is expected in more southerly positioned shallow basins, and where glaciers extended onto the Antarctic shelf, such as the nearby Ross Sea (Sorlien et al., 2007).~~

2.4 ~~Stratigraphic a~~Age model U1356

Oligocene sediments were recovered in the section from 894.68 mbsf (first occurrence (FO) *Malvinia escutiana*) to 432.64 mbsf (base of subchron C6Cn.2n) at IODP Hole U1356A (Bijl et al., 2018). The shipboard age model (Tauxe et al., 2012) was based on biostratigraphy with magnetostratigraphic tie points and chronostratigraphically calibrated to the Geologic Timescale of 2004 (Gradstein et al., 2004). We follow Bijl et al. (~~accepted~~2018), who recalibrated the existing age tie points to the Geologic Timescale of 2012 (GTS2012, Gradstein et al., 2012). The FO of *Malvinia escutiana* (894.68 mbsf; 33.5 Ma; Houben et al., 2011) and the last occurrence (LO) of *Reticulofenestra bisecta* (431.99 mbsf; 22.97 Ma) and the paleomagnetic tie points were used to convert the data to the time domain (see Fig. 4). For the Oligocene-Miocene Boundary, we also follow Bijl et al. (~~submitted~~2018) who infer a hiatus spanning ~22.5-17.0 Ma between Cores 44R and 45R (~421 mbsf). It is unknown whether additional short hiatuses exist within the Oligocene record, but this is likely considering the presence of MTDs (Salabarnada et al., submitted this volume; Fig. S1). In addition, the poor core recovery in some intervals dictates caution in making detailed stratigraphic comparisons with other records.

For the Miocene section of Hole U1356A we follow Sangiorgi et al. (2018), who applied the Constrained Optimization methodology (CONOP) of Crampton et al. (2016) on diatom and radiolarian biostratigraphic events to construct an age model. Based on the application of CONOP to the diatom and radiolarian biostratigraphic events a second hiatus was identified spanning approximately the interval between 13.4 and 11 Ma.

2.5 Glycerol dialkyl glycerol tetraether extraction and analysis

~~A~~ In addition to the 29 samples from the Miocene section presented in Sangiorgi et al. (2018), a total of ~~129~~ 132 samples from the Oligocene and early Miocene part of the sedimentary record (Table S1) ~~have been~~were processed for the analysis of glycerol dialkyl glycerol tetraethers (GDGTs) used for TEX_{86}. ~~Sample S~~spacing varies due to variability in core recovery and GDGT preservation. Furthermore, sampling of contorted ~~bedding~~ strata was avoided. Sample processing involved manual powdering of freeze-dried sediments after which lipids were extracted through accelerated solvent extraction (ASE; with dichloromethane (DCM)/methanol (MeOH) mixture, 9:1 v/v, at 100°C and 7.6 x 10^6 Pa). The lipid extract was separated using Al_2O_3 column chromatography and hexane/DCM (9:1, v/v), hexane/DCM (1:1, v/v) and DCM/MeOH (1:1, v/v) for separating apolar, ketone and polar fractions, respectively. Then, 99 ng of C_{46} internal standard was added to the polar fraction, containing the GDGTs, for quantification purposes (cf. Huguet et al., 2006). The polar fraction of each sample was dried under N_2, dissolved in hexane/isopropanol (99:1, v/v) and filtered through a 0.45-μm 4-mm-diameter polytetrafluorethylene filter. After that the dissolved polar fractions were injected and analyzed by high performance liquid chromatography/mass spectrometry (HPLC/MS) at Utrecht University. Most samples were analyzed following HPLC/MS settings in Schouten et al. (2007), while some samples (see Table S1) were analyzed by ultra-high performance liquid chromatography/mass spectrometry (UHPLC/MS) according to the method described by ~~(~~Hopmans et al., (2016). Only a minor difference between TEX$_{86}$ index values generated by the different methods was recorded by Hopmans et al. (2016) (on average 0.005 TEX$_{86}$ units). Reruns of 5 samples with the new method show an average difference between the two methods of 0.011 TEX$_{86}$ units (see Table S2), which translates to a 0.6°C temperature difference based on TEX$_{86}^{H}$ of ~~(~~Kim et al., (2010) and lies well within the calibration error of 2.5°C. GDGT peaks in the (U)HPLC chromatograms were integrated using Chemstation software. Sixteen of the ~~129~~ 132 samples had too low concentrations of GDGTs to obtain a reliable TEX$_{86}$ value and have been discarded.

We have used the branched and isoprenoid tetraether (BIT) index (Hopmans et al., 2004) to verify the relative contribution of terrestrial GDGTs in our samples, compared to marine GDGTs. As isoprenoid GDGTs (isoGDGTs), used for the TEX$_{86}$ proxy are also produced in terrestrial soils, albeit in minor amounts, they can alter the marine signal when there is a large contribution of soil organic matter to marine sediments. This contribution can be identified by determining the relative amount of branched GDGTs (brGDGTs), which are primarily soil-derived (Weijers et al., 2006), to that of the isoGDGT crenarchaeol (Hopmans et al., 2004). Samples with BIT index values above 0.3 indicate that the TEX$_{86}$-based temperature may be affected by a contribution of soil-derived isoGDGTs and thus should be discarded (cf. Weijers et al. 2006), although~~. However~~, a high BIT value ~~could~~ can sometimes also result from production of brGDGTs in marine sediments and the water column (Peterse et al., 2009; Sinninghe Damsté, 2016). ~~Still t~~The composition of the brGDGTs can be used to distinguish between marine and soil-derived GDGT input, in particular by using the #ring$_{tetra}$ index (Sinninghe Damsté, 2016). The #rings$_{tetra}$ index can discriminate between marine and soil-derived brGDGTs as the composition of soil-derived GDGTs typically show high amounts of the acyclic tetramethylated GDGT-Ia, while a dominance of cyclic tetramethylated (Ib and Ic) brGDGTs has been attributed to *in situ* production within the sediments (Sinninghe Damsté, 2016). ~~We have applied this index on samples analyzed by UHPLC/MS to see if TEX$_{86}$ values are reliable despite high BIT index values.~~ Oxic degradation of GDGTs does not affect the relative amounts of individual isoGDGTs (Huguet et al., 2009; Kim et al., 2009). However, oxic degradation may lead to an increased relative influence of soil-derived isoGDGTs, which could bias the TEX$_{86}$ in different ways depending on the composition of the soil-derived isoGDGTs (Huguet et al., 2009). Enhanced BIT index values are expected in samples with enhanced amounts of soil-derived isoGDGTs due to oxic degradation, and will be discarded. In addition, we calculated the Methane Index (MI) (Zhang et al., 2011), GDGT-0/crenarchaeol (Blaga et al., 2009; Sinninghe Damste et al., 2009), GDGT-2/crenarchaeol ratios (Weijers et al., 2011), and Ring Index (Zhang et al., 2016) to check for input of methanogenic or methanotrophic archaea, or any other non-temperature related biases to TEX$_{86}$.

2.6 TEX$_{86}$ calibrations

The TEX$_{86}$ proxy is based on the distribution of isoGDGTs preserved in sediments (Schouten et al., 2013, 2002). In marine sediments these lipids are assumed to originate from cell membranes of marine Thaumarchaeota, which are one of the dominant prokaryotes in today's ocean and occur throughout the entire water column (e.g. Karner et al.

2001; Church et al. 2010, 2003~~; Church et al. 2010~~). Applying TEX_{86} in polar oceans has been challenged by the observation that high scatter in the cold end of the core top dataset for TEX_{86} is present (Ho et al., 2014; Kim et al., 2010). -To overcome some of the scatter as well as the non-linearity of the TEX_{86}-SST relationship, Kim et al. (2010) ~~improved the calibration for the polar ocean, by proposing~~ proposed two isoGDGT-based proxies and calibrations:~~the~~ TEX_{86}^{L} and TEX_{86}^{H}. The latter is not considered here as it was particularly developed for low-latitude high-temperature surface waters, and high-latitude core-top values were left out of the calibration (Kim et al., 2010). The former was particularly developed for high-latitude low-temperature surface waters. However, it has been shown that TEX_{86}^{L} is sensitive to changes in the GDGT-2/GDGT-3 ratio ([2]/[3]), which are unrelated to SST (Taylor et al., 2013; Hernández-Sánchez et al., 2014). Instead these [2]/[3] changes result from changes in the Thaumarchaeotal community structure in the water column, because the community that thrives in deeper (>1000 mbsl) nutrient and ammonia-rich waters, produces significantly more GDGT-2 and thereby introduces a water-depth dependency into the calibration (Taylor et al., 2013; Hernández-Sánchez et al., 2014; Villanueva et al., 2015). Close to the Antarctic margin, the abundance of 'shallow' versus 'deep water' Thaumarchaeotal communities at deep-water sites, like Site U1356 during the Oligocene-Miocene, could be affected by the presence of sea ice and the relative influence of (proto-)~~Component Deep Water~~UCDW and (proto-)LCDW upwelling. For this reason, also TEX_{86}^{L}-based calibrations are not the focus of our study. Instead, we focus on TEX_{86}-based calibrations only. All existing $TEX_{86}^{(H)}$ and TEX_{86}^{L} calibrations have, however, been applied to our data and are presented as a supplementary figure (Figure S1).

The latest global calibration set that includes also the high-latitude core-top values is the linear SST calibration of Kim et al. (2010). Despite the scatter at the cold end of the calibration that results from the inclusion of Arctic surface sediment samples with deviating TEX_{86}-SST relations, this calibration (SST = 81.5*TEX_{86} – 26.6 with a calibration error of ±5.2°C) has been shown to plot onto the annual mean sea surface temperatures of the World Ocean Atlas 2009 (WOA2009; Locarnini et al. 2010) for the surface-sample TEX_{86} values obtained in the Pacific sector of the Southern Ocean (Ho et al., 2014). However, this calibration is likely to be influenced by regional differences in water depth, oceanographic setting and archaeal communities (Kim et al., 2015; 2016; Tierney and Tingley, 2014; Trommer et al., 2009; Villanueva et al., 2015). In addition, this calibration suffers from regression dilution bias caused by the uncertainty in the measured TEX_{86} values plotted on the x-axis (Tierney & Tingley 2014). Regression dilution bias causes flattening of the slope (Hutcheon et al., 2010) and therefore affects reconstructed TEX_{86}-based temperatures at the lower and upper end of the calibration range. Modern-analogue calibration methods exist today to overcome this regression dilution bias as well as some of the regional variability of TEX_{86}-SST relationships (Tierney and Tingley, 2015, 2014). These calibrations are based on a Bayesian spatially varying regression model (BAYSPAR), which infers a best estimate for intersection and slope of the calibration based on an assembly of 20° by 20° spatial grid boxes that statistically fit best with an estimate of the prior distribution of temperature (i.e. the prior) (Tierney and Tingley, 2014). As for deep-time temperature reconstructions this prior cannot be based on modern-day annual mean sea surface temperatures, the BAYSPAR method requires a user-specified mean and variance for this prior (Tierney and Tingley, 2014). The prior for Site U1356 is obtained from recent clumped isotope measurements (Δ_{47}) on planktonic foraminifers from Maud Rise (ODP Site 689)

(Petersen and Schrag, 2015), which show early Oligocene temperatures of 12°C. The BAYSPAR approach (Tierney & Tingley 2014; 2015) selects only those TEX$_{86}$ values from the calibration set of Kim et al. (2010) and an additional 155 core-tops from regional core-top TEX$_{86}$ studies, that are relevant for the study site, thereby generating a more regional calibration. Application of BAYSPAR on Site U1356 using a prior mean of 12°C does, however, result in the exclusion of the high-latitude core-top values. For this reason we find it useful to compare the BAYSPAR results to the results obtained by using the linear calibration of Kim et al. (2010). The BAYSPAR calibration method provides an estimate for SST and an upper and lower 90% confidence interval. For comparison to the linear calibration of Kim et al. (2010) a standard error (SE) has been calculated from these confidence intervals by assuming a normal distribution around the mean, in which case the 90% confidence interval boundaries can be calculated as the mean plus or minus 1.645 times SE.

Despite these recent efforts in improving the TEX$_{86}$-SST relationship, TEX$_{86}$ is known to overestimate temperatures at high latitudes due to multiple possible biases, such as seasonality (Ho et al., 2014; Schouten et al., 2013) and the incorporation of a subsurface signal (0-200 mbsl) at deep-ocean sites (>1000 mbsl) (Hernández-Sánchez et al, 2014; Huguet et al. 2007; Rodrigo-Gámiz et al., 2015; Yamamoto et al., 2012). There is, however, general consensus that TEX$_{86}$ is able to capture decadal and longer-term temperature trends (Richey and Tierney, 2016), which is why the main focus of this work is on relative SST changes. ~~In addition, Ho et al. (2014) showed that the scatter is more caused by regional TEX$_{86}$ variability in the Arctic Ocean rather than by the Southern Ocean core top. In turn, Southern Ocean TEX$_{86}^{L}$ values appear to be biased towards higher temperatures and correlate best with annual summer temperatures (Ho et al., 2014) due to relatively high amounts of GDGT-3 versus GDGT-2. In addition, it has been shown that the distribution of GDGTs and also the GDGT-2/GDGT-3 ratio in the water column is strongly influenced by the abundance of the 'shallow' and 'deep water' Thaumarchaeotal clades (Taylor et al., 2013; Villanueva et al., 2015), of which the deep community is strongly affected by changes in ammonia or oxygen concentrations (Basse et al., 2014; Villanueva et al., 2015). Close to the Antarctic margin, the abundance of 'shallow' versus 'deep -water' Thaumarchaeotal communities at deep water sites, like Site U1356, could be affected by the presence of sea ice and the relative influence of (proto-)Component Deep Water upwelling. Therefore, Site U1356 might have been susceptible to Thaumarchaeotal community changes, which affect the GDGT-2/GDGT-3 ratio. As GDGT-3 is not included in the nominator of TEX$_{86}^{L}$, changes in the GDGT-2/GDGT-3 ratio will affect TEX$_{86}^{L}$-based SST reconstructions to a large extent. For this reason, TEX$_{86}^{L}$-based calibrations are not the focus of our study, but have been included together with all existing TEX$_{86}^{(H)}$ calibrations as a supplementary figure (Figure S1).~~

~~It has been shown that highest GDGT fluxes are closely linked to highest organic matter, opal (diatom frustules) and lithogenic particle fluxes (Mollenhauer et al., 2015; Yamamoto et al., 2012).~~ Indeed, subsurface export of GDGTs is implicitly incorporated into the global TEX$_{86}$-SST calibration and has therefore no implications for reconstructing SST (Hernández-Sánchez et al., 2014). ~~It has been shown that h~~Highest GDGT fluxes are closely linked to highest organic matter, opal (diatom frustules) and lithogenic particle fluxes (Mollenhauer et al., 2015; Yamamoto et al., 2012)~~. A~~ and the lack of production of sinking particles that can incorporate GDGTs formed in deeper waters ~~prohibits~~ prevents biasing~~that~~ of surface-sediment TEX$_{86}$ values ~~are biased~~ towards deep-water temperatures (Basse et al., 2014; Mollenhauer et al., 2015; Yamamoto et al., 2012). Still, particular environmental settings (e.g., upwelling regions, regions with oxygen-depleted deep waters, fresh-water surface waters) might favor the transport of a subsurface temperature (subT) signal to the sediments (Kim et al., 2012a, 2012b; Lopes dos Santos et al., 2010; Mollenhauer et al., 2015). Also for polar oceans it has been suggested that reconstructed temperatures reflect ~~subsurface temperatures~~subT, ~~as~~ since today Thaumarchaeota are virtually absent in the upper 0-45 m of Antarctic low-salinity surface waters formed by seasonal retreat of sea ice (Kalanetra et al., 2009). Surface water conditions over Site U1356 during the Oligocene and the MCO were much like present-day regions ~~just~~ south of the Subtropical Front (STF) and likely not under the influence of a seasonal sea ice system (see Fig. 1) (Sangiorgi et al., 2018; Bijl et al., submitted this volume). ~~Thus~~For these time intervals, there is no reason to believe that surface waters were devoid of Thaumarchaeota due to the presence of sea ice and that TEX_{86} values are influenced by an increased subsurface ~~temperatures~~ signal~~as a result of low-salinity surface waters due to sea ice melt~~. For the earliest Oligocene and the MCT, the presence of *Selenopemphix antarctica* suggests that Site U1356 was under the influence of a seasonal sea-ice system (Bijl et al., submitted this volume). ~~Therefore, subsurface temperature TEX_{86} calibrations are not discussed. However, they have been included in Figure S1.~~For these periods, a reconstruction of subT values may be more appropriate, but this would still imply that SSTs are warmer. We limit our discussion to the TEX_{86}-based reconstructions to SST, notably, because it has been shown that TEX_{86}-based SST estimates based on the linear calibration of Kim et al. (2010) obtained from core-top samples from today's sea ice-influenced Southern Ocean, are in accordance with WOA2009 mean annual SST (Ho et al., 2014). This suggests that the effect of sea ice on surface and subsurface isoGDGT production is incorporated into the linear calibration of Kim et al. (2010). We therefore consider that despite the potential absence of Thaumarchaeota in the surface waters during the early Oligocene and the MCT, the calibration of Kim et al. (2010) does provide a reliable estimate of SST for these time intervals. Moreover, [2]/[3] ratios for the earliest Oligocene and the MCT are relatively low and show much less variability compared to the rest of the record (Fig. 2), which is opposite to what is expected when the relative influence of deep-water Thaumarchaeota increases (Hernández-Sánchez et al., 2014; Villanueva et al., 2015). Calibrations to subT (Kim et al., 2012a; Kim et al., 2012b; Tierney & Tingley, 2015) are therefore not considered here, but are included in supplementary Figure S1.

~~Based on the above, we here use the linear SST calibration in Kim et al. (2010). Despite the inclusion of Arctic surface sediment samples with deviating TEX_{86}-SST relations, this calibration ($SST = 81.5*TEX_{86} - 26.6$ with a calibration error of ±5.2°C) has been shown to plot onto the annual mean sea surface temperatures of the World Ocean Atlas 2009 (WOA2009; Locarnini et al. 2010) for the TEX_{86} values obtained from surface samples in the Pacific sector of the Southern Ocean (Ho et al., 2014). However, this calibration is likely to be influenced by regional differences in water depth, oceanographic setting and archaeal communities (Kim et al., 2016; Tierney and Tingley, 2014; Trommer et al., 2009; Villanueva et al., 2015). To evaluate the regional variability of the TEX_{86}-SST relation, we have compared the linear TEX_{86} calibration of Kim et al. (2010) with the calibration model of Tierney & Tingley (2014; 2015). The latter calibration is based on a Bayesian spatially varying regression model (BAYSPAR), which infers a best estimate for intersection and slope of the calibration based on an assembly of 20° by 20° spatial grid boxes that statistically fit best with a prior estimate of average SST for our SST record. The prior~~

~~for site U1356 is obtained from recent clumped isotope measurements (Δ_{47}) on planktonic foraminifers from Maud Rise (ODP Site 689) (Petersen and Schrag, 2015), which show early Oligocene temperatures of 12°C.~~

To get an estimate for the long-term average ~~SWT~~ SST trends and confidence levels a Local polynomial regression model (LOESS) has been applied using R, which is based on the local regression model *cloess* of Cleveland et al. (1992). This method of estimating the long-term average trend is preferred over a running average, because it accounts for the variable sample resolution. For the parameter *span*, which controls the degree of smoothing a value was automatically selected through generalized cross-validation (R-package fANCOVA; Wang 2010).

3 Results

3.1 Discarding potentially biased TEX_{86} values

A total of 113 samples spanning the Oligocene were analyzed for TEX_{86} in this study. ~~Of the 129 samples analyzed, 113 contained sufficient GDGTs to obtain a TEX_{86} value.~~ When the Miocene samples of Sangiorgi et al. (2018) are included, the total number of samples with sufficiently high GDGT concentrations is 145. However, only ~~69~~ 77 of these ~~113~~ 145 TEX_{86} values could be used for SST reconstruction for reasons ~~as~~ discussed below.

Although sampling of contorted strata was avoided, a total number of 46 Oligocene and Miocene samples proved to be obtained from MTDs after detailed logging by Salabarnada et al. (submitted this volume). ~~Twenty-eight samples were taken within distorted beddings, likely the distal reaches of MTDs originating from the slope or outer shelf of the Wilkes Land Margin (lithological Units IV, VI, VIII and IX) (Escutia et al., 2011).~~ Hence, samples from these beds may not reflect *in situ* material exclusively. ~~In addition~~For the EOT slumps, this is supported by a high degree of reworked Eocene specimens within the dinoflagellate cyst assemblage~~s show a high degree of reworked Eocene species~~ below 880.08 mbsf (Houben et al., 2013). ~~To avoid potential bias due to allochtonous input and reworking of older sediments, all samples from MTDs and from below 880.08 mbsf are also excluded from the SST reconstructions.~~ In addition, the clast-bearing deposits of Unit II and IV and decimeter-thick granule-rich interbeds of Unit VIII (Fig. 2) are interpreted as ice-rafted debris (IRD) deposits (Escutia et al., 2011; Sangiorgi et al., 2018), and thus indicate the presence of ice~~-~~bergs above the site during deposition of these intervals. To avoid potential bias due to allochtonous input and reworking of older sediments, all samples from MTDs are excluded from the SST reconstructions.

A contribution of terrestrial isoGDGTs can also bias the marine pelagic TEX_{86} signal, and can be verified by the BIT index (Hopmans et al., 2004; Weijers et al., 2006). In ~~nine~~ seventeen samples – none of which were derived from ~~mass waste or IRD~~MTDs ~~deposits~~ – the BIT index value was >0.3, which indicates that the reconstructed TEX_{86} temperatures are likely affected by a contribution of soil-derived isoGDGTs (Weijers et al., 2006; Hopmans et al. 2004). For ~~those~~ selected samples ~~which were analyzed by UHPLC/MS~~, the composition of brGDGTs was analyzed by UHPLC/MS (Hopmans et al., 2016), which showed that ~~to see if high BIT index values are the result of high marine brGDGT input, but none of these samples had~~ $\#rings_{tetra}$ were above 0.7 (Sinninghe Damsté, 2016) meaning that a significant portion of the brGDGTs was likely soil-derived. ~~All of these samples are therefore discarded.~~

Furthermore, the TEX_{86} signal may be influenced by a potential input of isoGDGTs from methanogenic archaea. Since methanogenic Euryarchaeota are known to produce GDGT-0 (Koga et al., 1998), but not crenarchaeol such a contribution may be recognized by GDGT-0/crenarchaeol values >2 (Blaga et al., 2009; Sinninghe Damsté et al., 2009). Similarly, methanotrophic Euryarchaeota may contribute significant amounts of GDGT-1, GDGT-2 and GDGT-3 ~~as well as~~that can be identified by values >0.3 for the Methane Index (MI) (Zhang et al., 2011) and/or GDGT-2/crenarchaeol values >0.4 (~~Blaga et al., 2009; Sinninghe Damsté et al., 2009;~~ Weijers et al., 2011~~; Zhang et al., 2011~~). In total ~~Thirteen~~ nineteen non-MTD-derived samples have too high GDGT-0/crenarchaeol ratios~~ > 2~~, ~~and/or~~ too high Methane Index values, or too high GDGT-2/crenarchaeol values ~~(Zhang et al., 2011)~~. Fourteen of these nineteen samples also have too high BIT values, meaning that in total 22 samples are discarded because of a potential contribution of soil-derived and methanogenic or methanotrophic archaeal isoGDGT input. ~~Eight of these also had too high BIT index values, and thus an additional five were discarded. No samples had GDGT-2/crenarchaeol ratios > 0.4, indicating no GDGT input from methanotrophs (Weijers et al., 2011).~~ As a final exercise, the Ring Index (|ΔRI|) ~~has been~~was calculated for our dataset to identify all other non-temperature related influences on ~~TEX_{86}~~ the distribution of isoGDGTs in the samples (Zhang et al., 2016). In addition to the non-temperature related influences discussed above, these could include oxygen concentrations (Qin et al., 2015), archaeal growth phase (Elling et al., 2014), ammonia oxidation rates (Hurley et al., 2016) and ecological factors (Elling et al., 2015). Using |ΔRI|>0.6 as a cutoff, ~~two~~ no additional ~~more~~ samples were discarded. All GDGT data and TEX_{86} values, including that of the discarded samples, are presented in the supplementary material (Figure S2, Table S1). ~~Table S1 also shows the GDGT-2/GDGT-3 ratios, which show a large variation among the non-discarded samples. This justifies our choice for a TEX_{86}-based SST reconstruction over a TEX_{86}^{L}-based SST reconstruction as large shifts in the GDGT-2/GDGT-3 ratio will affect the reconstructed SST trends, particularly below a value of 4 (Taylor et al., 2013).~~

3.2 Relation between TEX_{86} values and lithology

After excluding samples with potentially biased TEX_{86} values, the remaining~~, assumed *in situ* pelagic temperature signal could be interpreted. We note that the~~ record shows short-term variability ~~in the record seems to be~~that is strongly linked to the lithology (see Fig. 2)~~.:~~ S~~amples obtained~~ediments from the greenish laminated, carbonate-poor (glacial) facies produce statistically significant (t-test p-value < 0.005~~2 of t-test~~) lower TEX_{86} values than values obtained from the grey carbonate-rich bioturbated (interglacial) facies. ~~Between 600 and 879 mbsf~~For the entire record, TEX_{86} values are on average 0.50~~1~~ and ~~0.56~~0.53 for the glacial (laminated) and interglacial (bioturbated) lithologies, respectively. ~~Also in Units III and IV the bioturbated beds are associated with relatively higher TEX_{86} values compared to the values obtained from the (cross-)laminated beds, although the difference between intervals in those Units is slightly less.~~Paleoceanographic changes between glacial and interglacial periods may have affected the community structure of the Thaumarchaeota living over Site U1356, which may have introduced a non-thermal component to the TEX_{86} record that could contribute to the observed difference between TEX_{86} values from laminated and bioturbated facies. To test if changes in the composition of the Thaumarchaeotal community have contributed significantly to the observed difference between TEX_{86} values from laminated facies and bioturbated facies, a t-test was also performed on the [2]/[3] ratios of laminated and bioturbated lithologies for the entire record (Fig. 2). No significant difference was observed between the laminated and bioturbated facies (t-test p-value > 0.2).

3.3 Oligocene and Miocene long-term sea surface temperature trend

Based on the linear temperature calibration of Kim et al. (2010) (black curve in Fig. 3A), our TEX$_{86}$ ~~index~~ values ~~give an average SST of 16.3 (±5.2°C calibration error) for the Oligocene. Maximum and minimum temperatures are 25.1°C±5.2°C and 8.3°C±5.2°C, respectively. For 90% of the samples reconstructed temperatures fall between 10.5±5.2°C and 20.8±5.2°C (Fig. 3A). Apart from the~~ yield highest temperatures around 30.5 Ma (up to 22.6±5.2°C), 25.5 Ma (up to 25.1°C±5.2°C)~~, high SSTs are also reconstructed for the period~~ and around 17~~30.5~~ Ma (up to 19.2 ~~22.6~~±5.2°C), whereas lowest temperatures are recorded ~~the interval after~~ between 22 and 23.5 Ma ~~displays lower temperatures~~(minimum temperatures are 8.3°C±5.2°C), and around 13 and 10.5 Ma (minima around 7.6±5.2°C). On average SSTs based on the linear calibration of Kim et al. (2010) are 16.6°C, 16.7°C and 10.6°C for the Oligocene, MCO and MCT, respectively. Oligocene SST variability increases significantly (p-value<0.001 in F-test) after 26.5 Ma (see Fig. 3B). Before 26.5 Ma, the variation in the record ~~has a double standard deviation~~ (2σ) is of 3.6°C, while the 2σ is 6.8°C after 26.5 Ma. We note a strong (9.5°C) SST drop at the lower boundary of what is interpreted to represent~~as~~ subchron C6Cn.2n (23.03 Ma) (see Fig. 2 and 4); at the stratigraphic position of maximum δ^{18}O values related to Mi-1 in the deep-sea records (Beddow et al., 2016; Liebrand et al., 2011; Pälike et al., 2006b). Unfortunately, due to core recovery issues, limited high-resolution chronobiostratigraphic control in this interval~~and the nature of the sediments~~, the age model ~~is~~ generally ~~too crude~~lacks the resolution to identify some of the other known transient temperature drops in our record (~30 Ma, ~24 Ma) to Oligocene glaciation-related Oi-events (Fig. 4).

~~The BAYSPAR approach (Tierney & Tingley 2014; 2015) selects only those TEX$_{86}$ values from the calibration set of Kim et al. (2010) that are relevant for a study site, thereby generating a more regional calibration.~~ The SST ~~curve~~ record for Site U1356 based on the BAYSPAR model shows the same trend as the SST record generated with the linear calibration, but for SST values below 20.5°C it is ~~consistently~~ offset ~~by~~ towards slightly warmer values for SSTs based on the linear calibration below 20.5°C. Above 20.5°C, BAYSPAR-based SSTs are slightly offset towards cooler values. ~~1.0±0.7°C ,~~On average the BAYSPAR-based SSTs are 0.8°C warmer than the SSTs based on the linear calibration of Kim et al. (2010), and they have~~has~~ a smaller calibration ~~error~~ SE (~~3.5~~±4.0°C) (red curve in Fig. 3A). This offset and the smaller calibration error result primarily from the fact that BAYSPAR-calibration does not take the polar TEX$_{86}$ core-top values into account. Instead, it bases its calibration mostly on the modern 30-50° northern and southern latitudinal bands (see map in Fig. 3). Nevertheless, the ~~offset~~ BAYSPAR-based SSTs lie~~s~~ well within the ±5.2°C ~~calibration error~~SE of the transfer function from Kim et al. (2010), as well as within the ~~standard error~~SE of about ~~3.5~~±4.0°C for the BAYSPAR SST calibration. Average SSTs for the Oligocene, MCO and MCT based on the BAYSPAR SST calibration are 17.2°C, 17.3°C and 12°C, respectively. ~~In summary, SSTs from the BAYSPAR calibration are very similar to the SSTs derived with the linear calibration, in absolute values, long-term trends, as well as amplitude of variability.~~

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4 Discussion

4.1 Oligocene and Miocene Southern Ocean sea surface temperatures~~ estimates~~

Our TEX_{86}-derived ~~Southern Ocean SWT~~ SST record is the first for the Southern Ocean that covers almost the entire Oligocene. Absolute temperature values are relatively high considering the high-latitude position of Site U1356 (~59°S, van Hinsbergen et al., 2015)~~. However~~, but confidence can be obtained from the observation ~~considering~~ that TEX_{86}-based reconstructed SSTs ~~obtained~~ from ~~interpreted~~ glacial lithologies are generally lower than those ~~obtained~~ from interglacial lithologies (Fig. 4)~~, strongly supports that our TEX_{86} record is reflecting temperature~~. Several lines of evidence ~~seem to~~ support the relatively high Oligocene and mid-Miocene temperatures reconstructed for Site U1356. Dinoflagellate cyst assemblages from the same site (Sangiorgi et al., 2018; Bijl et al., submitted this volume) mostly contain taxa related to those found between the Polar (PF) and the Subtropical Front (STF) today, where mean annual sea surface temperature is between 8 and 16°C (Prebble et al. 2013).~~, which~~ This is on the low end of our reconstructed SSTs for the Oligocene and the MCO, but very comparable to SSTs for the MCT. Furthermore, the abundance of *in situ* pollen of temperate vegetation in these sediments (Sangiorgi et al., 2018; Strother et al., 2017), which are most likely derived from the Antarctic shores~~coastline~~, also suggests a relatively mild climate. Finally, the abundance of pelagic carbonaceous facies in some of the Oligocene interglacial intervals of these high-latitude strata is interpreted to occur under the influence of warmer northern-sourced surface waters at Site U1356~~-~~ (Salabarnada et al., submitted this volume).

~~TEX_{86}-derived SSTs for IODP Site U1356 are generally~~ In general, Oligocene SST estimates are higher than the SST estimates reconstructed with other proxies in other high-latitude Southern-Ocean Sites 511 and 689 (Fig. 3A). ~~ose reconstructed with other proxies in other high-latitude Southern-Ocean sites during the early Oligocene (between ~ 34 and ~ 32 Ma; Fig. 3A).~~ However, the reconstructed ~12°C (standard error: ±1.1-3.5°C) based on clumped isotopes from~~for~~ Site 689 is derived from thermocline-dwelling foraminifera, whereas the temperature of the surface waters ~~were~~ was likely higher than that at the thermocline (Petersen and Schrag, 2015). In addition, when the newest calibration for clumped isotope data is applied (Kelson et al., 2017) also higher temperature estimates, 12.8-14.5°C, are obtained. Temperature estimates between 6 ~~to~~ and 10°C have been obtained from ODP Site 511 (see Fig. 1) based on $U^{K'}_{37}$ (Plancq et al., 2014) and TEX_{86} values (Liu et al., 2009), the latter recalculated with the linear calibration of Kim et al. (2010) and the BAYSPAR calibration used here (Fig. 3A). The influence of the cold Antarctic-derived surface current ~~prevailing~~ at Site 511 (Bijl et al., 2011; Douglas et al., 2014) (Fig. 1) might be the reason of these colder estimates. ~~Meanwhile, s~~Similar to the Eocene, Site U1356 probably ~~represents~~ was one of the warmest regions around Antarctica during the early Oligocene (Pross et al., 2012), situated at a relatively northerly latitude (van Hinsbergen et al., 2015) and still under influence of relatively warm proto-Leeuwin current (PLC, Fig. 1) (Bijl et al. 2011; submitted this volume).

Sangiorgi et al. (2018) compared TEX_{86}^{L}-based reconstructed temperatures (based on the 0-200 depth-integrated calibration of Kim et al., 2012a) from the Miocene section of Site U1356 with Mg/Ca-based SST values from planktic foraminifera from ODP Site 1171, South Tasman Rise (Shevenell et al., 2004), and TEX_{86}^{L}-based seawater temperatures from the ANDRILL (AND)-2A core, Ross Sea (Levy et al., 2016). Based on these temperature reconstructions it was established that temperatures at Site U1356 during the MCO are very comparable to the Mg/Ca-based SSTs from the South Tasman Rise are and a few degrees cooler during the MCT, which was further supported by pollen and dinocyst assemblages (Sangiorgi et al., 2018). We reach the same conclusion based on the reconstructed SSTs using the linear calibration of Kim et al. (2010) and the BAYSPAR calibration for the Miocene TEX_{86} values from Site U1356 as well as site AND-2A (Fig. 3). Based on these recalibrated SST values, we conclude, like Sangiorgi et al. (2018), that there was a much reduced SST gradient between Site U1356A and Site 1171, which were at that time positioned at approximately 60.0°S and 53.6°S, respectively (van Hinsbergen et al., 2015). Notably, however, the latitudinal difference between the Site U1356 and Site 1171 increased as well and may be partly responsible for the increased temperature gradient between the two sites at 14 Ma (Site U1356 lay at 60.5°S and Site 1171 lay at 52.7°S; van Hinsbergen et al., 2015).

Biota-based temperature reconstructions at such high latitudes ~~can be~~are likely skewed towards summer conditions, as has also been suggested for Site 689 and Site 511 (Petersen and Schrag, 2015; Plancq et al., 2014). An important reason for this could be the light limitation at high latitudes during winter (e.g., Spilling et al. 2015), which is unfavorable for the growth and bloom of phytoplankton, and organisms feeding on phytoplankton. The potential summer bias in high latitude TEX_{86}-based SST reconstructions has been discussed extensively for other past warm periods (e.g., Sluijs et al., 2008; Bijl et al., 2009; 2010; 2013). Like in these past warm climates, we expect that primary productivity in the Oligocene Southern Ocean was in sync with seasonal availability of light, irrespective of the presence of sea ice or overall climate conditions. Indeed, isoGDGTs likely require pelleting to sink effectively through the water column to the ocean floor (e.g., Schouten et al. 2013), and therefore depend on the presence of larger zooplankton that feed on the phytoplankton. As phytoplankton blooms mostly occur during Antarctic summer/autumn, as do their predators~~, the copepods~~ (Schnack-Schiel, 2001), we expect the highest isoGDGT fluxes to the sediment during the summer in the Southern Ocean, despite their ~~primary~~ highest production during a different season (Church et al., 2003; Murray et al., 1998; Richey and Tierney, 2016; Rodrigo-Gámiz et al., 2015). A bias towards summer temperatures is confirmed by the presence of sea-ice dinoflagellate cysts in some parts of the record, which would suggest SSTs near freezing point during winter.

4.2 Long-term Oligocene and Miocene sea surface temperature ~~variability~~trends

We aim to ~~use~~ explore the implications of the long-term trends in our TEX_{86}-based SST record~~, to distinguish between the temperature and the ice-sheet signal captured in~~ by placing it in context of the global benthic $\delta^{18}O$ ~~trend~~and benthic foraminiferal Mg/Ca-based bottom-water temperature (BWT) records, in order to infer oceanographic changes or changes in ice volume. Due to the relatively low sample resolution, and discontinuous sampling due to core gaps~~, and poor age model of our record~~ in comparison to the complete and quasi-continuous

δ^{18}O records (Beddow et al., 2016; Billups et al. 2004; Hauptvogel et al., 2017; Holbourn et al., 2015; Liebrand et al., 2017, 2016; Pälike et al., 2006a; 2006b), we will here focus on the long-term temperature trends. ~~W~~However, we can use the glacial-interglacial alternations in the lithology, which cover the period between 32 and ~~25~~ 10 Ma, to differentiate between glacial and interglacial ~~reconstructed~~ SST~~s~~ and assess amplitudes (see Fig. 2). As was mentioned, SSTs derived from the glacial facies show a significantly lower mean than SSTs derived from interglacial facies. Separating glacial and interglacial signals allows us to interpret the long-term SST trend, as this removes a potential sampling bias ~~towards~~ caused by irregularly spaced~~more~~ glacial or more interglacial ~~deposits~~samples. To obtain both long-term glacial and interglacial SST trends, LOESS curves are plotted through SST estimates from the glacial and interglacial subsets of the Oligocene (Fig. 4). For the Miocene we averaged SSTs from glacial and interglacial samples for the three-sample 'cluster' (at ~17, ~13.5 and ~10.5 Ma). Glacial and interglacial LOESS curves plotted through the SST estimates based on the linear calibration of Kim et al. (2010) show the same trend, lying slightly below the BAYSPAR SST LOESS curves (Fig. 4).

A global benthic foraminiferal stacked δ^{18}O curve has been constructed by combining the benthic δ^{18}O records of the far-field Site 1218, eastern equatorial Pacific (Pälike et al., 2006b); Sites 1264/1265, Walvis Ridge, southeast Atlantic (Liebrand et al., 2017, 2016); Sites 926/929, Ceara Rise, equatorial Atlantic (Pälike et al., 2006a ; Zachos et al., 2001); Site U1334, eastern equatorial Pacific (Beddow et al., 2016); Site 1090, Agulhas Ridge, Atlantic sector of the Southern Ocean (Billups et al., 2004); Site U1337, eastern equatorial Pacific (Holbourn et al., 2015); and Site 588, southwest Pacific (Flower & Kennett, 1993). To obtain a global benthic δ^{18}O stack in which the global long-term trends are best represented, we have normalized the data to the Site 1264/1265 record of Liebrand et al. (2017, 2016), on which all records now overlap (Fig.4). Mg/Ca-based BWT records are obtained from Site 1218, eastern equatorial Pacific (Lear et al., 2004); Site 747, Kerguelen Plateau, Southern Ocean (Billups & Schrag, 2002); and Site 1171, Tasman Rise, Southern Ocean (Shevenell et al., 2004). LOESS curves have been plotted through the benthic δ^{18}O stack as well as the individual Mg/Ca-based BWT records (Fig. 4).

The LOESS curves through the glacial and interglacial data show similar trends and show a striking resemblance to the global benthic δ^{18}O stack (Fig. 4), particularly when considering the compromised sample resolution of our record. The temperature optima and minima in the LOESS curves can be directly linked to periods of relatively low and high benthic δ^{18}O values (maximum and minimum ice volume/BWT), respectively.~~:~~ ~~SSTs~~ Temperatures increase from the earliest Oligocene towards 30.5 Ma, while benthic δ^{18}O values show a decrease in the same interval, but reach a minimum earlier, around 32 Ma. It is difficult to determine whether SSTs are truly lagging the benthic δ^{18}O values in this interval or whether this is an artifact caused by the age model in this part of the record. The recorded post-Oi-1 SST warming coincides with the disappearance of IRD (Escutia et al., 2011) and sea-ice related dinoflagellate cysts (Houben et al., 2013) in the same record (Fig. 4).~~,~~ Following this temperature optimum, there is ~~followed by~~ a cooling trend until a minimum is reached around 28-27 Ma, which coincides with relatively high benthic δ^{18}O values and the Oi-2a and Oi-2b glacials. Subsequently, there is ~~followed by~~ a warming towards a long-term temperature optimum around ~~26~~ 25 Ma, which coincides with a minimum in the benthic δ^{18}O record known as the late Oligocene warming. This temperature optimum around 25 Ma is characterized by the influx of the temperate dinocyst species *Nematosphaeropsis labyrinthus* (Bijl et al., submitted this volume). This seems to indicate a strong influence of northern-sourced surface waters at Site U1356, as this species is currently associated with the Subtropical Front and winter and summer temperatures of 6–13°C and 8–17°C, respectively (Esper and Zonneveld, 2007; Marret and De Vernal, 1997; Prebble et al., 2013). Finally, the Oligocene LOESS temperature curves show a ~~and then~~ cooling towards the Oligocene-Miocene transition at 23 Ma. In comparison to the benthic $\delta^{18}O$ record this cooling trend is rather gradual and starts 1 Myr earlier than the steeper benthic $\delta^{18}O$ record increase that starts at 24 Ma and continuous towards the Mi-1 glaciation. We consider this to represent a realistic climate signal, notably so since the age model is sufficiently well-constrained in this part of the record. ~~The recorded post-Oi-1 SST warming coincides with the disappearance of IRD (Escutia et al., 2011) and sea-ice related dinoflagellate cysts (Houben et al., 2013) in the same record (Fig. 4). The second temperature optimum between 26.5 and 25 Ma is characterized by the influx of the dinocyst genus *Nematosphaeropsis* (Bijl et al., submitted this volume). This seems to indicate a strong influence of northern-sourced surface waters (PLC, Fig. 1) at Site U1356 , as this species is currently associated with the Subtropical Front and mean annual temperatures above 11°C (Esper and Zonneveld, 2007; Marret and De Vernal, 1997; Prebble et al., 2013).~~ Glacial and interglacial averages for the Miocene data clustered around 17, 13.5 and 10.5 Ma show a declining trend and follow the increasing benthic $\delta^{18}O$ trend that characterizes the MCT. High amounts of *N. labyrinthus* within the MCO interval support warm surface water conditions (Sangiorgi et al., 2018). After the MCO, increased amounts of sea-ice dinoflagellates and IRD indicate that Site U1356 came under the influence of seasonal sea ice, and therefore cooler conditions. However, increases of *N. labyrinthus* after the MCT indicate that warmer northern-sourced waters still periodically influenced Site U1356 (Sangiorgi et al., 2018).

The fact that the LOESS temperature trends mirror the benthic $\delta^{18}O$ record may suggest that (1) changes in the Wilkes Land SST correspond to SST changes in the region of deep-water formation, which is reflected in the benthic $\delta^{18}O$ records, (2) changes in the Wilkes Land SST reflect long-term changes in paleoceanography that simultaneously affect or are related to the size of the Antarctic Ice Sheet (AIS) and therefore the deep-sea $\delta^{18}O$ of the sea water, or a combination of both.

Considering the first, in the modern-day Southern Ocean, bottom water forms through mixing along the Antarctic Slope Front (ASF) of Circumpolar Deep Water (CDW) and High Salinity Shelf Water (HSSW), which forms in consequence of sea-ice formation (Gill, 1973; Jacobs, 1991). Associated with the ASF is the westward flowing Antarctic Slope Current (ASC), which contributes to the bottom-water formation and results from the geostrophic adjustment of Ekman transport to the south, which is driven by the predominantly easterly winds around Antarctica (Gill, 1973). It has been suggested that, after the establishment of its shallower westward flowing counterpart, the ~~Site U1356 probably was not in the region of deep-water formation, given it probably was the warmest region around Antarctica (Pross et al., 2012) likely also in the Oligocene. Nevertheless, because~~ Antarctic Circumpolar Countercurrent (ACCC), around 49 Ma (Bijl et al., 2013), ~~and bottom-water formation along the associated Antarctic Slope Front (ASF) were likely established~~ an ASC was established near Site U1356 in the early Oligocene (Scher et al., 2015). In areas where sea ice was formed during the Oligocene and Miocene the ASC could have enhanced mixing between HSSW and CDW similarly to today. For the Wilkes Land margin this might have been the case for the earliest Oligocene and MCT where we find sea-ice indicators in the dinoflagellate cyst assemblages

(Bijl et al., 2018; Houben et al., 2013). These sea-ice dinoflagellate cysts seem to indicate that winter temperatures at the Wilkes Land margin were cold enough to allow sea-ice formation and therefore maybe formation of deep waters along the Wilkes Land coast during the earliets Oligocene and MCT. However, most of the record is devoid of sea-ice indicators, suggesting that modern-day process of deep-water formation, is unlikely to have occurred at the Wilkes Land Margin. Still, neodymium isotopes of fossil fish teeth from Site U1356 have suggested that deep-water formation took place at the Adélie and Wilkes Land Margin during the Eocene (Huck et al., 2017), when pollen indicate near-tropical warmth (Pross et al., 2012) . Model studies have suggested that during such warm periods seasonal density differences may still induce deep-water formation or downwelling of waters around Antarctica (Goldner et al., 2014; Lunt et al., 2010). Alternatively and more likely, sea ice may have formed in the cooler Ross Sea and transported along the Wilkes Land coast similarly to today during the Oligocene and Miocene, meaning that deep water formed in the Ross Sea where glaciers extended onto the Antarctic shelf (cf. Sorlien et al., 2007). In that case, the absence of sea-ice dinoflagellate cysts during most of the Oligocene and the MCO at Site U1356 would mean that, in contrast to the earliest Oligocene and MCT, sea ice coming from the Ross Sea was prevented from reaching Site U1356 by too warm winter SSTs. This is in accordance with the relatively warmer (summer) SST values for Site U1356 during most of the Oligocene and the MCO. If the reconstructed SST trends of Site U1356 are representative for the~~, we expect that bottom-water formation was under the influence of the same long-term (million-year)~~ climatic trends~~ recorded in the SST reconstruction of Site U1356~~ of a larger region (i.e. including the Ross Sea as a potential region for deep water formation), ~~. In turn, Southern Ocean~~this climatic signal may have been ~~surface-water temperatures were likely~~ relayed to the deep ~~-~~ocean and recorded in the stable oxygen isotope composition of benthic foraminifera in far-field sites. In fact, Southern Ocean~~-~~sourced deep waters may have reached ~~all the way to~~ as far as the north Pacific during the Oligocene (Borelli & Katz 2015). If this is the case, the consistent long-term trends between the SST of Site U1356 and the benthic δ^{18}O record would imply that the size of the AIS is less variable on these long-term timescales than the benthic δ^{18}O record would suggest under the assumption of constant BWT (e.g., Liebrand et al., 2017; see Figure 4): much of the variation will be due to deep-sea temperature variation. The small AIS may have been relatively stable during the Oligocene and Miocene, most likely because there was less marine-based ice in comparison to land-based ice as topographic reconstructions of Antarctica would suggest (Gasson et al., 2016; Wilson et al., 2012).~~This suggests that deep-sea benthic foraminiferal~~ ~~δ^{18}O records have incorporated both a temperature and ice-volume signal present in the Antarctic-derived deep-waters. Indeed~~

~~, the o~~Only one ~~bottom-water temperature~~BWT record is available for the Oligocene, which is based on Mg/Ca ratios from Site 1218 (equatorial Pacific). Mg/Ca was obtained from~~f~~ the benthic foraminifer~~a~~ *Oridorsalis umbonatus* ~~from Site 1218 (equatorial Pacific)~~ (Lear et al. 2004; Fig. 4), an infaunal species that is to some extent insulated from long-term changes in carbonate ion concentrations (Ford et al., 2016; Lear et al., 2015). Although absolute temperatures may depend on local factors, such as pore water chemistry, the long-term trends should reflect the trends in BWT (Lear et al., 2015). The BWT record of Site 1218 shows a long-term deep-sea warming between 27 and 25 Ma, similar to our SST record. ~~Notably, Mg/Ca-based reconstructed bottom-water temperatures at Site 1218 are much lower than reconstructed SSTs from Site U1356: 3.7°C on average (Lear et al. 2004; Fig. 4). Likely,~~

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~~this difference results from the fact that bottom water forms at higher latitudes in the subsurface in winter (Jacobs, 1991), while our TEX_{86}-based SST record likely reflects summer temperatures.~~ The temperature ~~rise before~~optimum at 30.5 Ma ~~and the temperature decrease after 25 Ma~~ in our TEX_{86}-based SST record cannot be recognized in the ~~bottom-water temperature~~BWT record of Site 1218. Similarly to the benthic $\delta^{18}O$ record, an optimum is reached earlier (~32 Ma) and this mismatch could be due to uncertainties in the age model of the lower part of the Oligocene section of Hole U1356A. The continued temperature rise after 25 Ma in the BWT record of Site 1218 is also not observed in our TEX_{86}-based temperature trend. This could be because the equatorial Pacific mainly receives bottom water from a warmer Pacific sector of the Southern Ocean, east of the Tasmanian Gateway, and not from the Wilkes Land margin, and the Pacific sector is influenced by warming. Alternatively, there is an increasing influence of a warmer deep-water mass from elsewhere. Notably, Mg/Ca-based BWTs from Kerguelen Plateau (Site 747) show a temperature optimum around 25 Ma preceding the $\delta^{18}O$ minimum at 24 Ma, similar to the SST trend at Site U1356. For the mid-Miocene, BWT records of both Site 747 (Kerguelen Plateau) and Site 1171 (South Tasman Rise) show slowly decreasing trends consistent with decreasing TEX_{86}-based SSTs of Site U1356. The similarities of the three Mg/Ca records to our TEX_{86}-based SST record support the transfer of a regional SST signal towards the deep ocean through deep-water formation. However, the temperature differences between temperature optima (e.g., the late Oligocene and MCO) and minima (e.g., the mid-Oligocene and MCT) are much larger for the TEX_{86}-based SSTs than for the Mg/Ca-based BWTs. This difference in the degree of change could be explained by the fact that the formation of deep waters during winter is constrained at the lower end by the freezing point of water, which would limit the degree of change during relatively cold intervals. The degree of change could also be reduced by a shift in the location of deep-water formation to higher latitudes during warmer intervals.

~~Uncertainties about Mg/Ca ratio of the seawater and the influence of a changing carbonate ion saturation state of the deep waters at Site 1218 (Elderfield et al., 2006; Lear et al., 2010), as well as a lack of a high-resolution age model of our record and low sample resolution compromise a detailed comparison between the two records.~~

Alternatively, long-term SST trends as well as Southern Ocean BWT trends (Sites 747 and 1171) are governed by large-scale tectonic processes, such as the opening and closure of the Drake Passage, as was suggested by Lagabrielle et al. (2009). Opening of the Drake Passage could result in increased isolation of the Antarctic continent through the establishment of a (proto-)ACC. In turn, this would result in effective blocking of northerly sourced warmer waters as well as ice sheet expansion thereby resulting in a simultaneous benthic $\delta^{18}O$ increase and SST decrease.

As an alternative hypothesis, reconstructed SSTs at Wilkes Land may depend on the volume of the ice sheet in the hinterland. In that scenario most of the long-term trends in the $\delta^{18}O$ record is due to ice volume growth and decline. A more expanded ice sheet will lower SSTs and enhance the formation of sea ice around Antarctica (Goldner et al., 2014). Expansion of this cool (proto-)AASW and the ocean frontal systems to lower latitudes during glacials may have cooled SSTs at Site U1356, while ice-volume decrease and the retreat of the ocean frontal systems during interglacials may have resulted in warmer SSTs at Site U1356. However, the warmth of even the glacial SSTs in our SST record, as well as the overall absence of sea-ice indicators during most of the Oligocene in these glacial intervals, strongly argues against this alternative. Only during the MCT, where dinoflagellate cysts and IRD suggest

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an increased influence of icebergs or sea ice (Sangiorgi et al., 2018), the ice sheet may have been large enough during the glacial periods to allow the influence of cool (proto-)AASW at Site U1356.

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~~With the here reconstructed SST record, we can now evaluate what part of the long-term $\delta^{18}O$ trend can be explained by high-latitude SST changes. We compare our SST record to the high-resolution Oligocene deep-sea $\delta^{18}O$ record from the equatorial Pacific (Site 1218; Pälike et al. 2006), which is the only high-resolution $\delta^{18}O$ record that covers the entire Oligocene. To enable direct comparison, we have resampled the glacial (values above average $\delta^{18}O$) and interglacial (values below average $\delta^{18}O$) $\delta^{18}O$ trends at Site 1218 following the sample resolution of U1356 (Fig. 4). Part of the long-term benthic $\delta^{18}O$ trend from Site 1218 is reflected in our TEX_{86}-based SST record (Fig. 4): both glacial and interglacial SST LOESS curves show a decreasing trend towards 27 Ma co-occurring with the long-term 0.6‰ $\delta^{18}O$ increase observed between 32 and 27 Ma. The subsequent decrease in $\delta^{18}O$ is also matched by an increase in the long-term interglacial and glacial SST curves. This means that in this part of the record, long-term bottom-water temperature changes could account for part of the long-term $\delta^{18}O$ trends. However, other parts of the record show a mismatch between the long-term SST trend and the long-term $\delta^{18}O$ trend. For example, our reconstructed SST record shows increasing temperatures between 33 and 30.5 Ma, while $\delta^{18}O$ values decrease only between 33.5 and 32 Ma. Furthermore, reconstructed SSTs start decreasing after 25 Ma, while $\delta^{18}O$ values start increasing only after 24 Ma. However, low sampling resolution and uncertainties in the age model might account for these mismatches.~~

~~The striking similarity between the SST and $\delta^{18}O$ long-term trends in the interval between 30.5 and 25 Ma, despite reconstructed SSTs at Site U1356 being likely summer-biased, and deep-water formation likely occurring during wintertime and not exactly in the region of U1356, gives confidence that there is indeed a relation between Southern Ocean SSTs and benthic $\delta^{18}O$ values. Although not yet quantifiable due to the above-mentioned uncertainties, this relation will have implications for $\delta^{18}O$-based ice-volume reconstructions. Therefore, we have conducted a thought experiment by ignoring the uncertainties in the TEX_{86}-based SST record resulting from low sampling resolution and poor age model, and by assuming the reconstructed SST trend has been relayed to the deep ocean. Then, the reconstructed 1°C cooling in the TEX_{86}-based SST between 30.5 and 27 Ma could account for one third of the about 0.75‰ $\delta^{18}O$ long-term decrease between 32 and 27 Ma (1°C = 0.21-0.23‰; Ravelo & Hillaire-Marcel 2007). Similarly, the late Oligocene warming of 1.5°C in our SST record between 27 and 25 Ma would account for much of the coeval 0.50‰ decrease in $\delta^{18}O$. However, the further 0.02‰ decrease of benthic $\delta^{18}O$ between 25 and 24 Ma should then be related to ice volume loss, since our SWTs decrease with 2°C at that time. Recent ice-volume calculations by Liebrand et al. (2017) suggest that the ice-sheet volume around 27 Ma is at least as large as today's East Antarctic ice sheet, assuming deep-sea temperatures cannot drop below current bottom-water temperatures (Fig. 4). However, because their calculations are also based on a constant deep-sea temperature, they are overestimating the long-term growth and decline between 32 and 25 Ma (Liebrand et al., 2017). Hence, if the magnitude of deep-sea temperature long-term change is equal to our long-term reconstructed SST trends, current ice-volume estimates during periods of low benthic $\delta^{18}O$ (see Fig. 4) are underestimating the size of the Antarctic ice sheet. After 24 Ma, and towards Mi-1, the long-term $\delta^{18}O$ trend rises 0.6‰, while the reconstructed SST trends drop about 3°C. Although this cooling could fully account for the long-term $\delta^{18}O$ trend between 24 and 23 Ma, we acknowledge the existing physical evidence for a profound glaciation event during Mi-1 (Naish et al., 2001). Similarly, we fully recognize that ice volume variability took place during the Oligocene on the long term (Liebrand et al., 2017; Pekar et al., 2006; Pekar and Christie-Blick, 2008), but we suggest that ice-volume variability before 24 Ma was less than previously assumed, as part of the variation has to be attributed to likely changes in deep-sea temperatures over these timescales.~~

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4.3 Sea surface temperature variability at glacial–interglacial time scales

~~T~~For the Oligocene, the offset between the glacial and interglacial LOESS curves is constant over time (Fig. 4). Irrespective of the chosen calibration (i.e. TEX_{86} or BAYSPAR), SSTs are on average 1.5~~8~~-3.1~~2~~°C higher during interglacial intervals than during adjacent glacial times. This glacial-interglacial SST difference is smaller than the observed amplitude of the variability in our temperature record (2σ = 3.6°C before 27 Ma), because it takes relatively warm glacials and cool interglacial SST values into account. Also considering that part of the 2σ variability is due to the relatively large calibration error of the BAYSPAR calibration (±~~3.5~~4.0°C), the difference of 1.5~~8~~-3.1~~2~~°C may be a better representation of average glacial-interglacial SST variation than the 2σ.

The average consistent offset between glacial and interglacial values seems to disappear for each of the Miocene data clusters at ~17, ~13.5, and ~10.5 Ma. Several causes could explain this. It could be the result of a less variable climate during the Miocene, which causes both subsets to overlap more. Indeed, for the MCO this may be the case, because the MCO is a time interval of exceptional warmth, with retreated ice sheets and vegetated coastlines of Wilkes Land (Sangiorgi et al., 2018). In such a climate, the glacial intervals may not have been fundamentally colder than the interglacials. We cannot, however, explain the apparent absence of glacial interglacial-temperature variability around 14 and 10.5 Ma, where dinoflagellate cysts suggest profound variability in sea-ice extent, upwelling and temperature (Sangiorgi et al., 2018). It could be that the samples taken by Sangiorgi et al. (2018) do not capture the true glacial and interglacial extremes, but this cannot be verified at this stage. Because a detailed lithological log was not available to Sangiorgi et al. (2018), there is also an uneven distribution between glacial and interglacial samples.

If ~~such~~ the recorded glacial-interglacial SST variability in the Oligocene is representative for ~~the wider Southern Ocean region~~ the SST variability at the region of deep-water formation~~and relayed to the deep-sea~~, it should be considered when interpreting benthic foraminiferal $\delta^{18}O$ records in terms of ice-volume variability. As such, a larger part of the variability of $\delta^{18}O$ than so far assumed (Hauptvogel et al., 2017; Liebrand et al., 2017;~~ Hauptvogel et al., 2017~~) should be ascribed to deep-sea temperature rather than ice-volume changes. ~~To be more specific,~~If the region of deep-water formation experienced the same SST variability, 40-70% of the 1‰ deep-sea $\delta^{18}O$ variability over Oligocene glacial-interglacial cycles can be related to deep-sea temperature~~ (Fig. 5)~~. However, it is ~~likely~~ plausible that not the entire ~~amplitude~~ range of SST variability is relayed to the deep-sea, and that in the more southerly positioned Ross Sea, the most likely region of Oligocene deep-water formation, temperatures were not as variable as in the Wilkes Land sector. Indeed, Mg/Ca-based reconstructed bottom-water temperatures from Site 1218 show much less glacial-interglacial variation (1.1~~3~~°C, Fig. 5) (Lear et al., 2004) than our record. ~~This suggests that the amplitude of the glacial-interglacial temperature variation of the surface ocean is strongly reduced at the nearby bottom-water formation sites. Likely, because bottom water has likely formed in the subsurface during winter like today (Baines, 2009; Jacobs, 1991).~~ Still, our record provides ~~additional~~ evidence that polar SST experienced considerable variability, both on the short-term glacial-interglacial cycles as well as on the long-term.

~~Our data furthermore suggest that glacial-interglacial SST variability increased after 27 Ma (Fig. 3B), which suggests a lower contribution of ice volume to the deep-sea~~ ~~$\delta^{18}O$~~ ~~signal during the late Oligocene.~~ A ~~major~~ considerable influence of deep-sea temperature on benthic $\delta^{18}O$ could explain the level of symmetry in glacial-interglacial cycles in the Oligocene (Liebrand et al., 2017), as the temperature would vary in a sinusoidal fashion, whereas ice sheets would respond non-linearly to climate forcing. ~~Note that this reasoning is still rather speculative as t~~The sedimentary record of Site U1356 lacks the potential of~~to~~ obtaining a resolution comparable to those~~at~~ of deep-sea $\delta^{18}O$ records, in order to verify these claims. However, ice-volume reconstructions from $\delta^{18}O$ records on both long-term and short-term time scales should consider that an important component of the signal could potentially be ascribed to temperature variability.

~~4.4 Implication for the Antarctic Circumpolar Current~~

~~Today the ACC and the associated Antarctic divergence isolate the continent from lower-latitude influence and are keeping sea-surface temperatures south of the divergence relatively cool (Orsi et al., 1995). The strength and development of the ACC during the Oligocene co-depends on the opening (and depth) of the Tasmanian Gateway and Drake Passage (Hill et al., 2013). If the Tasmanian Gateway and the Drake Passage were open to allow for some deep-water throughflow during the Oligocene, modeling of ocean currents suggests that a strong ACC could only develop once the ocean gateways are in line with the latitudinal position of the westerly winds (Hill et al., 2013). Dinoflagellate cysts (Stickley et al., 2004) and neodymium isotopes from east and west of Tasmania (Scher et al., 2015) indicate that significant eastward throughflow started south of Tasmania around 35-30 Ma. Instead, the TEX~~$_{86}$~~-based SST record and dinoflagellate cyst record (Bijl et al., this issue) of Site U1356 suggest an influence of these warmer northerly waters also at higher latitudes. This suggests that Site U1356 is not fully isolated by a strong flowing ACC and that the eastward flowing current south of Tasmania might have been deflected towards Site U1356. Alternatively, warmer surface water may have reached Site U1356 through eddy-induced heat transport (Dufour et al., 2015; Thompson et al., 2014). It remains a matter of debate when Drake Passage opened sufficiently to allow for a significant ACC throughflow (Lawver & Gahagan 2003; Livermore et al. 2004; Scher & Martin 2006; 2008; Barker et al. 2007; Lagabrielle et al. 2009; Maldonado et al. 2014; Dalziel 2014). Depending on whether Drake Passage was closed or open, modeling suggests that the westward flowing ACCC was stronger or weaker, respectively (Hill et al., 2013). Site U1356 would then be respectively more or less under the influence of the ACCC. If Drake Passage was closed, a stronger ACCC would be able to transport the warm waters recorded at Site U1356 further along the Antarctic coastal margin and thereby explain also the relatively warm temperatures at Site 689.~~

5 Conclusions

We reconstruct ~~a~~ (summer-biased) SSTs of around 17°C on average for the Wilkes Land Margin during the Oligocene, albeit with ~~much~~ a high degree of variability (up to a 6.8°C double standard deviation during the late Oligocene). The reconstructed temperatures are a few degrees higher than previously published high-latitude early Oligocene Southern Ocean estimates. Because alternations in the lithology reflect glacial-interglacial cycles, an estimated temperature difference of 1.5~~2~~ to 3.1°C between glacials and interglacials could be ~~determined~~interpreted for the Oligocene. The long-term trends of both glacial and interglacial records show a temperature increase towards 30.5 Ma, followed by a minimum around 27 Ma, an optimum around ~~and a decrease after~~ 25 Ma and finally a decrease towards the end of the Oligocene, generally following the long-term trends in the global benthic $\delta^{18}O$ record as well as parts of the available Mg/Ca-based BWT records for the Oligocene. Recalibrated SSTs based on previously published TEX$_{86}$ data for the mid-Miocene decrease from around 17°C to 11°C between ~17 and ~10.5

Ma. A distinct glacial-interglacial SST difference was not observed for the mid-Miocene. Nevertheless, the recorded temperature decline also follows the trend observed in benthic $\delta^{18}O$ and Mg/Ca-based BWT records. Our results suggest that considerable SST variability prevailed during the Oligocene and Miocene.~~,~~ ~~which might~~ This may have implications for the dynamics of marine-based ~~continental~~ ice sheets, if present, and the extent of the Antarctic ice sheet in general. Assuming that the reconstructed SST trends and glacial-interglacial variability have been relayed to the deep water at nearby bottom-water formation sites, our results ~~imply~~ indicate that the long-term $\delta^{18}O$ trend may be controlled for a considerable part ~~be controlled~~ by bottom-water temperature ~~in addition to ice-volume fluctuations~~. This implies that the Antarctic Ice Sheet was less dynamic during the Oligocene and Miocene, which could be due to the presence of relatively more land-based versus marine-based ice. ~~This would mean that the Antarctic ice sheet was less sensitive to polar climate changes than previously assumed.~~

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7 Author contributions

FS, PKB, HB and SS designed the research.~~-~~ JDH, PKB and AJPH carried out Oligocene GDGT analyses. CE and AS incorporated the lithological data. PKB, FP and SS assisted in GDGT analytical procedures and interpretation. JDH wrote the paper with input from all authors.

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