## Review 1 comments

**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, <u>or as a result of changes to latitudinal heat transport as the SWW weakened</u>.' 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.