<u>Review 1 comments</u>

This paper presents a new high-resolution diatom based sea surface temperature reconstruction over the past ~14 ka from the modern Permanent Open Ocean Zone between the Antarctic Polar Front and winter sea ice edge in the western Indian Sector of the Southern Ocean. The high-resolution record resolves centennial- to millennial-scale climate variability that enables a detailed comparison to Antarctic ice core records. Complex processes involving reorganization of atmospheric and oceanic circulation, such as CO2 levels, Southern Westerly Winds, and AMOC, have been attributedtothein-phasevariationbetweenthemarineandicecorerecords. Periodicities of 200-260 years were identified in the Mid-Late Holocene interval, they were related to high latitude atmospheric circulation and Southern Ocean convection.

This paper provides a novel sea surface temperature record from an area very limited records are available, especially compared to the Atlantic and Pacific sectors of the Southern Ocean. Thus, the new data from this study augment valuable information to a more comprehensive understanding of environmental changes in the Southern Ocean. However, there are a few aspects that the authors can clarify or improve before publication.

We would like to thank reviewer 1 for the very helpful comments provided, which we feel have improved the manuscript.

1. Study area. This part is too extensive. The text can be more concise and focused on information directly related to this study.

We have removed sections of the study area not relevant to the Conrad Rise so that it is shorter and concise.

2. Methods

(a) Age model: Line 117-122: The authors claim that the reservoir applied in the Atlantic sector of the Southern Ocean derived from comparison between 14C ages and 226Ra-in-barite ages (van Beek et al., 2002) are not reliable "because large variations of~400 years were observed between consecutive depths", and listed studies showing relatively constant reservoir in the Southern Ocean (Hall et al., 2010; Siani et al., 2013). Regarding this statement, I hold different opinion. The 226Ra-inBarite ages are consistent and in good order in van Beek et al. (2002). The resulted large variation in calculated reservoir ages are mostly because 14C ages measured in different labs (Kiel & Aarhus). The 14C ages from Aarhus is systematically ca. 300 years younger than those from Kiel, which lead to 300-400 years variation of reservoir changes in consecutive depth. For this reason, a mean value of ca. 1100+-210 years reservoir was taken for mid-late Holocene, and adopted to other South Atlantic cores (e.g., Xiao et al., 2016). As such, the results in van Beek et al. (2002) do not really conflict with a relatively constant reservoir during the mid-late Holocene in the South Atlantic. Besides, in Hall et al. (2010), the authors propose reservoir ages of 1144+-120 years for the mid-late Holocene in the Ross Sea sector of the Southern Ocean, similar to the results from the South Atlantic. In Siani et al. (2013), their record MD07-3088 is located at ~ 46◦S, much north of the modern Subantarctic Front. We could expect different reservoir effect in

different water masses, such as in cores south of the Polar Front and north of the Subantarctic Front. It is good that the reservoir effect applied in this paper results in a good alignment between the marine and ice core records. However, due to the lack of knowledge of precise reservoir variation through time, slight phase shifts in marine records can be attributed to age uncertainty.

Thank you for alerting us to the issue of different labs in the van Beek et al (2002) paper, we have removed the sentences about these reservoir ages not being reliable. We have also added that the Siani reservoir calculations come from north of the subantarctic front but also acknowledge that it is bathed in water from the Southern Ocean which is deflected north along the South American continent (see our full response to this in reviewer 2 comment L. 115-125). The paragraph as a whole has been rephrased, so that instead of justifying the use of a constant reservoir age, we instead acknowledge that in other SO sectors there is evidence for some changes. We conclude that a lack of evidence for the Indian sector has guided our decision to use a constant estimate of reservoir age and that as a result there is some age uncertainty particularly in the older part of the record. We hope that this provides an open and balanced acknowledgement of the chronological issues effecting records from the SO. Nevertheless, we feel that the good correlation between the SST record and ice core records over the deglacial supports that our chronology is fairly accurate. See lines 105-119.

(b) SST reconstruction Line 132: Do the SSTs reconstructed in this study represent true surface (0 m) temperatures? Because other transfer functions estimate temperatures at 10 m water depth (Esper et al., 2014), which could result in some difference when comparing with other records (e.g., variation amplitude).

This reconstruction represents SST at 10 m depth. As there is very little difference in temperature between 0 m and 10 m depth, in the order of 0.05°C when considering the whole database, this can be considered as representative of the true surface temperature. Previous studies that refer to sea-surface temperatures (SST) when reconstructing paleo-temperatures are also calibrated against 10 m depth (Zielinski et al., 1998; Esper et al., 2014; Xiao et al., 2016; etc…), so this cannot account for differences with other records. We have now specified in section 3.3 that the SST represents the 10 m depth and was calibrated against modern 10 m depth temperatures. See lines 122 and 125.

3. Discussion (a) Line 216: cores located north of the modern APF generally show a late Holocene warming trend. The referenced cores showing late Holocene warming cited here include TN057-17 (Nielsen et al., 2004; Divine et al., 2010) from the Southern Ocean Atlantic sector close to the modern Polar Front, and MD07-3088 off Chilean margin far north of the Subantarctic Front (Siani et al., 2013). However, there are reconstructions adjacent to these two cores do not show such warming. For example, PS1654/ODP1093 close to TN057-17 do not show clear warming during the late Holocene, although the resolution is much lower in PS1654/ODP1093 in the midlate Holocene interval (Xiao et al., 2016). Further north, a mid-late Holocene cooling was inferred from ODP1098 and ODP1090 (Xiao et al., 2016). Alkenone-derived SST records off Chilean margin (including MD07-3088) also suggest a mid-late Holocene cooling which is in contrast to the MD07-3088 SST record derived from foraminifera assemblage using modern analogue

technique (Lamy et al., 2010, Nat. Geosci.; Haddam et al., 2018, QSR). In general, the majority of the available records show a midlate Holocene cooling in the Southern Ocean (e.g., Bostock et al., 2013; Xiao et al., 2016). While the late Holocene SSTs reconstructed in core TN057-17 far exceeding modern temperatures (by~2 ◦C) (Nielsen et al., 2004; Divine et al., 2010) need more explanation.

Lines ~225:

We have removed the Siani et al (2013) reference from here as it is true that it is located north of the SAF and also is in the Pacific sector, and as such may not be expected to share the temperature changes observed in the Atlantic or Indian sectors. We have altered the wording so that it no longer states that temperatures warmed north of the PF and cooled to the south but instead states that there is some regionally heterogeneity (line 235). As suggested we have added that the cores nearby to TN057-17 (PS1654/ODP1093) show little change in the mid-late Holocene but acknowledged that they are very low resolution in this Holocene section of the core (lines 232-235). We have not added a detailed discussion of why temperatures in TN057-17 show warming, as we consider this to be outside of the scope of this paper and this section of the paper is about discussing patterns of temperature change, rather than the causes.

(3b) Line 291-293: Given the timing and synchronicity between CO2 increases and some of the temperature records, it is possible that CO2 caused much of the warming... -> How do you quantify the warming by redistribution of heat between northern and southern hemispheres during the period of AMOC slow-down (bipolar seesaw), and the warming due to CO2 rise? I understand the positive feedback of CO2 increase on warming, but I do not understand how does it reach the conclusion that CO2 is the main driver of Southern Ocean warming just based on the synchronicity of warming and CO2 rise.

It was not our intention to say that CO_2 was the only cause, rather to observe that the relative importance of different contributing factors is still not known and that the similarity between the COR1GC SST and CO_2 changes indicates a possible link. We have rewritten the section (lines 305-314) to now emphasise that we are questioning the relative importance of factors such as CO_2, rather than suggesting that this could be the primary cause. We now state that through positive feedback processes in response to initial warming CO_2 likely contributed to the amplitude of the warming trend.

(3c)In chapter 5.2.2, the authors cited several references showing a weakening of SWW during the early Holocene (Fletcher and Moreno, 2011; Saunders et al., 2018). However, it needs to be mentioned that, the weakening of SWW at this time interval was north of modern Polar Front. A southward shift of the SWW was inferred during this time interval (as suggested by opal accumulation, Anderson et al., 2009; Xiao et al., 2016), which indicate the SWW in regions further south can be stronger. Such interpretation is misleading in terms of eddy transport of heat and atmospheric circulation, which occurred also in the following text. The core latitudinal band of the SWW shifts with the warming/cooling of the Southern Hemisphere.

We have re-written the paragraph from lines 315-325 to now consider the SWW shifts and slightly alter the interpretation. In Lamy et al (2010) the sites at 53°S show the SWW's were stronger in the early Holocene, and therefore at the Conrad Rise at 54°S there were also likely stronger winds as you suggest, despite an overall weakening of the SWW. We now observed that the generally weaker winds more widely likely reduced the northward Ekman transport of cold water from the south resulting in warming (e.g. Hall and Visbeck, 2002; Lovenduski and Gruber, 2005) and warmer air may have more frequently crossed the area due to the meridional circulation. However we also now note that as there were likely stronger winds over the Conrad Rise (Lamy et al., 2010) as you suggest, this potentially increased the heat loss from the ocean to the atmosphere damping the warming.

In the conclusions (at lines 389-391) we have also adjusted it so it now reads: 'It is suggested that the early Holocene warmth may have resulted from spring insolation increasing the heat accumulation in the Southern Ocean during the spring-summer season, or as a result of changes to latitudinal heat transport as the SWW weakened.' This acknowledges both the increased southward heat transport from the meridional atmospheric circulation and also the reduced cold water from Ekman transport.

(3d) Line 310-311: ... the few high resolution SST records from the open ocean do not show a cooling (Figure 7; TN057-13PC4; TN057-17TC)... -> Do you mean a cooling event? Because TN057-13, together with many other South Atlantic cores south of the modern Polar Front, show persistent cooling after ca. 8 ka (Divine et al., 2010; Xiao et al., 2016). In fact, the SiZer analysis of SST (Fig. 5) and cold water species (Fig. 3) show many cooling episodes during the mid-late Holocene, with amplitude similar or even steeper than that around 8 ka. It may reflect millennial-scale climate variability during the mid-late Holocene, rather than linking to a single cooling event in the Northern Hemisphere.

We have corrected the wording to make our meaning more clear, at line 335. We meant a cool event rather than a persistent cooling. As we discuss the late Holocene high SST variability in the following paragraphs we have not added anything about this here.

(3e) The 220-260 yrs periodicity found in the SST record needs more explanation. The authors listed a number of published records around Antarctica with similar cyclicities, that most of them were related to solar activities in their respective publications. The authors then introduced other studies linked such cyclicity to atmospheric circulation such as SAM and ENSO, and rapid climatatic events globally. This part is confusing as it seems related to so many processes and how exactly they work needs better elaboration.

We agree with both reviewer 1 and 2 that this was unclear in the original paragraph. Therefore this has now been rewritten (lines 351 to 374) and we put forward two possible explanations: 1) SST/SAM variability resulting from internal variability and ocean-atmosphere interactions, 2) solar forcing that influenced both the ocean and atmosphere. We have added more explanation of the link between ocean convection, SST and atmospheric circulation as proposed in Latif et al. (2013). We have added additional references to show that there is evidence for the link between solar forcing and the SAM in the modern period. For clarity and to avoid too many possible causes being suggested we have removed the part about ENSO and rapid climate events globally, as these were perhaps the most speculative parts of this paragraph and were not discussed elsewhere in the paper.

Some minor points are as follows: Thank you for these corrections particularly the suggested references

Line 34: For example during ... -> For example, during... Younger Dryas (13.02-11.76 ka BP) -> 12.9-11.7 ka (Rasmussen et al., 2014 Quat. Sci. Rev. 106, 14-28) This has been corrected

Line 35: accumulate in the South Atlantic -> accumulate in the Southern Ocean causing a "bipolar seesaw" characterized by... -> causing a "bipolar seesaw" pattern characterized by.. Corrected

Line 63: during the Holocene there is... -> during the Holocene, there is... Corrected

Line 71-72: extending from the Subantarctic Front in the north... -> extending from the Polar Front in the north... (Diekmann, 2007, Deep-Sea Res. II 54, 2350-2366) Corrected

Line 74: (Park et al., 1998) -> Park et al. (1998) is not a sea ice study. This can be replaced by more recent satellite observations of sea ice extent, such as Parkinson & Cavalieri, 2012, The Cryosphere 6, 871-880. Corrected

Line 101-102: ...in the southwestern Indian sector of the Southern Ocean... -> To make the text more concise, this can be removed as there is an extensive description of the study region in the previous chapter. Corrected

Line 108: Neogloboquadrina pachyderma -> species name should be italic. Corrected

Line 134: Winter sea ice concentration was... -> abbreviation (WSIC) should be noted here Corrected

Line 173: A number of references describing environmental preferences of the species need to be mentioned before referring certain species to, e.g., PFZ species, POOZ species, and sea ice species. References can be cited are Zielinski and Gersonde, 1997, Palaeo 3; Crosta et al., 2005, Palaeo 3; Armand et al., 2005, Palaeo 3; Romero et al., 2005, Palaeo 3; Esper et al., 2010, Palaeo 3.

References have been added (in paragraph from line 182)

Line 234: This record was constrained... -> The MD07-3088 record... Corrected

Line248: warming in the COR1GC and ice core records... -> warming in the COR1GC and Antarctic ice core records... Corrected

Line 262: Hogg et al., 2007 -> Hogg et al., 2008 Corrected

Line 299: Reconstructions support that the SWW were weaker between 11 and 7 ka BP... -> The authors need to mention that the weakening of SWW at this time interval was north of modern Polar Front. A southward shift of the SWW was inferred during this time interval (as suggested by opal accumulation, Anderson et al., 2009; Xiao et al., 2016), which indicate the SWW in regions further south can be stronger. This point has been addressed in major correction 3c

Line 303-304: This is uncertain as modern observations instead show that weaker SWW's cause reduced eddy activity and less poleward heat transport across the ACC, resulting in cooling (Hogg et al., 2007; Screen et al., 2009). ->

Reference error: Hogg et al., 2008 As above, SWW did not weaken at all latitudinal bands. The point about SWW weakening at all latitudes has been addressed in correction 3c above, and the reference error has been corrected.

Line 306-309: The duration and timing of the SST cooling observed in the COR1GC record coincides with an AMOC reduction and North Atlantic cooling associated with the 8.2 event (Ellison et al., 2006) however it has not generally been observed in records from the southern hemisphere (Alley and Ágústsdóttir, 2005). -> Modeling study by Renssen et al. (2010) suggests the upwelling of cooler NADW in the Southern Ocean could result in the drop of surface temperature between 9 and 7 ka. A sentence about this study has now been added to the paragraph (line 330)

Line 315: From the mid to late Holocene the high latitude insolation decreased (Divine et al., 2010) -> Unclear expression. Do you mean southern high latitude? Summer insolation increased during the mid-late Holocene in southern high latitude. Do you mean winter or spring insolation? or annual insolation? Divine et al., 2010 is not the proper reference for insolation, use Laskar et al., 2004 instead. It is now clarified that we meant spring southern high latitude insolation, again suggesting that this caused a change in the length of the summer season (line 340). The Laskar et al 2004 citation has also been added

Line 315-316: causing the SWW's to shift northward -> coherent with the northward shift of the SWW Corrected

Line 317: Divine et al., 2010 -> use Laskar et al., 2004 for insolation reference Corrected

Line 317: causing the SWW's to strengthen (e.g. Saunders et al., 2018) -> as above, need to mention strengthening in areas north of the modern Polar Front. It can be weakening in the south. We have added a sentence at the end of this paragraph to acknowledge that and also included it in our explanation for why productivity and upwelling did not increase here (lines 348-350).

Line 319-320: The strengthened winds may also have increased upwelling and therefore productivity. ->south of the Polar Front, upwelling was reduced during the mid-late Holocene (Anderson et al., 2009). This citation and point has been addressed, along with the previous correction, at lines 348-350.

Line 336: in the atmosphere may... -> in the atmosphere circulation This line was removed when addressing correction 3e

Line 356: spring insolation extending the summer season -> what does it mean? By this we meant that if the spring was warmer then the length of time when the ocean would warm up during the spring and summer period would be extended and the duration of winter cooling reduced. This has previously been suggested by Shevenell et al., 2011 and Etourneau et al., 2013. This is now more fully explained in the discussion at line 315-318. We have reworded the sentence in the conclusion at line 390 to try and make this clearer.

Fig. 2: as the last age control point is at 240.9 cm (13.93 ka BP), why there is a sudden increase in sedimentation at the core base, where no actual age constraint is available? This was a mistake and has been corrected.

Fig. 3: I would suggest to arrange the species from left to right according to their ecological preferences in terms of temperature. For example, F. separanda, F. rhombica and T. gracilis are cold water species, which can be placed next to the sea ice species. Such arrangement will show evolution pattern of the diatom assemblage more clearly, which reflect environment changes. We feel that the graph as it is best shows the temperature preferences of the species, which are already ordered from left to right in order of water mass, going from cooler POOZ > PF> SA species. We agree however that the sea ice species should be closer to the cold water species for easy comparison, so have moved this to the left of the graph.

Fig. 8: the opal flux record in panel (d) seems incomplete? There are breaks in the curve. This has been corrected.

<u>Reviewer 2</u>

The sequence of warmings and coolings associated with the last deglaciation and the Holocene has shown contrasting patterns between southern and northern high latitudes. Global-scale processes such as variations of AMOC strength and the alteration of atmospheric circulation seem responsible for this contrast. Most of the high resolution paleorecords studied so far were gained from Antarctic ice cores. Therefore, acquiring high-resolution proxy records of past sea surface temperature is relevant for finding out how spatio-temporal patterns of water temperature evolved in the Southern Ocean and whether any links with Antarctic temperature variability are recognized. Orme and co-authors present a high-resolution, diatom-based record of sea-surface temperature gained in the western Indian sector of the Southern Ocean (Core KH-107 COR1GC, ca. 54.27°S, 39.77°E, WD 2834 m). Their sediment record spans the past 14.2 Ka BP. The age model bases on fifteen AMS radiocarbon dates obtained on mono-specific samples of the planktic foraminifera Neogloboquadrina pachyderma sin. The average temporal resolution of their diatom counts is ca. 60 years (diatom analysis was conducted every cm in the 2.48 m gravity core). By using the Modern Analogue Technique applied to diatom assemblages, Orme and colleagues estimate the summer SST and the winter sea ice concentration. They describe and discuss patterns, timing and magnitude of sea-surface temperature variability through the late deglaciation and the Holocene in the western Indian sector of the Southern Ocean and possible links to global and regional forcings and mechanisms. The Introduction presents basic information on (1) deglacial events and Holocene intervals, and (2) main mechanisms/forcings behind temperature in the Southern Ocean; it reads well and helps the reader less familiar with issues addressed later in the MS. The Methodology is clearly written. Results are concisely presented; the results representation however can improve (see suggestions below). Figures are self-explanatory and necessary in number. References are satisfactory.

A major concern is how the Discussion is organized. Throughout the Discussion, there are several inconsistencies and several vague statements that lack scientific support. Some ideas are shortly presented, without any further and deeper discussion. Too many forcings and mechanisms are offered as possible explanations for the SST variations (solar forcing, internal climate variability, sea-ice and productivity changes, ocean-atmosphere coupling, rapid climate

change events globally, establishment of modem ENSO amplitude and frequency), without clearly distinguishing which mechanism/forcing/s was/were more important when, and the reader gets lost. Please consider: (1) shortening and focusing the discussion, and (2) adding a Table summarizing with main mechanism/forcing/s for each for each of the discussed intervals.

We would like to thank reviewer 2 for the very helpful comments provided, which we feel have improved the manuscript.

In the discussion, particularly the first two paragraphs of section 5.2.1., the text has been shortened to make the discussion more focused. See lines 270 to 290.

In line with a similar comment from reviewer 1 (number 3e) and the comment here labelled L326-340 the paragraph about cycles/variability at the end of the discussion (lines 351-374) has been reorganized and re-written. We start by presenting the evidence for 200-300 year cycles in both Southern Ocean records and those reflecting westerly winds/SAM and then use this as a basis for stating two hypotheses 1) that there was shared internal variability and ocean-atmosphere coupling or 2) a shared external forcing (solar). In support for the first point we describe the model findings of Latif et al (2013) about centennial internal variability in the Southern Ocean and atmospheric circulation triggered by changes in deepwater formation. We have added more detail about this. In support of the second point, that solar forcing may have caused the changes, we have linked to modern evidence for the effect of solar activity on the SAM during the instrumental period. We have removed the parts of the discussion about ENSO and rapid climate events which were more speculative, and instead focused on the two causes we consider most likely.

As suggested we have now added a table to summarise the main causes suggested for the Younger Dryas, millennial changes and mid-late Holocene variability (lines 730, table 2) and referred to this in the text (line 268)

Below I list several minor comments and give some suggestions which might be helpful to improve your MSL.

66-67: this is repeated several times throughout the Intro. Please revise. This sentence has been shortened and merged with the previous sentence to reduce the repetition (lines 66-68).

L. 93-94: since the authors state that 'Topography has a strong influence on the position and form of the ACC in this region', they should provide a more detailed figure of the study area in Fig. 1, including bathymetric information.

We have now included in figure 1 a bathymetric map of the Conrad Rise adapted from Ansorge et al (2008) including the current strength (shown by absolute geostrophic velocity).

L: 108: Neogloboquadrina pachyderma should be in italics. Corrected.

L. 115-125: Using reservoir age from a core gained in a mid-latitude coastal upwelling system is -at the least-risky and caution is advised. Oceanographical and nutrient conditions in the SE Pacific Ocean are quite different from those in the Conrad Rise and can hardly be straightforwardly applied. The high-resolution sampling (every cm) make the age model uncertainties even larger. Additionally, reworking should be considered/discussed.

The paragraph as a whole has been rephrased to explain the different evidence for reservoir changes in different locations (lines 105-119), which justifies our decision for choosing to use a consistent reservoir age through the record. We hope that this balanced assessment of the limited available evidence shows the reader that there are age uncertainties associated with the selection of reservoir ages.

We have included the evidence of reservoir ages from the Siani et al (2013) study mentioned here in this paragraph for couple of reasons. The first is that this site carries a Southern Ocean signal, as it is bathed in waters from the Southern Ocean that are deflected northward by the South American continent, and is outside of the Peruvian upwelling system, with little evidence for local upwelling (e.g. low primary productivity; Abrantes et al., 2007). The second reason is that this is the only core to have reservoir age estimates for both the last deglacial and the Holocene. Therefore while we did not base our chosen reservoir ages on this study, we feel that the consideration of different evidence from the Southern Ocean does help show the reader the current limited and challenging nature of reservoir age estimates. Though there might be some discrepancies in reservoir age changes through time between basins, the good correspondence between COR1GC SST and ice core records (figure 7) suggests that the corrections made in the present study are adequate.

L. 145-46: these three processes strongly impact your diatom signal (the basis of your SST reconstructions), but it is hardly discussed in 5. Discussion.

This answer also covers the correction for line 241-243 below.

Many studies have shown that diatom sedimentary signals, though imperfect, preserve the main features of diatom productivity/assemblages in surface water (Zielinski and Gersonde, 1998; Gersonde and Zielinski, 2000; Armand et al., 2005; Crosta et al., 2005; Romero et al., 2005). As such, diatoms have been robustly used to quantitatively infer past surface conditions through several statistical techniques (Gersonde and Zielinski, 2000; Crosta et al., 2004, 2020; Nielsen et al., 2004; Esper et al., 2014; Esper and Gersonde, 2014; Ferry et al., 2015; Benz et al., 2016; Xiao et al., 2016), generally in agreement with other techniques based on other micro-fossils or geochemical proxies (Becquey et al., 2002,2003; Panhke et al., 2005; Ho et al., 2016).

We have added a paragraph to the methods section 3.3 about the dissolution of diatoms (lines 135-146). We feel that this fits better at this point in the paper rather than in the discussion. We observe that the dissolution of poorly silicified diatoms, often those from cold waters, could result in reconstructed warmer temperatures and less sea ice (Xiao et al 2016). However we note also that temperature is the dominant factor effecting species assemblages, and that diatom dissolution is at a minima at 50-55°S (Pichon et al., 1992; Esper et al., 2010). This means that while dissolution may have altered the assemblages to some degree, the effect on the reconstructed temperature should not be strong particularly at the latitude of the Conrad Rise. During analysis we observed good preservation through the core, with (1) well preserved diatom valves in which the fine ornamentation was still visible, (2) diverse diatom assemblages containing diatoms along the whole size spectrum and (3) little fragmentation. Finally, the good general agreement of the new SST record with previous records from similar realms and with the ice core temperature records, gives confidence in that the assemblages in COR1GC are reflecting climate and that our diatom-based reconstruction are therefore robust.

L. 172: please give age ranges for the Holocene (which age definition of Holocene did you follow?) I suggest adding a box in the upper part of Fig 4, indicating the main intervals of the last deglaciation (YD, ACR, etc.) and Holocene (early/middle/late). This is presented later in Fig 7, but it should be earlier when Results are described.

We have included reference to the formal defined boundaries of the early Holocene of 11.7-8.2 ka BP (Walker et al., 2018) in the introduction at line 51. We do not separate between the mid and late Holocene in the discussion and results, therefore the age boundaries of these have not been specified or separated in the figures.

We have added the lines and labels to figure 4 as suggested, and also added the time periods to figure 3.

L. 173-183: References for the paleoecological information of the diatom species should be provided here. The reader does not know where the species ecology does come from

This has been corrected (line 182-195)

L. 184: 'The estimated total diatom abundance shows a decreasing trend through the record', please revise this statement. It is not quite correct to state that the total diatom abundance (TDA) shows an overall decreasing between last deglaciation and the latest Holocene. Indeed, TDA varies strongly up to 5.5 Ka BP and experienced afterward a two-step decrease, first around 5.5 Ka BP and later between 4 and 1 ka BP.

We decided to change this to the diatom flux rather than the diatom abundance. Diatom flux is a closer proxy for productivity and upwelling than diatom abundance because it accounts for changes in sedimentation rate and sediment density. We used the approach of Romero et al. (2015). We had the required data on diatom abundance and sedimentation rate for COR1GC however not the density data for this core. We therefore used the density data for COR1bPC, which was taken from the same location during the same cruise. As both cores have good chronological constraints (COR1bPC has 13 radiocarbon dates for the last 14.2 ka BP) it was possible to transfer the density values from COR1bPC to COR1GC by identifying the depths that were closest in age. The largest age difference between samples that were transferred was 20-30 years.

The results now show a decrease in diatom fluxes at 14.2-12 ka BP, low fluxes from 12-10.3 ka BP, higher fluxes between 10.3 and 5.2 ka BP and lower fluxes after 5.2 ka BP.

We have altered the methods (lines 147-154), results (lines 195-198) and discussion at lines 294 and 347 (see also our response to corrections below).

L. 190-198: all short intervals mentioned here should be easily recognizable in Fig 4. Please add some arrows to help the reader to better understand what you are trying to communicate. Moreover, add marks between millennial ages in

Fig 4: your Results description goes into centennial-scale description (e.g., Between 11.6 and 8.7 ka BBT, etc). Without these centennial-scale marks is even more difficult to recognize whichever trends and shifts occurred.

We have added tick points every 200 years to Figure 4 so the reader can assess the centennial timings as suggested. We have added arrows to highlight the two significant centennial events at c.8.2 and c.2.2 ka BP as identified by SiZer and explained in this paragraph. We have also added a line to show the increasing trend during the Younger Dryas. These changes are in addition to the alterations made for the comment below labelled Figure 4.

L. 210: 'high temperatures between 11.6 and 8.7 ka BP during the Early Holocene, followed by a cooling trend thereafter': this is a matter of interpretation. The range of SST variability is larger (larger amplitude) between 8 and 1 ka BP than earlier between 8.2 and 11.8 ka BP. However, is it correct to state that a cooling occurred during the middle to late Holocene? I am not able to recognize a clear decreasing trend in your data depicted in Fig. 7d.

This sentence is referring to the findings in other records rather than the COR1GC record, although we are stating that these other records show similar findings to the COR1GC record. There is evidence for a slight cooling trend in that the mean decreases from 4.3-3.9°C between the early to mid-late Holocene, there were lower minimum temperatures and reconstructed sea ice increased in the mid-late Holocene but was absent in the early Holocene. However this cooling is shown by the SiZer analysis to not be statistically significant.

We have added to the results the word 'slight' in places to show the cooling wasn't large (between lines 202-205) and added a sentence to state that the cooling is not significant in the SiZer analysis section of the results (line 208). In the discussion section 5.1 we have added a sentence to acknowledge that unlike some other records the COR1GC cooling in the Holocene was slight (lines 230) but acknowledge here that there were cool events (low SST excursions, sea ice species). We have also adjusted the wording in the discussion (line 348) and conclusion (lines 379) to acknowledge that the reconstructed temperature difference is minimal.

L. 215: 'Although most records, including COR1GC, show a long-term cooling over the Holocene (Xiao et al., 2016)'. Please revise: the PS2606-6 SST record shows similar values during YD and the entire Holocene. SO, where is the Holocene cooling?

This sentence is about the Holocene, not the temperature difference between the YD and late Holocene. During the Holocene the PS2606-6 record is showing a cooling, whereby temperatures at c.12-9 ka BP in this record were warmer than the period after 9 ka BP (Xiao et al., 2016). This is in support of other records which generally also show cooling (e.g. Bianchi and Gersonde, 2004; Anderson et al., 2009).

This PS2606-6 record shows an abrupt change at 9 ka BP, rather than a gradual cooling, therefore to acknowledge that there is a difference between the gradual cooling shown in some records and the rapid cooling in others, we have added:

'Furthermore, while most records show cooling over the Holocene, either gradually or as an abrupt cooling at the end of the early Holocene (Xiao et al., 2016), there are some differences between records' at line 228.

L. 218: 'The records from Bouvet Islands', where is this? Which sector of the SO? Please provide more accurate information.

We have added 'in the eastern Atlantic sector of the Southern Ocean' after this statement at line 237.

L. 222-23: 'Our new record from core COR1GC conversely shows SSTs were 1◦C lower during the ACR compared to the mid-late Holocene', Is this 1◦C difference statistically significant? 1◦C of SST difference lays surely within the range of variability of your SST reconstruction.

Given that the temperature difference between the ACR and late Holocene is close to being significant (given the RMSEP of 1°C) and there is a good similarity between the magnitude and patterns of temperature change between the COR1GC SST and ice core records, we feel confident that the cooler temperatures during the ACR are real.

However we have added a sentence to acknowledge that transfer function prediction error is a possible cause of the differences between records (such as other records showing no difference in temperature between the ACR and mid-late Holocene), as this is a factor potentially effecting other transfer function based records as well. Lines 243-245:

'The contrasting findings between SST reconstructions may be explained by the reconstructed temperatures being close to the prediction error of SST transfer functions, which is ~1°C in this study and 0.86°C in Xiao et al. (2016).'

L. 233: can a 2-3◦C rise of SST during the Holocene -compared to last deglaciation- as WARM conditions? I understand that it was warmer, but it is not a warm environment per se, mainly when your SST reconstructions is compared with records from mid and low latitudes.

We did not mean to imply that conditions were warm, rather that they were warmer compared to the rest of the record. We have changed the wording from 'relatively warm conditions through the Holocene' to 'leading to slightly warmer conditions through the Holocene' (line 257)and also later in the section referred to the 'marginally warmer early Holocene' (line 260). In the conclusions we have also adjusted the sentence at line 378 to clarify that these temperature changes were slight.

L. 241-43: I agree with these mechanisms and forcings impacting the reconstructed SST record at your core site. However, since diatoms experience dissolution between sea surface and the bottom of the ocean, I can assume that your reconstructed SST values vary depending on which species did it to the sediment. There is, however, no discussion on the possible role of preferential dissolution/preservation of diatoms (see also l. 145-46).

Please see our response for point L145-146 which addresses this. The discussion of this has been incorporated into the methods section rather than here (line 135-146). We consider that the oceanographic conditions at the site have not changed enough through time to alter the amount of diatom dissolution and therefore the SST signal.

L. 245: 'Southern high latitude warming (Termination 1b) during the Younger Dryas', this is given as one unique interval before (see l. 209-10). Please revise and rephrase correspondingly.

It is not clear what is meant here, but for clarity we have removed the term 'termination 1b' and instead used the Younger Dryas throughout the paper.

L.266-67: 'Greater upwelling has been shown by higher opal deposition to the south of the Polar Front in the Southern Ocean (Atlantic, Indian and Pacific sectors) through the period 12.7- 11.5 ka BP', this is true. However, your TDA data do not show any significant difference among ACR, YD, and early Holocene. Therefore, your data offer no convincing evidence of an intensification of upwelling following the last deglaciation.

This paragraph (now lines 277-290) is about the explaining the identified sequence of events and evidence for this based on previous studies, rather than linking with our evidence which comes in the following paragraph. Therefore we have not changed this statement but have adjusted the part where we discuss our results (see next comment).

L.275-76: 'as tentatively inferred from the slightly increased diatom abundances at 12.7-12 ka BP'. This is hardly recognizable in your COR1GC record. Your TDA does not actually differ from earlier and later values. Please revise.

We have changed the diatom abundance to diatom fluxes, as explained above in response to the correction L184. The new diatom flux record however also doesn't support that there was higher diatom productivity or upwelling at this time, as the values decrease from 14.2 to 12 ka BP. Therefore we have altered this sentence to read: 'However there is no evidence of increased productivity and therefore upwelling at the Conrad Rise, as diatom fluxes instead decreased through this period (Figure 8E)' (lines 294-295)

L. 283-84: 'Indeed a southward shift is indicated by an increase in Polar Front species at c. 12 ka BP', you mean Thalassionema nitzschioides var. nitzschioides? The increase is not that clear in F. kerguelensis.

Yes this was in reference to the increase in *Thalassionema nitzschioides* var. *lanceolata.* We have specified this now at line 302

L. 296: 'has been attributed to high annual, winter and spring insolation levels', please clarify: do you mean average annual insolation or winter and spring insolation?

We have changed this to spring insolation and now cite the papers Shevenell et al. (2011) and Etourneau et al (2013) who also concluded that spring insolation caused early Holocene warming due to a longer summer season. Lines 315-318.

L. 315: SSW's, misspelling. See also below l. 317.

This has been corrected

L. 316: 'together can explain the gradual cooling in the COR1GC record', please provide SST range, average and 1 STD for your mid and late Holocene SST record.

We have now ensured that the mean, standard deviation and range is now provided for the three key periods (ACR, early Holocene and mid-late Holocene) in the results section, lines ~200. These show that the mean decreased from 4.3 to 3.9 °C and there were more frequent low temperature excursions in the mid-late Holocene, with the minima changing from 3.3 to 2.2°.

We have adjusted the wording as follows at line 342:

'which together can explain the <u>slight</u> cooling in the COR1GC record, <u>the increased frequency of cold events and increase in sea ice</u>'

Which we feel provides the reader with clarity about the evidence for the mid-late Holocene cooling in this record.

L. 320: 'however it is not clear if this occurred as although there was a gradual increase in sedimentation rate, potentially reflecting an increased deposition of diatoms'. Be cautious with this: according to your data, no increase in total diatom abundance occurred at this time.

We have re-written this sentence to show that the evidence of a decreasing diatom flux does not support increasing productivity, and removed the sentence about the sedimentation rate increasing, which has a less direct link with productivity. At the recommendation of reviewer 1 we have also added a sentence about the reason for this decrease. (lines 346-350)

L. 326-340: this is a quite different story from all the above discussion and confuses the reader. Several forcings are mentioned/shortly discussed in 14 lines (solar forcing, internal climate variability, sea-ice and productivity changes, ocean-atmosphere coupling, rapid climate change events globally, establishment of modem ENSO amplitude and frequency). Presenting an alternative climate scenario at the very end of the manuscript (rapid climate change events globally and establishment of modem ENSO amplitude and frequency), without any further discussion makes this subsection even more confusing and does not add anything valuable to your overall Discussion.

This point was shared by reviewer 1 and to address it we have re-written this final paragraph. Please see our response to reviewer 1 and the above comment at the start of this response.

Figures

Fig 1: please consider (1) zooming into the closest area to core COR1GC (include bathymetry), and (2) identifying the Atlantic, Indian and Pacific sectors of the Southern Ocean. In the caption the references for cores TN057-13-PC4, TN057-17PC1, MD07-3088, EDML, and EDC should be presented.

We have now included in figure 1 a bathymetric map of the Conrad Rise adapted from Ansorge et al (2008) including the current strength (shown by absolute geostrophic velocity). We have added labels for the Atlantic, Indian and Pacific sectors to panel (a) and referenced each of these records as recommended.

Fig. 3: note that you name core COR1GC differently depending on the figures. Please revise. var. in Thalassionema nitzschioides var. nitzschioides should not be italics. Thalassiosira oestrupii has been renamed for years already, the current name is Shionodiscus oestrupii. Consider using exponential nomenclature for x-axis of TDA. Consider adding some arrows to lead the reader in better understanding major shifts/changes in (1) the species composition of the diatom assemblage, and (2) total diatom abundance.

We have changed all the figure captions so they are COR1GC rather than KH-10-7 COR1GC. We have changed Thalassiosira oestrupii to Shionodiscus oestrupii, both here and in the manuscript. We have corrected the labelling so var. is not in italics. We have added arrows to show the major trends in the diatom species abundances and the diatom flux data. The axis label is now in exponential nomenclature.

Fig. 4: Please consider adding a box in the upper panel indicating YD, early/mid/late Holocene, etc. (see Fig 7) Consider also adding the (1) average and 1STD of your own data, and (2) present-day summer and winter SSTs., and (3) present-day mean winter sea ice concentration.

We have added and separated the sections in the COR1GC record as advised and highlighted the modern summer SST and sea ice concentration. As diatom records reflect summer SST rather than winter SST, we have not included the winter SST as this would have no relevance to the record presented. We also decided not to present the average and standard deviation on the plot, as it was our view that this could make the graph look crowded. The average and standard deviation for the different sections are included in section 4 as advised previously.

Fig. 7: the long-term pattern of your SST data is pretty similar to that of East Antarctica cores: low ACR values, increase during the YD, and warmer Holocene SST. A simple statistical analysis should help you to better understand the trends. Your SST record shows ten SST minima (cooling) during the Holocene: it seems to me that most of these minima are made by only ONE sample. This can be part of regular variability of the diatom assemblage and not at all related with actual SST variations. Caution is advised in the interpretation of these minima!

The SiZer analysis already represents a step forward to statistically understand the significance of the short-term variability. We feel that additional statistical tests, like providing a correlation matrix, is hampered by the age uncertainty and low resolution of many records. In this vein, a direct correlation test between COR1GC SST record and ice core records, though possible, will imply important resampling and standardization steps that may alter the results and may not bring many new information. However to show more clearly the similar timing of changes between the COR1GC SST record and those from ice cores, we have added a supplementary information file including the COR1GC SST record and EDML temperature (δ18O) and sea ice extent (ssNa) records. These have been normalised and smoothed using SiZer (using the local linear kernel estimator) and a bandwidth of 400 years. The results highlight the close association between the SST, atmospheric temperatures and sea ice extent in the region. The Supplementary Information has been referred to in the paper at lines 251 and 293.

Although some of the minima are single data points they represent temperature excursions of 1-2°C which is above the prediction error for the record. Despite the same methods, material and location, the early Holocene does not have these large oscillations in temperature, supporting that the occurrence of these minima in the mid-late Holocene reflect real climate changes rather than just diatom assemblage variability, which would be present through the whole period. We discuss the most persistent cold excursion at 8.2 ka BP but not any of the later minima specifically, other than in relation to the increasing variability, so feel that these are not over interpreted in the manuscript. As such we have not altered the text.

Main corrections

- **Study area section shortened**
- **Section added about diatom dissolution to methods**
- **Diatom flux used rather than total diatom abundance**
- **Edit/re-write of age model methods section**
- **New supplementary information added (comparison with ice core proxies)**
- **Various small edits to discussion**
- **Rewrite of paragraph about variability in the Holocene**
- **Arrows added to some figures**
- **New table added summarising the findings**

Sea surface temperature in the Indian sector of the Southern Ocean over the Late Glacial and Holocene

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Abstract. Centennial and millennial scale variability of Southern Ocean temperature over the Holocene is poorly known, due to both short instrumental records and sparsely distributed high-resolution temperature reconstructions, with evidence for past temperature variations in the region~~bility instead~~ coming mainly from ice core records. Here we present a high-resolution (~60 year), diatom-based sea-surface temperature (SST) reconstruction from the western Indian sector of the Southern Ocean that spans the interval 14.2 to 1.0 ka BP (calibrated kiloyears before present). During the late deglaciation, the new SST record shows cool temperatures at 14.2-12.9 ka BP and gradual warming between 12.9-11.6 ka BP in phase with atmospheric temperature evolution. This supports that the ~~temperature~~ evolution of the Southern Ocean SST during the deglaciation was linked with a complex combination of processes and drivers associated with reorganisations of atmospheric and oceanic circulation patterns. Specifically, we suggest that Southern Ocean surface warming coincided, within the dating uncertainties, with the reconstructed slowdown of the Atlantic Meridional Overturning Circulation (AMOC), rising atmospheric CO_2 levels, changes in the southern westerly winds and enhanced upwelling. During the Holocene the record shows warm and stable temperatures from 11.6-8.7 ka BP followed by a slight cooling and greater variability from 8.7 to 1 ka BP, with a quasi-periodic variability of 200-260 years ~~as~~ identified by spectral analysis. We suggest that the increased variability during the mid- to late Holocene ~~may~~ reflects the establishment of centennial variability in SST connected with changes in the high latitude atmospheric circulation and Southern Ocean convection.~~, as identified in models.~~

1 Introduction

Research into the sequence of events associated with the deglacial period has highlighted that there were contrasting patterns of millennial-scale warming and cooling between the southern and northern high latitudes, considered to have resulted from global-scale processes, namely fluctuations in the strength of the AMOC and latitudinal shifts in the major atmospheric circulation cells. For example, during the Younger Dryas (12.9-11.7 ka BP; Rasmussen et al., 2014) a prolonged weakening of the AMOC reduced the northward heat transport in the Atlantic allowing heat to accumulate in the Southern Ocean~~h Atlantic,~~ causing a "bipolar seesaw" characterised by opposite ocean temperature anomalies between the two hemispheres (Denton et al., 2010 and references therein). These temperature changes caused a rapid alteration of the atmospheric circulation, with a southward shift of the Intertropical Convergence Zone (ITCZ) and Southern Westerly Winds (SWW). A combination of processes including enhanced eddy transport of heat across the Antarctic Circumpolar Current (ACC), upwelling of warm water and dissipation of sea ice then resulted in warming of the Southern Ocean and Antarctica (Levermann et al., 2007; Screen et al., 2009; Denton et al., 2010). Finally, the increased upwelling in the Southern Ocean enhanced CO_2 outgassing and thus warming globally. Despite many of these processes occurring within the Southern Ocean the strongest evidence for the patterns and magnitude of southern high latitude warming during the Younger Dryas mainly comes from Antarctic ice cores (e.g. Stenni et al., 2011). Although a number of records from the Southern Ocean show warming during the Younger Dryas, the timing, magnitude and duration of warming are far from consistent between records (Bianchi and Gersonde, 2004; Divine et al., 2010; Siani et al., 2013; Xiao et al., 2016). In the same vein, the cooler Antarctic Cold Reversal (ACR, 14.7-12.7 ka BP; Stenni et al., 2011), preceding the Younger Dryas, similarly displays a strong regional heterogeneity that is not fully understood (Pedro et al., 2015). Acquiring high-resolution proxy records of past sea surface temperature (SST) is therefore important for establishing the spatio-temporal patterns of warming in the Southern Ocean and their link with Antarctic temperature variability.

During the Holocene the majority of records from the open ocean of the Atlantic and Indian sectors of the Southern Ocean show that the early Holocene, defined as the period ~~(~~11.7-8.2 ka BP (Walker et al., 2018~~~12 to 9 ka BP~~), was warmer than the subsequent ~~the~~ mid to late Holocene (e.g. Bianchi and Gersonde, 2004; Nielsen et al., 2004; Anderson et al., 2009; Divine et al., 2010; Xiao et al., 2016). The suggested causes of the~~se~~ temperature ~~changes~~ evolution~~s~~ during the Holocene include variations in southern hemisphere insolation (e.g. Shevenell et al., 2011; Xiao et al., 2016), in the interplay of southern and northern hemisphere insolation (e.g. Nielsen et al., 2004) and in the weakening of the AMOC in response to northern hemisphere deglaciation (Renssen et al., 2010).

There is also evidence of centennial variability of southern high latitude climate through the Holocene as shown by some palaeoclimate records, including those from the Southern Ocean (e.g. Leventer et al., 1996; Crosta et al., 2007; Katsuki et al., 2012) and those reflecting atmospheric circulation changes such as the Southern Annular Mode (SAM) (e.g. Moreno et al., 2014; Turney et al., 2016). Observational and modelling evidence have suggested that centennial fluctuations in deep convection in the Southern Ocean (Weddell Sea) lead to variability in the surface water temperature of the Southern Ocean and the strength of the atmospheric circulation (Latif et al., 2013). Others have linked the oscillations to AMOC variability (Debret et al., 2009) or solar activity (e.g. Leventer et al., 1996; Crosta et al., 2007; Turney et al., 2016). To understand further how the Southern Ocean temperature has varied during the Holocene, there is a need for high-resolution records capturing ~~multicentennial to~~ centennial to multi-centennial scale variations.

We here present a new diatom-based SST reconstruction from the western Indian sector of the Southern Ocean spanning the last 14.2 thousand years with an average temporal resolution of 60 years, to show~~. The length and high resolution of the record provides new information about~~ the patterns, timing and magnitude of temperature variability through the late deglaciation and the Holocene.

2 Study Area

The Conrad Rise is located in the west Indian sector of the Southern Ocean (around 54 °S, 40°E, Figure 1) close to the Atlantic Sector. The rise is <3000 m depth, with two sea mounts (Ob Bank and Lena Seamount) at depths of 300 m (Ansorge et al., 2008). The Conrad Rise is situated within the diatom ooze belt, which circles Antarctica, extending from the Polar Front in the north to the late winter/spring sea ice extent in the south (Diekmann, 2007).

Today the site is located within the Permanent Open Ocean Zone (POOZ), with the mean winter sea ice limit lying to the south at 59°S (Park et al., 1998; Parkinson and Cavalieri, 2012). The mean summer SST at 10 m depth is 3.5°C (Locarnini et al., 2013), while s~~. S~~ummer measurements show that at the Conrad Rise the surface mixed layer extends to 70-80 m depth with temperatures of 2-2.5 °C and salinity of 33.90 – 33.95 psu (Park et al., 1998; Anilkumar et al., 2006). ~~Beneath persists the Winter Water layer, a remnant of the previous winters mixed layer capped by seasonal warm, fresh water, which at the Conrad Rise is estimated to have minimum temperatures (0.5 – 1.5 °C) at 150-200 m and salinity of 34.05-34.1 psu (Park et al., 1998).~~ The surface oceanographic characteristics are likely influenced by the atmospheric climate and circulation. The core of the SWW has been situated north of the Conrad Rise at approximately 52 °S during the period 1979-2010 AD (Swart and Fyfe, 2012). Across the Southern Ocean positive SAM anomalies cause stronger, southward shifted westerlies, and this also alters SST, causing cooling in the Antarctic Zone due to stronger Ekman transport of cold Antarctic surface water to the north (Lovenduski and Gruber, 2005).

The Conrad Rise is situated within the Antarctic Circumpolar Current (ACC) and close to ~~, which consists of several fronts. To the north of the Conrad Rise is a merged front (combined Agulhas Return Front, Southern Subtropical Front and northern Subantarctic Front) at 40-43°S, which has a steep surface temperature range of 10 to 19 °C (Anilkumar et al., 2006) while the southern Subantarctic Front (SAF) lies at approximately 45°S (Sokolov and Rintoul, 2009). T~~the Polar Front, which is defined by the maximum northern extent of the 2°C isotherm between 100-300 m. Some modelling and observations support that two branches of the Polar Front flow to the north and south of the Conrad Rise, transporting 35 and 25 Sv of water, respectively, with low flow velocities over the rise itself (Figure 1b; Pollard and Read, 2001; Ansorge et al., 2008; Sokolov and Rintoul, 2009). However, assessments of the Polar Front position based on identification of a subsurface temperature minima indicate that it is in fact situated to the north, passing between the Conrad Rise and Crozet Islands at approximately 50°S ~~where it varies by season and year over a range <2° latitude~~ (Pauthenet et al., 2018). Topography has a strong influence on the position and form of the ACC in this region. ~~To the west of the Conrad Rise across the Enderby Basin the lack of~~

~~topographic constraint means that large meanders in the ACC are likely (Pollard and Read, 2001) and variations in the Polar Front position also occur over the flat region to the east of the Conrad Rise (Pauthenet et al., 2018). However, a~~At the Conrad Rise, branches of the Polar Front become topographically trapped and therefore have low spatial variability through time (Pollard and Read, 2001; Pauthenet et al., 2018).

3 Materials and methods

3.1 Core sampling and sediment description

The 2.48 m long core KH-10-7 COR1GC was retrieved from the Conrad Rise (54.2673°S, 39.7663°E, Fig. 1, water depth of 2834 m) using a gravity corer during the expedition KH-10-7 on board the R/V *Hakuho-Maru* in 2010.

The sediment consisted of homogenous diatom ooze; from 2.48 to 2.2 m the sediment colour was greenish-grey, while above this the sediment had a pale yellow colour. At approximately 5 cm depth there was a dark grey horizon.

3.2 Age model

Fifteen AMS radiocarbon dates were obtained on mono-specific samples of the planktic foraminifera *Neogloboquadrina pachyderma* sinistral. The core chronology was constructed in Bacon version 2.3.3~~.~~ (Blaauw and Christen, 2011), an age-depth modelling technique that uses Bayesian statistics to reconstruct accumulation histories for deposits, by combining radiocarbon and other dates with prior information. This analysis used the Marine13 calibration dataset (Reimer et al., 2013). The shape of sedimentation rate and memory strength parameters used in the Bacon modelling were set to 1.5 and 4, respectively.

To correct the raw radiocarbon ages we used a constant reservoir age of 890 ± 100 years recommended for this region (http://radiocarbon.LDEO.columbia.edu/) (Butzin et al., 2005). However, we acknowledge the possibility that the reservoir age may have varied through time, particularly during the deglaciation when ventilation of deep waters occurred. In the Atlantic sector of the Southern Ocean, the comparison of radiocarbon ages and ^{226}Ra decay in barite suggests ~~large variations~~ a change in regional reservoir ages ~~during the~~ between the early and mid to late Holocene of ~800 years (van Beek et al., 2002). ~~However, because large variations of ~400 years were observed between consecutive depths, we believe that this method is not reliable. Therefore age reservoir variation during the past 14 ka are unknown for this sector. Fortunately~~ In the Pacific sector, Holocene reservoir ages have been estimated in the Ross Sea through a comparison of ^{14}C and U-Th dating of corals, which showed limited changes in reservoir age during the last 6 ka BP (Hall et al., 2010). I~~I~~n the east Pacific sector (core MD07-3088, Figure 1), a comparison between radiocarbon and tephra dating of marine sediments suggests that at 14 ka BP and 11.5 ka BP the reservoir age was 975-920 years, while in the mid-late Holocene it was 800 years (Siani et al., 2013), indicating a change of just 100-175 years ~~over our study period~~. ~~Assuming that the magnitude of changes in reservoir ages were comparable across the Southern Ocean this supports a maximum change in reservoir age of 100 to 200 years through the~~

~~late deglacial to Holocene transition. Because there were seemingly limited variations in the mean reservoir age over the last 14 ka, and we are not assessing leads and lags between records~~While this study was located north of the Subantarctic Front in a different oceanographic setting to the Conrad Rise, the MD07-3088 study site is bathed in waters originating from the Southern Ocean that are deflected north along the coast of South America, supporting that changes here reflect Southern Ocean reservoir age variability. Given ~~the contrasting evidence between~~ the information delivered by ~~different~~these remote studies and ~~a~~the lack of evidence from the Indian sector of the Southern Ocean, we believe it is more sensible to apply a constant reservoir age correction, ~~, e~~but acknowledge that there is greater age uncertainty in the late deglacial section of the COR1GC reconstruction.

3.3 Diatom analysis

Diatom analysis was conducted at ~1 cm intervals. Slide preparation and counting of over 300 diatom valves per sample followed standard methods (Crosta and Koç, 2007). Summer SST (at 10 m depth) and winter ~~sea~~ sea-ice concentration (WSIC) were estimated using the Modern Analogue Technique (MAT) applied to diatom assemblages (Crosta et al., 2020~~2004~~). This method uses a modern database composed of 249 surface sediment samples. Modern summer (January-February-March) SSTs from 10 m depth were interpolated on a 1°~~*1°~~ grid from the World Ocean Atlas 2013 (Locarnini et al., 2013) using Ocean Data View (Schlitzer, 2014). Winter sea ice concentration (WSIC), represented by the month of September when sea ice is at its maximum extent around Antarctica (Parkinson, 2019), was interpolated on a 1°~~°*1°~~ grid from the numerical atlas of Schweitzer (1995). The MAT was implemented from the "bioindic" package (Guiot and de Vernal, 2011) built on the R-platform (http://cran.r-project.org/) and used the relative abundances of 32 diatom species and the chord distance, as a similarity metric, to select the five most similar modern analogs. The threshold above which modern analogs are supposed to be too dissimilar to the fossil assemblage is fixed at the first quartile of random distances on the validation/modern dataset. Quantitative estimates of summer SST and WSIC are a similarity-weighted mean of the SST or WSIC associated with the selected modern analogs (Guiot et al., 1993). This method yields a R^2 of 0.96 and a root mean square error of prediction (RMSEP) of ~1°C for summer SST and a R^2 of 0.92 and a ~~root mean square error of prediction~~RMSEP of ~10% for WSIC.

The relative abundance of different diatom species and predictions of SST and WSIC may be altered by differential dissolution and preservation between species. While temperature is the dominant control on diatom species assemblages (Pichon et al., 1992; Esper et al., 2010), the dissolution of weakly silicified species, which are often those from cold waters, could potentially result in warmer reconstructed temperatures or an underestimation of sea-~~-~~ice extent (Xiao et al., 2016). However, as the dissolution of species is strongest in the Subantarctic Zone (SAZ) and sea-~~-~~ice zone~~s~~ of the Southern Ocean (Esper et al., 2010) and a dissolution minima (of 10%) is centred on 55°S (Pichon et al., 1992), the Conrad Rise is a region likely to be less influenced by diatom dissolution than locations at both lower and higher latitudes in the Southern Ocean. Furthermore, s~~S~~everal studies have shown that the surface water~~s~~ gradients in most abundant diatom species are preserved in the surface sediments (Gersonde and Zielinski, 2000; Armand et al., 2008a,b; Cárdenas et al., 2019). The strong association between ocean surface conditions and diatom assemblages within the sediment is supported by several statistical techniques that have been used to quantitatively infer past surface conditions using diatom analysis (e.g. Gersonde and Zielinski, 2000; Crosta et al., 2004; Esper and Gersonde, 2014).

The total diatom flux (DF), or diatom accumulation rate, was calculated to provide an approximation of productivity through time, following the method described in Romero et al. (2015). To calculate the DF, the number of valves per gram of dry sediment (diatom absolute abundance) was multiplied by the bulk density of wet sediment and the sedimentation rate. The resulting value was then divided by two to represent the number of diatoms rather than valves. The sedimentation rates and diatom abundances were calculated for core COR1GC, however because density was not measured on core COR1GC the wet bulk density measurements for core COR1bPC were instead used (Oiwane et al., 2014), as this core was recovered from the same location. The density measurements were transferred from COR1bPC to COR1GC using the chronologies of the two cores.

~~The total diatom , or the number of diatom valves per gram of dry sediment, was calculated to provide an approximation of the productivity through time following the method described in Crosta et al. (2008). This method allows only an approximation of the surface productivity because the diatom abundance in the sediment can also be affected by factors such as diatom dissolution during settling and deposition, lateral transport within the water column or at the water-sediment interface, and variable dilution by lithogenic particles. Additionally, the number of diatoms is only a broad approximation of biogenic silica in that large diatoms export much more silica and carbon than small ones.~~

3.4 SiZer analysis

SiZer (Significance of Zero Crossings of the Derivative) (Chaudhuri and Marron, 1999) is a scale-space technique that was applied to explore statistically significant features in the reconstructed SST. A key idea in SiZer is that significant features are found at different time scales, that is, at different levels of data smoothing. This makes it particularly useful in paleoclimate studies since the salient features in a timeseries may depend heavily on the time horizon on which it is analysed. This method has been used previously in a number of palaeoclimate studies (e.g. Divine et al., 2010).

In SiZer the observed data are viewed at varying levels of resolution while the notion of scale is controlled through the bandwidth h in the local linear kernel estimator. For each scale h and time t of the signal, a test is performed to see whether the smoothed data series has a local derivative significantly different from zero, in other words, to see if the slope at a specific time point for a given scale is significantly different from zero. The Gaussian kernel estimator embedded in SiZer does not require an analysed timeseries to be evenly spaced, the method is therefore applied to the data directly without any prior resampling. SiZer visualises the output of the analysis in a feature map where the results are displayed as a function of time and scale.

3.5 Spectral analysis

Many geophysical time series have distinctive red noise characteristics that can be modelled by a first order autoregressive (AR1) process. REDFIT spectral analysis (Schulz and Mudelsee, 2002) was carried out on the Holocene section of the SST reconstruction to establish whether quasi-periodic variability existed. This method of spectral analysis was selected as it has been designed for unevenly spaced paleoclimate data, therefore avoiding the need to resample and interpolate the data, which can introduce bias in the inferred spectrum (Schulz and Mudelsee, 2002). The analysis was conducted using the REDFIT tool integrated in the PAST 3.25 software (Hammer et al., 2001) using the Welch window ~~= Welch,~~with two overlapping segments~~ = 2~~ (Schulz and Mudelsee, 2002).~~and oversampling = 2. The tau value was 27.46.~~ The appropriateness of the AR1 model to describe the analysed data was tested using a nonparametric runs test (Bendat and Piersol, 1986) embedded in the package.

4 Results

~~T~~According to the constructed chronology the core covers the period from 14.2-1 ka BP and has a mean sedimentation rate of ~20 cm ka^{-1} (Table 1; Figure 2). The sedimentation rate decreased from 14 to 12 ka BP when it stabilised at its lowest values until 10 ka BP. It subsequently increased over the course of the Holocene to reach values >20 cm ka^{-1} during the late Holocene.

The diatom assemblage of COR1GC is dominated by pelagic open ocean taxa, particularly *Fragilariopsis kerguelensis* and *Thalassiosira lentiginosa* (Zielinski and Gersonde, 1997; Crosta et al., 2005), with accompanying species typical of the Polar Front Zone (PFZ) and POOZ (Figure 3). Species from the PFZ (*F. kerguelensis*, *Thalassionema nitzschioides* var *lanceolata*) and Subantarctic Zone (SAZ) (*Shionodiscus oestrupii*, previously known as *Thalassiosira oestrupii*; ~~) species~~Crosta et al., 2005; Romero et al., 2005), were more abundant in the interval 12-9.5 ka BP, with lowest relative abundances at 14.2-12 ka BP and 4-1 ka BP. Conversely, POOZ species abundances (especially *Thalassiothrix antarctica*, *Thalassiosira gracilis*, *Fragilariopsis separanda* and *Fragilariopsis rhombica*; Zielinski and Gersonde, 1997; Crosta et al., 2005) were lower at 14.2-9.5 ka BP, after which point they gradually increased in proportion over the Holocene. Diatom species associated with sea ice, including *Fragilariopsis ritscheri*, *Fragilariopsis curta*, *Fragilariopsis cylindrus, Porosira glacialis*, *Fragilariopsis obliquecostata* and *Thalassiosira tumida* (Zielinski and Gersonde, 1997; Armand et al., 2005), had individually low average abundances of ≤0.3%. These species have been grouped together (Figure 3). The sea ice species were present in low abundances through the record, but were slightly more abundant between 14.2-12.6, 7.6-6.2 and 3.9-1 ka BP and lower from 12.6-7.6 and 6.2-3.9 ka BP.

The diatom flux record of COR1GC (Figure 3) shows a range from ~2000 to 14,000 million diatoms cm^2 ka^{-1}. From 14.2 to 12 ka BP the diatom flux decreased (from ~12,000 to 2000 million diatoms cm^2 ka^{-1}). Concentrations remained low between 12 and 10.3 ka BP followed by higher fluxes with an average of 7200 million diatoms cm^2 ka^{-1} between 10.3 and 5.2 ka BP. After 5.2 ka BP fluxes decreased, with an average of 4500 million diatoms cm^2 ka^{-1} between 5.2 and 1 ka BP.

The SST reconstruction for COR1GC shows that during the 14.2 - 12.9 ka BP period the average temperature was 2.9 °C with a range of 1.8-4.1 °C and standard deviation of 0.6 °C (Figure 4), which was followed by a phase of warming between 12.9 and 11.6 ka BP when temperatures increased from 2.1 to 5 °C. Between 11.6 and 8.7 ka BP SST's wasere on average 4.3 °C, with a range of 3.3-5 °C and a standard deviation of 0.4 °C. After 8.7 ka BP the SST record shows a slightly lower average of 3.9 °C, a slight cooling trend, a range of 2.2-5.2 °C, a and standard deviation of 0.7 °C and a slight cooling trend. The record shows that during the slightly warmer interval at 11.6-8.7 ka BP the temperature varied less than after 8.7 ka BP, indicating a potentially more stable climate during the early Holocene and a a cooler and more variable climate during the mid to late Holocene. SiZer analysis flags three events as statistically significant: the two short-term cooling events at ~8.2 ka BP and ~2.2 ka BP and the warming trend during the deglaciation, the latter of which is marked as significant when identifying variability over a broad range of timescales (Figure 5). Conversely, SiZer did not find Thethe cooling through the Holocene was not shown to be significant. Spectral analysis conducted using the REDFIT method shows that during the Holocene there were quasi-periodic oscillations of 220 and 260 years, significant above the 95% false alarm level (Figure 6).

Summer sea ice did not reach the Conrad Rise through the last 14.2 ka BP (reconstruction not shown) and winter sea ice concentrations were very low and below the RMSEP throughout the period (Figure 4). These data however suggest slightly more extensive sea ice cover between 14 and 12 ka BP and after 8 ka BP, and a slight retreat ofabsent winter sea ice between 12.2 and 8 ka BP when SSTs were ~1°C higher than today. Relatively low values of the inferred winter sea ice concentration suggest only sporadic and relatively short-term (perhaps decadal to multi-decadal scale) expansions of winter sea ice to the coring location throughout the mid-late Holocene.

5 Discussion

5.1 Southern high latitude temperature

The millennial trends in the COR1GC temperature record are similar in timing toto those of SST records from the Atlantic sector of the Southern Ocean (Nielsen et al., 2004; Anderson et al., 2009; Divine et al., 2010; Xiao et al. 2016; Figure 7 A and B) within the age uncertainty of each record. Many of these show cooler temperatures at ~14.2-12.9 ka BP during the interval known as the Antarctic Cold Reversal (ACR: (14.7-12.7 ka BP; Stenni et al., 2011), gradual warming during the Younger Dryas (or Termination 1b), high temperatures between 11.6 and 8.7 ka BP during the Early Holocene, followed by a cooling trend thereafter. Another SST reconstruction from the Conrad Rise (PS2606-6; Figure 7C; Xiao et al., 2016), with lower temporal resolution than the COR1GC record, shows warm temperatures during the ACR and the early Holocene along with a slight cooling during the Younger Dryas, at odds with the other records from the POOZ. We suggest that the opposite trend in the PS2606-6 record during the late deglaciation could be related to either chronological issues, as it is the only SST record that is out-of-phase during this period, or the result of different reconstruction techniques. Furthermore, while most records~~,~~ show ~~a long-term~~ cooling over the Holocene, either gradually or as an abrupt cooling at the end of the early Holocene (Xiao et al., 2016), there are some differences between records. For example, the cooling in the COR1GC is ~~slight~~small compared to other records as~~whereby;~~ the change in mean temperature from the early ~~Holocene~~ to mid-late Holocene was ~~just~~ ~0.4°C, although~~.~~ ~~s~~Superimposed ont~~o~~ this long-term trend~~changes,~~ ~~, although had intervals~~~~experienced~~ were centennial events with 1-2°C cooler temperatures during the mid-late Holocene (Figure 4). ~~O~~We note, on the other hand, that core TN057-17 close to the Polar Front in the Atlantic sector shows a ~~a Holocene~~ warming trend since ~4 ka BP (Figure 7; Nielsen et al., 2004), in contrast to a nearby low resolution record (cores PS1654/OPD1093) which indicates that ~~there~~SST were ~~rpreelatively~~relatively stable ~~temperatures~~over the late Holocene (Xiao et al., 2016). Despite many records having similar long-term patterns, ~~The~~ these results therefore ~~show~~suggest some regional heterogeneity of temperature evolution at the centennial to multi-millennial scales through the late deglacial and Holocene.

The records from the Bouvet Island region, in the eastern Atlantic sector of the Southern Ocean, and the Conrad Rise (Figure 7 A-D; cores TN057-17-PC1, TN057-13-PC4 and PS2606-6; Xiao et al., 2016) show that the magnitude of warming between the ACR and early Holocene was 1-2°C. Nevertheless, there are variations in the exact magnitudes of the temperature fluctuations between the different records. Some previous records suggested that the SST during the ACR and the mid-late Holocene were similar (Nielsen et al., 2004; Anderson et al., 2009; Divine et al., 2010; Xiao et al., 2016; Figure 7 A-C). Our new record from core COR1GC ~~conversely~~ however shows SSTs were 1°C lower during the ACR compared to the mid-late Holocene, in agreement with reconstructions of air temperature from ice cores~~records~~ (Figure 7E-F). The contrasting findings between SST reconstructions may be explained by the reconstructed temperatures being close to the prediction error of SST transfer functions, which is ~1°C in this study and 0.86°C in Xiao et al. (2016).

The millennial temperature evolution of the COR1GC record during the deglacial and early Holocene closely resembles the patterns of atmospheric temperature and sea ice extent, reconstructed from Antarctic ice core water isotope records and sodium flux records respectively (Figure 7 E and F; EPICA community members, 2006; Fischer et al., 2007; Jouzel et al., 2007; Stenni et al 2011). This is particularly evident when comparing the smoothed and normalised reconstructions of temperature ($\delta^{18}O$) and regional sea ice extent (ssNa) from the closest ice core, EDML, with the COR1GC SST record (Supplementary Information 1). The start of the COR1GC record at 14.2 ka BP is after the beginning of the ACR (at 14.7 ka BP; Stenni et al., 2011) meaning that the timing of the onset of the ACR at the Conrad Rise cannot be established. However despite some degree of dating uncertainty ~~, in part caused by potentially variable reservoir ages,~~ the warming from 12.9 - 11.6 ka BP appears closely aligned with the timing of warming identified in the ice core records at 12.7-11.9 ka BP (Stenni et al., 2011). A good synchronicity between Southern Ocean SST and Antarctic temperature evolution over the deglacial was also shown by a planktic foraminifera-based SST reconstruction from core MD07-3088 from the eastern Pacific sector, which like the COR1GC record showed cold temperatures during the ACR, followed by gradual warming between c.12.7 and 11.5 ka BP leading to~~and~~ slightly warmer conditions through the Holocene (Siani et al., 2013; Haddam et al., 2018).

The MD07-3088 record was constrained by both radiocarbon dates and tephra horizons minimising dating uncertainties (Siani et al., 2013), which supports the chronological framework of core COR1GC and the new SST record. The marginally warmer early Holocene temperatures that followed at 12-8.7 ka BP are observed widely in ice core, terrestrial and coastal records from across Antarctica (Stenni et al., 2011; Verleyen et al., 2011; Figure 7E and 7F). Together this evidence suggests that the sea surface and atmospheric temperatures across the southern high latitudes varied synchronously during the deglacial to Holocene transition.

5.2 Causes of temperature variability

The SST variations may have been due to a number of interrelated factors, including in response to atmospheric temperature changes, variations in the AMOC, changes in the strength and position of the SWW and shifts in the location of the ACC fronts relative to the core site. Here these causes will be discussed in relation to the Younger Dryas and Holocene climate patterns, with the suggested causes summarised in Table 2.~~.~~

5.2.1 Younger Dryas ~~and Termination 1b~~

Southern high latitude warming ~~(Termination 1b)~~ during the Younger Dryas is widely considered to be the result of a slowdown in the AMOC (McManus et al., 2004; Figure 8A), which caused reduced northward heat transport and the accumulation of heat in the southern hemisphere (Broecker, 1998; Stocker and Johnsen, 2003). ~~This is supported by a close agreement between the timing of warming in the COR1GC and ice core records with reconstructed AMOC weakening (McManus et al., 2004; Figure 8A).~~ It is considered that t~~T~~his~~e~~ hemispheric temperature change ~~AMOC weakening between 12.8-11.7 ka BP is thought to have caused a reduced northward heat transport, cooling of the North Atlantic and warming of the South Atlantic, which~~ caused a~~the~~ southward shift of the ITCZ ~~to be positioned further south~~ (Figure 8B; Hughen et al., 1996), which~~. It is considered that this~~ in turn caused poleward-shifted and strengthened SWW (Denton et al., 2010; Pedro et al., 2018). Evidence from the Southern Ocean supports that the SWW were stronger over a longer interval from 14 to 11 ka BP but only shifted southwards to a more poleward position at 12.5 ka BP (Fig 8C; Fletcher and Moreno, 2011; Saunders et al., 2018).

The changes to the SWW during ~~Termination 1b~~the Younger Dryas are thought to have warmed the Southern Ocean in a number of ways, including through the southward migration of the Polar Front, causing local warming in regions currently to the~~just~~ south of the Polar Front ~~of the Polar Front~~ (e.g. Barker et al., 2009)~~,~~ and through strengthening of the eddy transport of heat across the ACC (e.g. Pedro et al., 2018) ~~and by enhanced upwelling,~~ causing a more widespread warming of the POOZ. Although there is a lack of palaeo-proxy evidence for stronger eddy transport of heat across the ACC, this mechanism has been identified in both model simulations and modern observations (Meredith and Hogg, 2006; Screen et al., 2009). It is considered that this initial ~~The~~ warming of the Southern Ocean resulted in reduced sea ice in the Indian and Atlantic sectors at 12 ka BP (Bianchi and Gersonde, 2004; Iizuka et al., 2008),~~which~~ promoting~~ed~~ further ocean warming in the newly ice-free region ~~and~~

~~upwelling~~ (Denton et al., 2010; Xiao et al., 2016; Pedro et al., 2018)~~. There is no palaeo-proxy evidence for eddy transport across the ACC, however modern observations and models show that stronger, southward-shifted SWW cause an increase in eddies (Meredith and Hogg, 2006), leading to an increased poleward heat flux and warmer Southern Ocean temperatures, as well as a southward displacement of the sea ice equilibrium line (Hogg et al., 200; Screen et al., 2009). During the Younger Dryas the SWW changes may have caused a similar oceanographic response, as both ice cores (Dome Fuji) and marine records support that in the Indian and Atlantic sectors sea ice extent reduced at c.12 ka BP (Bianchi and Gersonde, 2004; Iizuka et al., 2008; Xiao et al., 2016). This~~ and ~~would have promoted~~ warming of the lower troposphere and Antarctica by ice-albedo feedbacks (Pedro et al., 2018). Greater upwelling, caused by stronger winds and a reduction in sea ice extent, has been shown by higher opal deposition to the south of the Polar Front in the Southern Ocean (Atlantic, Indian and Pacific sectors) through the period 12.7-11.5 ka BP~~, which has been attributed to increased wind-driven upwelling and a response to the reduction in sea ice extent~~ (Figure 8D; Dezileau et al., 2003; Anderson et al., 2009; Siani et al., 2013). ~~Finally, t~~The combination of greater upwelling and reduced sea ice allowed more outgassing of CO_2 to the atmosphere (Figure 8F~~G~~), causing warming globally (Monnin et al., 2001; Anderson et al., 2009; Clark et al., 2012; Saunders et al., 2018).

The warming and reduced sea ice shown by the COR1GC reconstructions during the Younger Dryas (Figure 3 and Figure 4) coincide~~s~~ with many of these changes, including the AMOC weakening, strengthened and southward-shifted SWW, increased upwelling, reduced sea ice, ~~and~~ rising CO_2 and warming over Antarctica (Figure 8; Supplementary Information 1). However, there is no~~This sequence of events is also supported by~~ evidence of increased productivity and therefore upwelling at~~on~~ the Conrad Rise, as ~~tentatively inferred from the slightly increased~~ diatom fluxes instead decreased through this period ~~abundances at 12.7-12 ka BP~~ (Figure 8E). Although the marine records have sources of age uncertainty~~, including potential changes in reservoir ages of 100-200 years (Siani et al., 2013)~~, the similarity in the timing of changes in marine and terrestrial records supports that warming was a result of processes connected with the interhemispheric oceanic and atmospheric reorganisation (Figure 8).

One challenge is to establish the relative importance of each of the outlined causes of warming, because although changes occurred synchronously they may not have all contributed equally to warming of the Southern Ocean. For example, the Conrad Rise is located close to the modern Polar Front and therefore a southward shift of the SWW during the Younger Dryas may have pushed the Polar Front to the south, leading to warming. Indeed, a southward shift is indicated by an increase in the Polar Front species *Thalassionema nitzschioides* var. *lanceolata* at c.12 ka BP (Figure 3). Although observations and models show that the fronts of the Polar Front are topographically constrained in this region (Pollard and Read, 2001; Graham et al., 2012; Pauthenet et al., 2018), it is possible that larger magnitude changes in the SWW were able to divert the Polar Front to the south of the Conrad Rise. The relative importance of CO_2 in contributing to the warming of Antarctica and the Southern Ocean, which resulted from the above described changes in circulation and Southern Ocean conditions, is also not clear. Principle component analysis on a synthesis of global temperature reconstructions spanning the last deglaciation indicate that temperatures globally were primarily controlled by greenhouse gas concentrations (Clark et al., 2012) and temperature over

Antarctica rose synchronously with CO_2 increases during the Younger Dryas (Parrenin et al., 2013). The synchronicity between the CO_2 record and some of the temperature records (COR1GC, MD07-3088 and ice core records) over the deglaciation, suggests that the CO_2 increase, following the initial warming and sea--ice loss, contributed to the amplitude of the deglacial warming and subsequent early Holocene temperatures through a strong positive feedback on the climate system (Past Interglacials Working Group, 2016).

5.2.2 Holocene

The warmth during the early Holocene (12-8.7 ka BP) in the southern high latitudes following the Younger Dryas warming can be~~has been~~ attributed to ~~high annual, winter and~~high ssppring insolation~~ levels~~ causing a longer summer season (Shevenell et al., 2011; Etourneau et al., 2013~~; Xiao et al., 2016~~), which would have enhanced the duration of summer warming and reduced the duration of winter cooling of the open ocean~~. In the open ocean the insolation may have resulted in enhanced surface warming due to an extended spring-summer season compared to the late Holocene~~. ~~Alternatively,~~Insolation-driven ~~the strength of the~~changes to the SWW may have also influenced the SST. Reconstructions support that the SWW were weaker generally between 11 and 7 ka BP (Fletcher and Moreno, 2011; Saunders et al., 2018; Figure 8C), shifted southward (Lamy et al., 2010) and that atmospheric circulation was more meridional (Mayewski et al., 2013). The more meridional circulation may have led to a greater poleward penetration of warm air masses and therefore warming over the Southern Ocean. A general weakening of the SWW may have reduced the amount of northward Ekman transport of cold water (e.g. Hall and Visbeck, 2002; Lovenduski and Gruber, 2005), again leading to warming further north. However at the latitude of the Conrad Rise (54°S) it is likely the SWW strengthened, as the southward SWW caused stronger winds in South America at c.53°S ~~.~~(Lamy et al., 2010), and this may have potentially increased heat loss from the ocean surface, damping the warming.~~ SWW's cause eddy activity and poleward heat transport across the ACC, resulting in (Hogg et al., 200; Screen et al., 2009).~~

At ca. 8.2 ka BP the SiZer analysis indicated that there was a significant cool interval~~ing~~ in the COR1GC record (Figure 5), while the diatom record by Katsuki et al. (2012) from the Conrad Rise also showed a peak~~n increase~~ in cold species at 8 ka BP. The duration and timing of the SST cooling observed in the COR1GC record (from 8.5-7.9 ka BP)~~ record~~ coincides with an AMOC reduction and North Atlantic cooling associated with the 8.2 event (Ellison et al., 2006). The AMOC reduction should have caused a warming of the Southern Ocean via the bipolar seesaw. However~~,~~ ~~and~~a modelling study~~ies~~ suggests that cooler NADW was formed in the North Atlantic, due to the retreat of the Laurentide Ice Sheet, and~~may have~~ this upwelled in the Southern Ocean causing a cooling in the POOZ between 9 and 7 ka BP (Renssen et al., 2010). T~~however t~~he 8.2 event~~it~~ has not generally been observed in records from the southern hemisphere (Alley and Ágústsdóttir, 2005). ~~t~~While there are some indications of a longer period with lower temperatures in Antarctic ice core records at this time (Figure 7 E and F; EPICA Community Members, 2006; Jouzel et al., 2007) and evidence of colder SST at the Antarctic Peninsula (Etourneau et al., 2019), ~~this spans a longer interval and~~ the few other high resolution SST records from the open ocean do not show a cool event (Figure 7; TN057-13PC4; TN057-17TC; Nielsen et al. 2004; Anderson et al., 2009; Divine et al., 2010). Therefore although there appears to have been a cooling on the Conrad Rise at this time it cannot be reliably associated with the 8.2 ka event in the northern hemisphere without additional evidence from other high resolution marine sediment records.

From the mid to late Holocene the spring southern high latitude insolation decreased (Laskar et al., 2004~~; Divine et al., 2010~~), causing a shorter summer duration and cooling, which is coherent with the northward shift of the SWW (Lamy et al., 2001)~~., which~~ T~~t~~ogether this can explain the ~~gradual~~ slight cooling in the COR1GC record, the increased frequency of cold events and increase in sea ice (Figure 4). The winter and summer ~~Spring~~ latitudinal insolation gradient also increased (Laskar et al., 2004; Divine et al., 2010) causing the SWW~~'s~~ to strengthen (e.g. Saunders et al., 2018), which may have caused cooling by promoting enhanced northward Ekman transport of cooler water from the south towards the Conrad Rise (e.g. Hall and Visbeck, 2002; Lovenduski and Gruber, 2005). The strengthened winds may also have increased upwelling and therefore productivity, however at the Conrad Rise this does not seem to have~~it is not clear if this~~ occurred as ~~although there was a gradual increase in sedimentation rate, potentially reflecting an increased deposition of diatoms (Figure 2),~~ the estimated diatom ~~abundance~~ flux decreased, particularly after 5 ka BP (Figure 3). Potentially, a strengthening of the SWW to the north, rather than over the Conrad Rise, may explain why upwelling and productivity did not increase, which agrees with evidence from the Atlantic sector that during the mid to late Holocene productivity decreased south of the Polar Front (Anderson et al., 2009).

The COR1GC SST record also shows increasingly variable SSTs through the mid to late Holocene after 8 ka BP (Figure 4). Another record from the Conrad Rise found an increased frequency of cold events from 5.5 ka BP onwards (Katsuki et al., 2012) and the closest ice core record, EDML, shows increasing variability in the $\delta^{18}O$ record from c.6 ka BP onwards (EPICA Community Members, 2006; Fischer et al., 2007; Figure 7E). Spectral analysis conducted on the COR1GC SST record identifies significant quasi-periodicities of ~220 to 260 years (Figure 6) during the last 12,000 years. Similar quasi-periodicities of 200-300 years have previously been observed in Southern Ocean palaeoceanographic records, including those reflecting SST, sea ice and productivity changes (Leventer et al., 1996; Bárcena et al., 1998; Nielsen et al., 2004; Crosta et al., 2007). Furthermore, quasi-periodicities of 250 years have been identified in a record of westerly wind intensity from the Falkland Islands (Turney et al., 2016) and multi-centennial variations were similarly identified in a 3000 year reconstruction of the SAM (Moreno et al., 2014). These similar patterns of cyclicity in records reflecting both ocean and atmospheric conditions suggest that they were caused by 1) internal variability and ocean-atmosphere coupling, or 2) ocean and atmosphere responses to a shared forcing. ~~Towards t~~In support of the first hypothesis, ~~M~~model simulations have shown similar 200-300 year oscillations in Southern Ocean temperature and atmospheric circulation (Latif et al., 2013). In a simulation by the Kiel Climate Model, centennial episodes of strong (weak) deep convection in the Weddell Sea caused warm (cold) SST's and reduced (expanded) sea ice, which altered atmospheric pressure patterns and led to weakened (strengthened) atmospheric circulation (Latif et al., 2013). In this case, internal oscillations in the climate system have a~~n~~ hemispheric impact, which may ~~therefore~~ explain the similar variability observed in the COR1GC record and other records. In support of~~Towards~~ the second hypothesis, ~~E~~external forcing~~s~~, such as cycles in solar activity, may have caused these changes (Leventer et al., 1996; Bárcena et al., 1998; Crosta et al., 2007; Turney et al., 2016), with changes in solar irradiance directly altering ocean SST, and potentially regulating the SAM and associated changes in atmospheric and oceanic circulation~~s~~, as suggested by some modern evidence that shows a connection between the SAM and the 11-year solar cycle (e.g. Kuroda and Kodera, 2005; Kuroda, 2018). While it is yet not possible to establish the cause of this cycle, the enhanced variability in the mid-late Holocene appears to reflect the establishment of modern coupled ocean-atmosphere relationships over the Southern Ocean.

6 Conclusions

The COR1GC reconstruction of SST variability at the Conrad Rise in the west Indian Sector of the Southern Ocean spans the period from 14.2 to 1 ka BP with an average resolution of ~60 years. SST's were cool (~2.9°C) from 14.2-12.9 ka BP during the ACR before temperatures increased to 5°C between 12.9 and 11.6 ka BP during the Younger Dryas~~/Termination 1b~~. During the Holocene ~~there was a gradual decrease in temperatures;~~ SST's were ~~warmer and~~ more stable and marginally warmer between 12 and 9 ka BP, before a sharp cooling event occurred at c.8.2 ka BP,~~ which was~~ followed by greater SST variability and slightly cooler conditions through the period 8-1 ka BP.

The timing and duration of warming in the COR1GC record at 12.9-11.6 ka BP reflects warming also shown by a precisely dated marine record of SST from the Pacific (Siani et al., 2013) and Antarctic ice core temperature records, supporting that atmospheric and ocean temperatures varied in phase. The COR1GC warming also coincides with palaeo-evidence for a weakened AMOC, rising CO_2 levels, greater upwelling in the Atlantic sector of the Southern Ocean, southward displacement and strengthening of the SWW and reduced sea ice, each of which may have contributed to warming in the Southern Ocean. The results support that the warming was initiated by an interhemispheric oceanic and atmospheric reorganisation during the Younger Dryas but does not allow attribution of the relative importance of each process to warming.

For the Holocene period, the most striking change in the COR1GC record is the switch from~~ warm and~~ stable and slightly warmer conditions to variable and slightly cooler~~ and variable~~ conditions at 8.7 ka BP, potentially linked with a global reorganisation of the climate system. It is suggested that the early Holocene warmth may have resulted from higher spring insolation increasing the duration of heat accumulation in the Southern Ocean during the spring-summer season, or as a result of ~~increased poleward~~changes to latitudinal heat transport~~ of heat in the atmosphere~~ as the SWW weakened. During the mid to late Holocene the enhanced variability may represent the establishment of modern coupled atmosphere-ocean relationships ~~outlined in Latif et al. (2013)~~, whereby the SAM and SST's in the Southern Ocean vary in phase over centennial timescales. This is supported by the identification of a quasi-periodic oscillation of ~200-260 years in the Holocene section of the COR1GC SST reconstruction, which mirrors similar centennial variability identified in reconstructions of the SAM and westerly winds.

Code/data availability

The completed dataset can be obtained at pangaea.de

Author Contributions

LCO performed the diatom analysis and wrote the manuscript. XC produced the SST record, did training and writing/editing of the manuscript. DD did ~~SiZER~~ SiZer analysis. AM, DD, KH, EI, RM edited the manuscript. AM, KH, EI, XC, RM, DD conceptualised and supervised the project. LW and OT conducted laboratory analysis. MI provided core material.

Competing interests

The authors declare that they have no conflict of interest.

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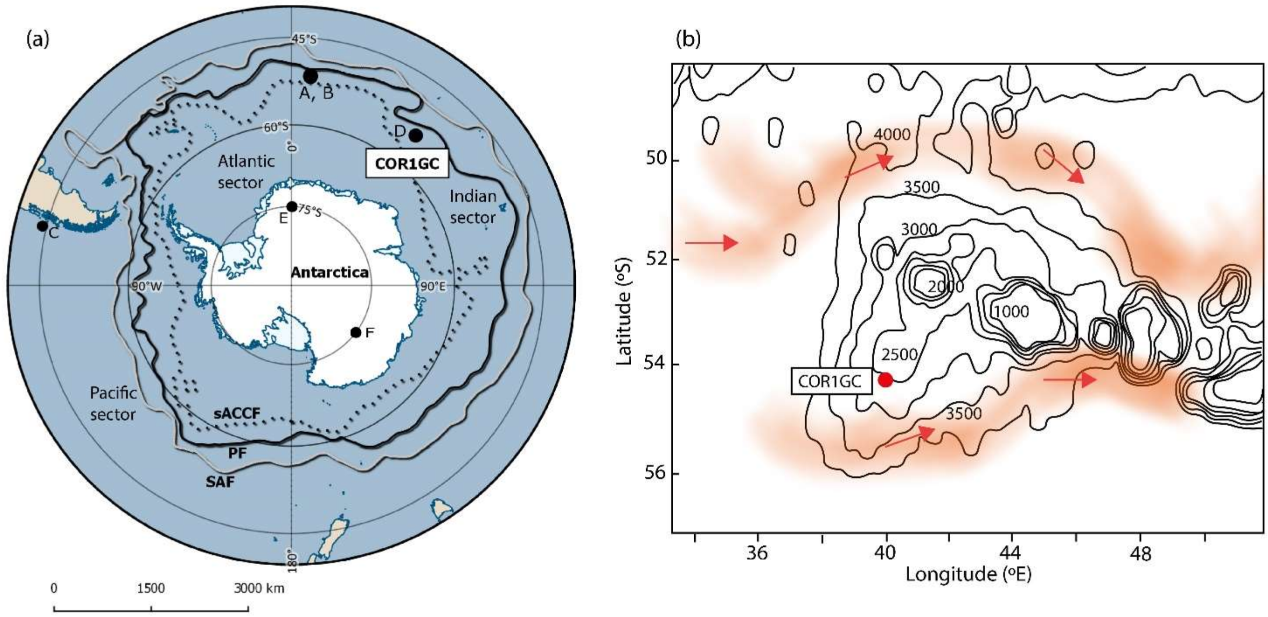

Figure 1: Location of core ~~KH-10-7~~ COR1GC in the western Indian sector of the Southern Ocean. a) Map of the Southern Ocean and Antarctica. ~~Includes the mean location of the southern Antarctic Circumpolar Current Front (sACCF; dotted line), the Polar Front (PF; black line) and Subantarctic Front (SAF; grey line) according to Orsi et al. (1995).~~ KKey terrestrial ice and marine sediment cores mentioned in the text and in Figure 7 are labelled: A) TN057-13-PC4 (Anderson et al., 2009; Divine et al., 2010), B) TN057-17-PC1 (Nielsen et al., 2004), C) MD07-3088 (Siani et al., 2013), D) COR1GC (this study), E) EDML (EPICA Community Members, 2006), F) EDC (Jouzel et al., 2007). The mean location of the southern Antarctic Circumpolar Current Front (sACCF; dotted line), the Polar Front (PF; black line) and Subantarctic Front (SAF; grey line) according to Orsi et al. (1995) are shown. b) Bathymetric map of the Conrad Rise adapted from Ansorge et al. (2008) including areas of high absolute geostrophic velocity in red shading and direction of flow shown by red arrows.

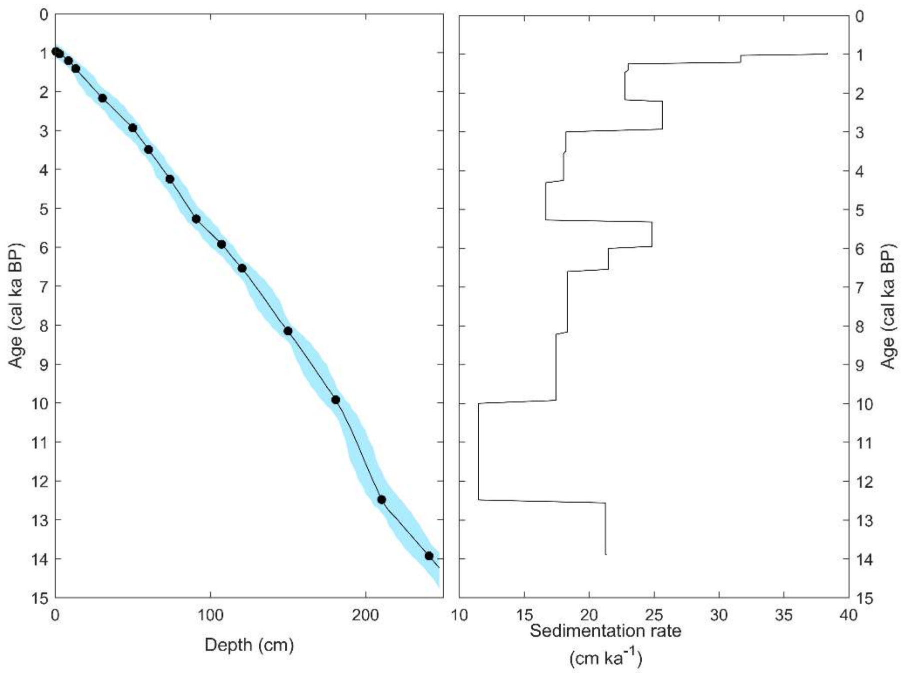

Figure 2: Left: Age-depth model for core ~~KH-10-7~~ COR1GC. The age model is constrained by 15 calibrated radiocarbon dates, the continuous line is the median age and shaded area represents the 95% confidence interval of the modelled core chronology. Right: Sedimentation rate estimates for COR1GC based on median modelled ages for AMS ^{14}C dates.

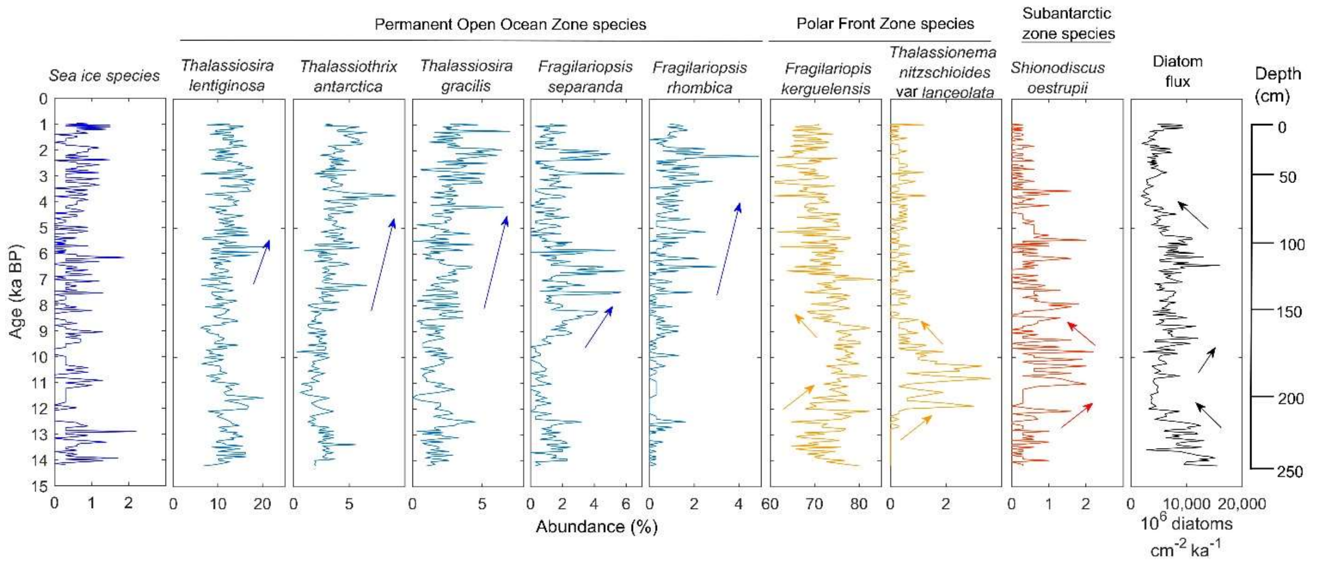

Figure 3: COR1GC diatom abundances as percentages of total sample and the total diatom ~~abundance~~flux. Note that the species are plotted on different x-axis scales.

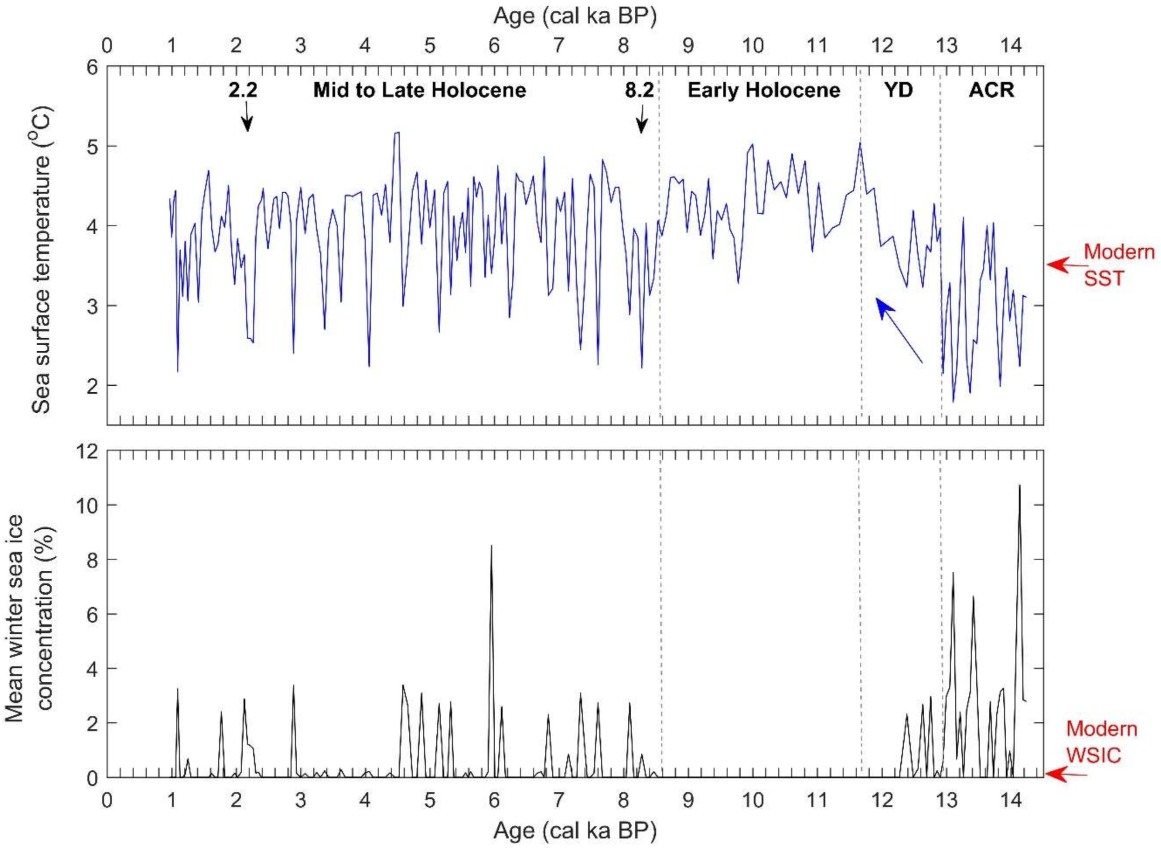

Figure 4: Reconstructed mean summer (January-March) sea surface temperature and mean winter (September) sea ice concentrations for core COR1GC. Key periods discussed are highlighted, along with significant centennial cool events at c.8.2 and 2.2 ka BP, as identified by the SiZer analysis (Figure 5). The modern average summer SST at 10 m depth is 3.5°C (World Ocean Atlas, 2013) is marked on the graph, while the modern winter sea ice concentration (WSIC) is marked as 0 as the sea ice limit is at 59°S (Park et al., 1998; Parkinson and Cavalieri, 2012).

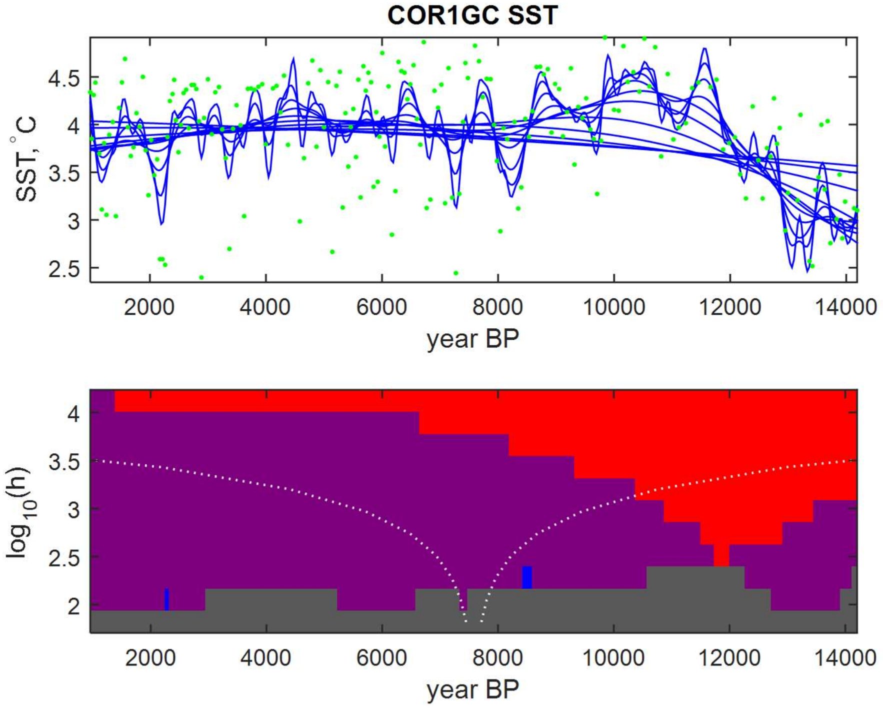

Figure 5: SiZer analysis of the COR1GC SST reconstruction. Upper panel: Family plot of the reconstructed SST. The green dots represent the raw data. Blue lines show the family of smoothings obtained by the local linear kernel estimator for a range of bandwidths (scales h). Bottom panel: A SiZer map, given as a function of location (time t) and scale h. A significantly positive (increased SST) derivative is flagged as red while a significantly negative (decreased SST) derivative is flagged as blue. The color purple is used at locations where the derivative is not significantly different from zero. The color dark gray is used to indicate that too few data points are available to do a correct inference. The distance between the two dotted lines in the cone-shaped curve for a horizontal line in the SiZer plot can be interpreted as the scale for that level of resolution.

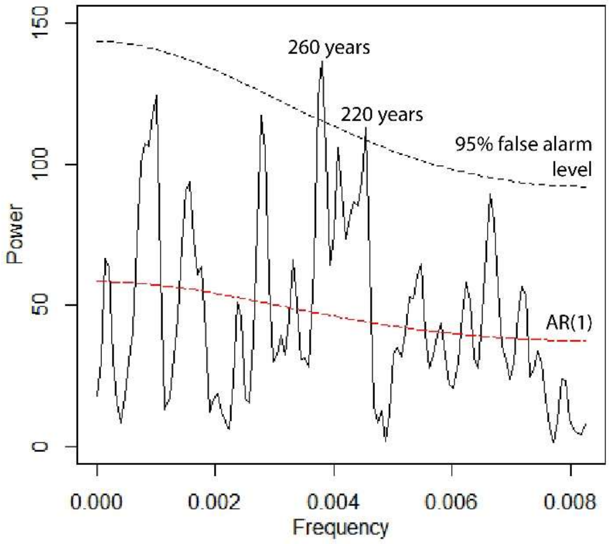

Figure 6: REDFIT spectral analysis of the COR1GC SST reconstruction during the period 12-1 ka BP. The 95% significance level (Chi2) is shown by the dashed black line. The time series is fitted to an AR(1) red noise model (dashed red line).

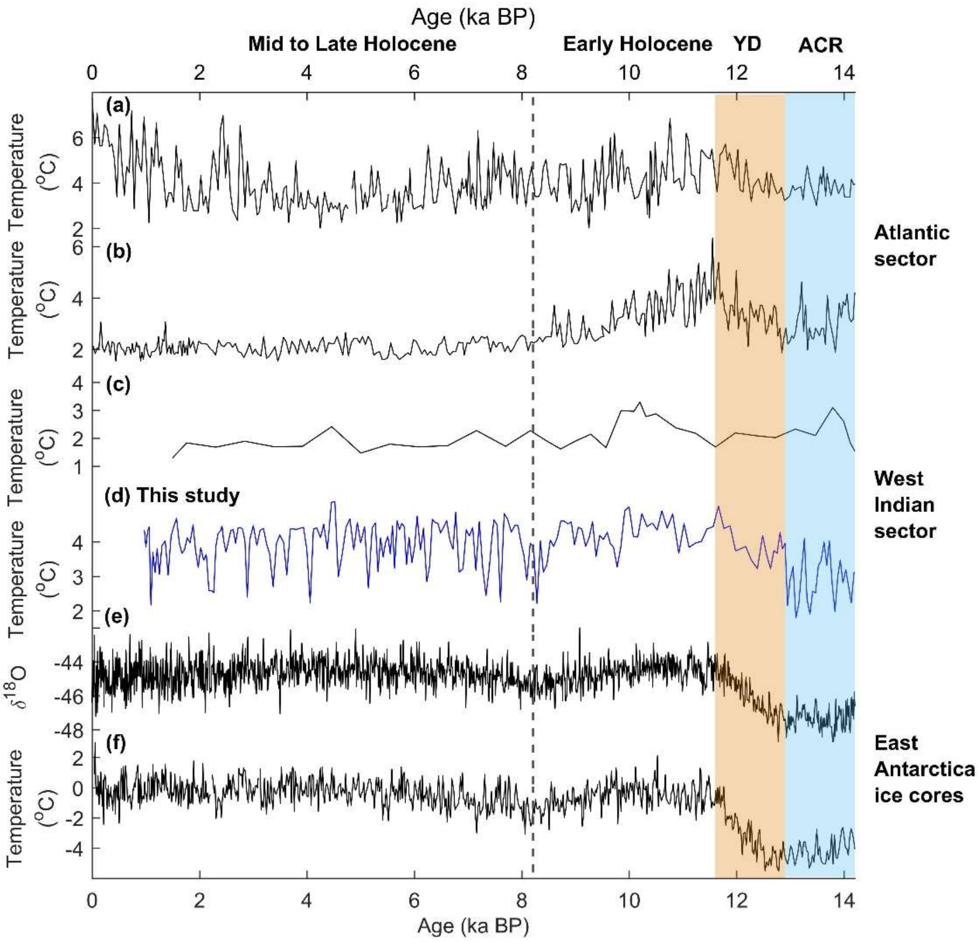

Figure 7: Reconstructions reflecting temperature since 14.2 ka BP from the Southern Ocean and Antarctica at locations shown in Figure 1. A) TN057-17-PC1 diatom-based SST reconstruction (Nielsen et al., 2004), B) TN057-13-PC4 diatom-based SST reconstruction (Anderson et al., 2009; Divine et al., 2010), C) PS2606-6 diatom-based SST reconstruction from the Conrad Rise (Xiao et al., 2016), D) COR1GC SST reconstruction (this study) from the Conrad Rise, E) EDML ice core $\delta^{18}O$ reconstruction (EPICA Community Members, 2006), F) EDC ice core temperature reconstruction (Jouzel et al., 2007).

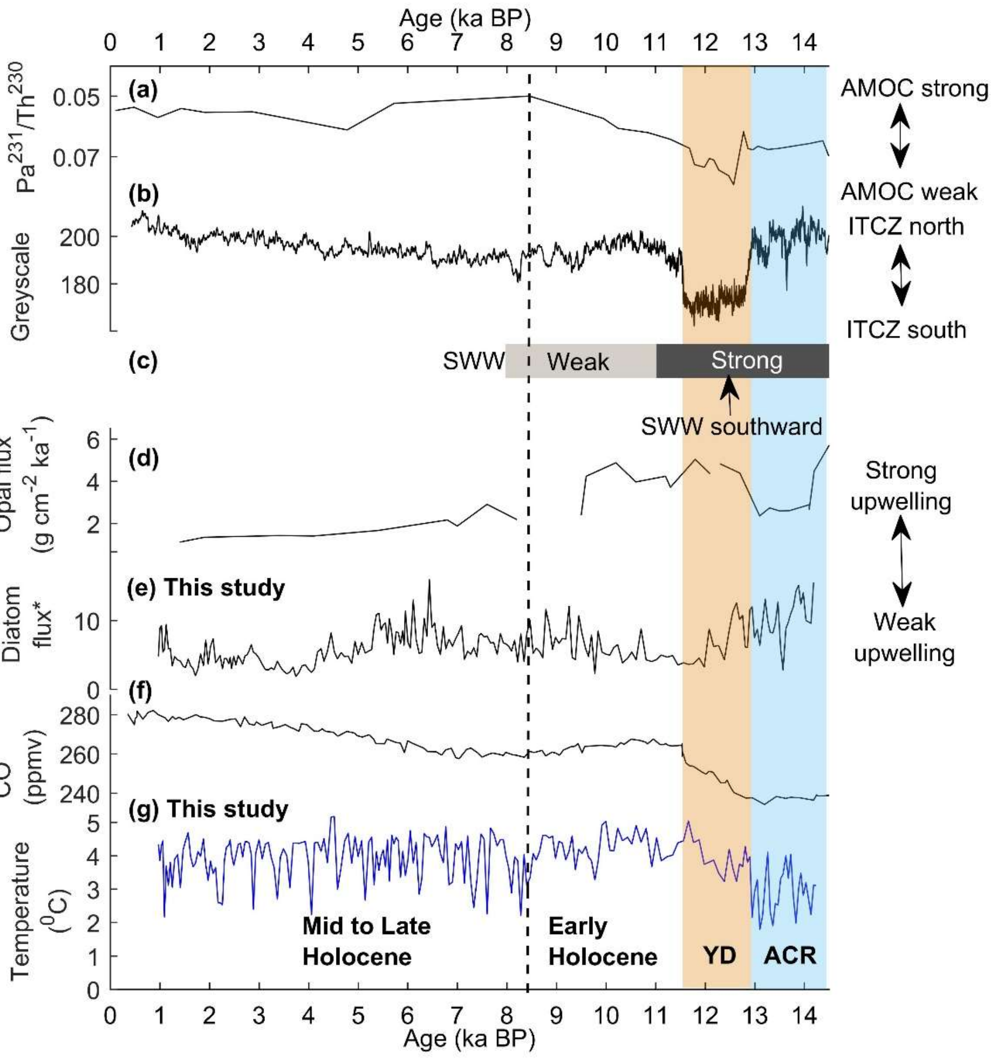

Figure 8: Summary of key reconstructions showing the late deglacial to Holocene variations in the AMOC, atmospheric circulation and Southern Ocean. A) AMOC reconstruction based on Pa^{231}/Th^{230} from a core from the western subtropical North Atlantic (McManus et al., 2004); B) greyscale measurements from cores from the Cariaco Basin related to productivity, interpreted as reflecting ITCZ position (Hughen et al., 1996); C) summary of reconstructed SWW strength based on a collation of palaeoclimate data from the southern mid latitudes (41–52°S; Fletcher and Moreno, 2011); D) upwelling in Atlantic sector of Southern Ocean (core TN057-13PC4) based on opal flux (Anderson et al., 2009; Divine et al., 2010); E) productivity at the Conrad Rise inferred from the diatom flux in COR1GC, *measured in units: 10^9 diatoms cm^{-2} ka^{-1}; F) EDC CO_2 reconstruction (Monnin et al., 2001); G) COR1GC reconstruction of SST (this study).

Table 1: AMS radiocarbon dates and calibrated age estimates.

Laboratory code	Depth (cm)	^{14}C age (years BP)	Age error (years)	Calibrated median age and 95% confidence age range (calibrated years BP)
ETH-80023/24	0.6	2003	60	970 (770 – 1160)
BETA-485984	2.9	1910	30	1030 (850 – 1200)
BETA-485985	8.6	2040	30	1210 (104 – 1390)
ETH-80025/26	13.2	2370	65	1410 (1210 – 1640)
BETA-488823	30.5	3000	30	2170 (1900 – 2460)
ETH-80027/28	50	3521	65	2930 (2640 – 3280)
BETA-488824	60.2	4070	30	3490 (3200 – 3800)
ETH-80029/30	73.9	4634	70	4250 (3920 – 4640)
BETA-488825	90.9	5480	30	5270 (4900 - 5560)
ETH-80031/60	107.3	5966	70	5930 (5670 – 6230)
BETA-488826	120.4	6580	30	6540 (6290 – 6840)
BETA-488827	150.1	8160	30	8160 (7860 – 8440)
BETA-488828	180.8	9600	40	9920 (9530 – 10350)
BETA-488829	210.3	11570	40	12490 (11740 – 12840)
BETA-488830	240.9	12890	40	13930 (13530 – 14400)

Table 2: Summary table of the suggested forcings of the core COR1GC SST reconstruction, as proposed in Section 5.2

Time interval	Initial forcing	Feedbacks and processes
Younger Dryas	Slowdown of the AMOC	**Direct cause of warming:** Heat accumulation in the Southern Ocean **Indirect causes of warming:**

		i) ITCZ and SWW shifted southwards and SWW strengthened (greater eddy-transport of heat across the ACC) ii) Sea ice loss (ice-albedo changes and amplification of warming. This also increased upwelling) iii) Increased upwelling (greater outgassing of CO_2 and atmospheric warming)
Holocene millennial changes	Spring insolation and winter and summer insolation gradients	**Early Holocene / mid-late Holocene** Length of the summer season: Extended/reduced SWW: weaker and meridional / stronger and zonal • increased/reduced atmospheric heat transport southwards • reduced/increased Ekman transport of cold water northwards
Mid-late Holocene variability	Internal atmosphere-ocean interactions or solar forcing	i) Internal variability and ocean-atmosphere interactions (variable deep convection rates > SST and sea-ice extent > heating of atmosphere > atmospheric circulation) ii) Solar variability: impact on atmospheric and oceanic circulation