REPLY LETTER

Received: 23 August 2017

In the following document, the original reviewer comments are in **Bold**. The author's responses are in plain font, and the alterations in the text are in *Italics*. Please note that a separate detailed reply for each referee is provided.

Referee #1: Anonymous referee

Overall I am satisfied with the revision. The authors explained the processes governing AABW formation in each product. I just have a few minor concerns.

Since it could take thousands of years to reach equilibrium conditions, even after twelve years adjustment could be in progress. I don't think "a one year spin-up procedure" would lead to equilibrium conditions. The weakening of vertical stratification that induces polynya could be a part of adjustment. There is nothing the authors can do concerning the adjustment, but I don't think ignoring it is not a proper interpretation.

We would like to thank the referee again for taking the time to review the manuscript, and also for the minor suggestions. We agree that addressing the small or lack of spin-up period in the reanalysis products are necessary, since it could be one of the issues that lead to polynya opening in both ECCO2 and UR025.4. In order to clarify that, the following statement was added in the summary section of the manuscript:

"*In this matter, the low spin-up period of 1 year in SoSE and lack of spin up in ECCO2 could have allowed instability in water column in the reanalysis, hence weakening stratification."*-Page 20, Lines 4 to 6.

Lines 9-12 I am not sure what the authors are trying to convey. Are you trying to say that even in data assimilated products the error is not fixed?

Yes. We have also added the *assimilatory* adjective to the statement, in order to make the idea clear. The new text is:

"Although those events are well described in non-assimilatory ocean simulations, the recent appearance of a massive open-ocean polynya in the Estimating the Circulation and Climate of the Ocean Phase II reanalysis product (ECCO2) raises questions on which mechanisms are responsible for those spurious events and if they are also present in other state-of-the-art assimilatory reanalysis products." - Page 1, Line 9-12.

Thank you again for the suggestions.

Referee #2: Celine Heuzé (celine.heuze@gu.se)

The manuscript has gained a lot in clarity, but part of the narrative is still confusing and does not seem to hold. In particular, from section 3.1 to 3.2, then 3.2 to 3.3, the years where the described events start seem to change. I suggest changes in this document in order to clarify the chronology of the events and verify that the proposed mechanisms are valid.

We would like to thank again the referee for taking the time to review the manuscript in such a detailed manner, and also for all the specific comments. We believe that the valuable review and suggestions have translated into a great enhancement on the manuscript quality. We have noted that the dates of the anomalous events in each sections are different, but that is because the timing of the event in the Sea Ice, Temperature, Salinity and Neutral density is not necessarily the same. For example, when discussing the signature in sea ice averages, the SIC of ECCO2 in Weddell Sea starts to decrease in 2004, even though the polynya had open in November 2003. That is because the sea ice values are annual averages, and since the polynya only appeared in Weddell Sea at the end of 2003; thus the decrease in SIC during this year is not enough to diminish spatially and annually averaged SIC values. In Section 3.3 we highlight that the cooling and freshening of the bottom layer of each sector of ECCO2 happens after 2006, even though the Weddell Polynya opened in November 2003. But that again is because the temperature and salinity anomaly trends are averages for each cell of the model contained within the layer described in the Methods section. Hence, the trends in temperature and salinity only appear in the monthly averages after the newly formed AABW had substantially spread through the bottom layer, i.e. years later. We agree that the lack of this information can create confusion to the reader, and hence the information was added to the text.

For the ECCO2, was added:

"It is important to highlight that the timing of the signals in SIC, SIT, temperature, salinity and neutral density are different. First, even though the polynya appearing in ECCO2 opens in November 2003, the signal of decreasing SIC and SIT appear only from 2004 onwards. That is because the sea ice data used in this study are annual averages, and since the polynya only opened at the end of 2003, its signal was not enough to diminish the SIC and SIT annual averages. Also, even though the polynya was already established in Weddell Sea in 2004, the freshening and cooling signals in the bottom layer of ECCO2 are noticeable only after 2006 (Figure 8c and 8f). Again, that is because the monthly average temperatures and salinities were calculated, for each cell, as a mean weighted by the volume of the cell. Hence, the signals in temperature and salinity only appear in the bottom layer after the new volume of the bottom water has been replaced. Finally, it is also important to note that, even though the Polynya had opened in November 2003, the bottom water production (WSDW and WSBW) signal appeared in the intermediate layer in 2007 onwards (Figure 11e)." – Page 13 , Lines 30 to 33 and Page 14, Lines 1 to 6.

For the SoSE,

"*The timing of the events in SoSE are more tied together, but that is because as soon as the polynya opens, WSDW is formed and transported to the bottom layer (Figure 12c), thus having minimum lag between the ice-free area opening and the WSDW formation. Hence, we can see prior and during the polynya opening a clear warming of the bottom layer and cooling of intermediate layer, which weakened vertical stratification and allowed WSDW to be transported downwards.*" – Page 15, Lines 1 to 4.

And for the UR025.4

"With respect to timing, signals in sea ice variables and ocean variables in UR025.4 had minimum lag. That is because the AABW is formed here rather abruptly. SIT annual averages only reached its peak in Weddell Sea in 2009, even though the AABW formation in this sector occurred in the winter of 2008. However, the sea ice increase in the annual average is noticeable from 2006 until 2009, showing that the major sea ice production happened during this period, which is in agreement with the AABW formation in 2008 at Weddell Sea Sector by brine release. Regarding the salinity anomaly signals in the Indian Ocean Sector, it is possible to see that the minimum salinities happened almost simultaneously in the intermediate and surface level (Figure 9 d and e). That is because the UCDW entrainment responsible for this fresh signal happened simultaneously in the intermediate and surface layer. Moreover, the following high salinity signal in all three layers are simultaneous (Figure 9 d-f), as the newly formed bottom water is swiftly injected to the bottom layer (Supplementary 2). Finally, pulses of WSDW production were described in Weddell Sea sector from 2005 until 2008, however their magnitude were too small to print signatures in temperature and salinity mean values." – Page 18, lines 19 to 29.

Major changes
For each reanalysis, please indicate
- In the text at the beginning of section 3.2, the dates of the polynyas given in section 3.1;

Thank you for the suggestion. As requested, in the paragraphs which we discuss each reanalysis, we added the timing of the polynya opening. For ECCO2, the sentence in page 8 line 9 and 10 was written as "The WDW is warmer and saltier than AASW, so intensive winter surface cooling of this water mass has the potential to form WSDW and even WSBW through open ocean convection". The sentence now is:

"*The WDW is warmer and saltier than AASW, so intensive winter surface cooling of this water mass due to polynya opening from November of 2003 until the end of the reanalysis period has the potential to form WSDW and even WSBW through open ocean convection."* – Page 8, Lines 13 to 15.

And for the SoSE
"*From May until November of 2005, i.e. while an open ocean polynya is open in Weddell Sea, the relatively high-water volume of 32.6% of WDW swiftly decreases to 26% (Figure 3 - WDW)*." – Page 8, Lines 32 and 33.

- On figures 3 to 7, these same dates should be represented as vertical bars with different colours and/or line styles, for example.

Thank you for the suggestion. A green vertical shading bar was added to those figures to highlight the period in which the polynyas stays open in SoSE, and a yellow shading bar for when ECCO2 polynya is open. Figures 3-7 are now located from page 28 to 32.

- In the text at the beginning of section 3.3, the dates at which AABW formation occurs in each sea inferred from figures 3 to 7;

Thank you for the suggestion. The following addition was done in the first paragraph in order to cite the AABW formation dates:

"*The investigation of the temperature and salinity time series focus on the periods and locations of identified AABW formation in each reanalysis output, which in ECCO2 was from 2004 until 2012 at Weddell Sea, Indian Ocean and Western Pacific Sectors; in SoSE at the Weddell Sea in 2005; and in UR025.4 at the Indian Ocean and Western Pacific Sectors in 2004 and Weddell Sea Sector in 2008."* – Page 10, Lines 18 to 21;

- On figures 8 to 10, again potentially as vertical bars or shaded rectangles of different colours for the different regions.

Thank you for the suggestions. Vertical bars were added for the periods of AABW formation in the three reanalysis. Figures 8-10 are now from page 33 to 35.

Then throughout the text, check that you do describe what happens at those dates that are specific to each region and each reanalysis. For example page 11 line 18, you explain that the Weddell Sea sector does not show the same changes as the other two regions in 2004 in UR025.4. That is not surprising, since as you write page 8 lines 22-23, there WSBW is formed only in 2008 and 2009! Likewise, page 12 you write that WSBW formation occurs "in the first few months of the time series" for SoSE, yet your description page 8 mentions WBSW pulses later, in 2006 and 2007.

Thank you again for the suggestion. We agree that is necessary to also cite the dates of AABW production in SoSE after 2005. So the sentence was edited to add the information requested:

"Finally, in SoSE, the WSBW and WSDW formation occur mostly during the first few months of the time series in 2005, with smaller total formation pulses (WSBW +WSDW) in 2006 and 2007 also (Figure 3- WSDW and WSBW)." – Page 12, Lines 19 to 20;

We also agree that the sentence
"The Weddell Sea sector does not show either of these strong freshening or salinity increasing patterns in the intermediate layer."
on page 11, line 18 was redundant, so the sentence was removed from the manuscript.

Minor changes

Throughout the text: despite the language check, there are a lot of typos, blank spaces or letters missing.

Thank you again. The typos and blank spaces were checked.

P1, l9: Change "despite" into "although".

The suggested change was done.

P1, l23: "longer and more elegant" than what?

We agree that the use of the comparative words are incorrect. We instead changed the words to adjectives since we are not using comparison:

"Recently, different groups of experts have developed several state-of-the-art eddy-permitting general ocean circulation models with long simulations, elegant and efficient assimilation methods." – Page 1, Lines 23 to 24;

P3: Potentially split section 2 into two subsections, one about "Reanalysis and observational products" starting line 10, and one about "Methods" starting P5 l7.

We have split the section as proposed. Thank you for the suggestion. Section 2.1 (Ocean Reanalysis Datasets and Observations) starts now on page 3, line 10. Section 2.2 (Methods) starts now in Page 5, Line 8.

P4, l25-26: This sentence has no clear link with the one after. Move it somewhere else, or add some transition.

This sentence was supposed to be located in the end of the previous paragraph, after describing the difference in the simulation frameworks of the three reanalysis products. We agree that it was misplaced during the reviewing process, and hence the phrase was put back in the end of the paragraph, on lines 24 to 26 of page 4.

P5, l32: "their links with the processes being evaluated" – reference needed.

Thank you again. As requested the reference used was added:

"The depth limits of the three layers were chosen specifically due to their links with the processes being evaluated (Orsi et al., 1999)." – Page 6, Lines 1 and 2.

P7, l14: mostly in the Weddell Sea.

Thank you for the suggestion. We added the location reference on the sentence:

"*Although no observational SIT database that efficiently covers the Southern Ocean is currently available to our knowledge, the comparisons among the three reanalysis thicknesses and the magnitudes of the signals suggest an UR025.4 overestimate, especially in Weddell Sea."* – Page 7, Lines 16 to 19.

P8, l12 and l20: this comment is valid throughout the manuscript and was already made during the previous round of reviews: give the actual values! Don't just write that it increases

Thank you for the suggestion. As requested values were added throughout the text. It follows the detailed description of the additions.

- Page 8, previous Lines 13 where it was written "volume percentages increase sharply.", now is written "*volume percentages increase sharply in 10% during the following 4 years."* placed now in line 17.

- Page 8, previous lines 13 and 14 where it was written "During the WSBW formation, WSDW is no longer formed, and rapid conversion of WSDW to WSBW occurs.", now is written "*During the WSBW formation, WSDW is no longer formed, and rapid conversion of 42% of WSDW to WSBW occurs."* placed now in lines 18-19.

- Page 8, previous lines 18 and 19, it was written "Thus, the total volume of AASW declines throughout the time series", now it is "*Thus, the total volume of AASW declines in total 5.5% throughout the time series."* now placed in lines 23 to 24.

- Page 8, previous lines 19 and 20, it was written "During consecutive winters, the WDW volumes drop, whereas the percentages of WSDW and WSBW slightly increase." now is written "*During consecutive winters, the WDW volumes drop by 2 to 6%, whereas the percentages of WSDW and WSBW slightly increase by the same total percentage volume*." now in lines 24 to 26.

P8, l22: for clarity, write ECCO2 instead of "the previous reanalysis product".

The alteration was done as suggested.

P8, l25: the behaviour of SoSE is similar to that of ECCO2 only until 2008. Please discuss what happens from 2008 onwards.

Thank you for the suggestion. We agree that the following paragraph was missing the information on the water mass changes after 2008. Since there is no AABW formation in SoSE after 2008, we then added the following sentence:

"After 2008, SoSE do not show either WSDW or WSBW formation (Figure 3 – WSDW and WSBW), while both AASW and WDW increase steadily by less than 5% from 2008 until 2010." – Page 9, Lines 7 and 8.

Also, to make clear that the similarity described happen only prior to 2008, the first sentence of the paragraph was changed to:

"The SoSE reanalysis product shows similar water mass alterations to that of the ECCO2 product prior to 2008." – Page 8, Line 30.

P10, l13: see major comment, give clearly "the periods and locations".

Thank you again. We agree that detailed pointing of place and timing of AABW formation in each reanalysis was necessary here. The following statements were added:

"*The investigation of the temperature and salinity time series focus on the periods and locations of identified AABW formation in each reanalysis output, which in ECCO2 is from 2004 until 2012 at Weddell Sea, Indian Ocean and Western Pacific Sectors; in SoSE is at Weddell Sea in 2005; and in UR025.4 at Indian Ocean and Western Pacific Sectors in 2004 and Weddell Sea Sector in 2008*." – Page 10, Lines 18 to 21.

P10, l27-28: no, it is not apparent that cooling was the main mechanism. You do not show it, and you even soften your argument several lines later by writing that cooling could be "favouring deep convection". I'd remove the sentence l27-28 and keep the ones after.

Thank you again. As you suggested, we believe that the use of the word "apparent" was misplaced in this part of the text. The idea that was being transmitted was that as density increase is necessary to create AABW, and freshening experienced in ECCO2 sectors would decrease neutral densities, then cooling is likely the process by which waters gained enough density to create AABW. However, the word "apparent" gives an idea of certainty that can be misleading, and hence we changed the phrase to the following structure:

"*Since freshening lowers water mass densities, cooling might be one mechanism responsible for AABW formation in ECCO2."* – Page 11, Lines 3 and 4.

P11, l12: what do you mean by "consistent with the changes in temperature"? That it happens simultaneously? That the increase in salinity and temperature makes sense you think (if so, explain why)?

Yes, we mean simultaneously. For clarity, the sentence was changed to:

"The salinity anomalies in UR025.4 show alterations during the AABW formation period (2004) simultaneously with the changes in temperature. Before 2004, the bottom layer salinity appeared to decrease slowly (Figure 9d)."- Page 11, Lines 20 and 21.

P11, l24 onwards: not proven. You need to talk more about the timing of the events, how the salinity anomaly would propagate from the surface down.

Thank you for this comment. We see that the analysis of AABW formation in Prydz Bay still cast doubts. In order to further clarify the process, we have constructed two animations with SIT anomalies in Prydz Bay and Salinity anomalies too, during the year 2004, i.e. when the AABW is formed. Because the process of AABW formation in this area in UR025.4 is related to sea ice formation, then salinity can be used as a *tracer* of the dense water mass formation, and hence positive salinity anomalies can be linked the waters being formed. In the animation, it is also included the year before the AABW formation (2003), as an example of the natural seasonal cycle in Prydz bay when AABW is not formed. Note in the animation with the sea ice thickness anomaly (Suplementary1.gif), that the depth used is close to the one on figure 13 of the main manuscript, where we show the sea ice velocities. In 2004 (Suplementary1.gif, April-2004), a region with high positive SIT anomalies appear west of Prydz bay, and the water column under it immediately respond with a high salinity signal, from sea ice formation. The high SIT signal persists locally until July, while the high salinity anomaly is present until mid-2005. The period with the highest salinity anomalies happen between May and October of 2004, which is the period where AABW pulse is identified in the section 3.2 of the manuscript, in Indian Ocean Sector. In a second animation, we present salinity anomaly contours, also in Prydz Bay, but in three different depths (457 m, 2262 m, and 3513 m). The deepest contour belongs to the bottom layer definition of the layers used in section 3.3. In this second animation (Suplementary2.gif) it is possible to see that in March the region with high salinity anomaly appears in the intermediate layer. In the following month (April) we can already see that this signal had propagated to the 2262 m layer, and in May it reached the deepest salinity anomaly contour. In the following months (July-2004 until October-2004), we can clearly see the high salinity anomaly moving downwards from the intermediate layer, and spreading laterally, showing that the dense water formed due sea ice formation reached density values enough to be transported to the bottom layer. Even after October 2004, the plume of high salinity persisted in the bottom layer, expanding laterally, showing the lateral advection of this dense saline water. Now, the period of downslope flow of this high salinity water coincides with the period of AABW formation in Indian Ocean Sector in section 3.2, showing that the salinity increase due to brine release was likely the process responsible to raise the neutral density of coastal waters enough to create AABW, and transport it downslope until the bottom layer. The period from October-2004 to Jan-2005, when high salinity waters in the 3513 m layer are still expanding, there was no AABW formation according to the volumes calculated through neutral densities (section 3.2). Hence, we believe the high salinity AABW is only being horizontally advected along that layer.

Relative to the time scales, as can be seen in the animation, one month after the salinity anomalies appear in the intermediate layer, it appears in the top of the bottom layer too. Hence, as the reanalysis has monthly averaged output, it is not possible to calculate accurately the timing of the propagation of salinity anomalies to the bottom layer due to lack of temporal resolution.

We added also the following animations as supporting material to the article, in order to make this explanation available to anybody that has access to the manuscript. Also, the supplementary material content is referenced on the text:
"*In fact, neutral density contours along Prydz Bay show salinity anomalies increasing and being exported to the bottom layer as SIT anomalies grow (Supplementary material)*." – Page 12, Lines 4 to 6.

P13, l4-6: where do you show the properties of the AABW varieties?

Thank you for the comment. In lines 4 to 6, we are specifically addressing the cooling and freshening noticed in the bottom layer properties of ECCO2. Since the bottom layer of the Weddell Sea sector, as divided in the manuscript, is mainly comprised by waters of AABW, the cooling and freshening described in Weddell Sea bottom layer in the section 3.3 translates into a cooling and freshening of AABW. However, it seems that the sentence as described did not properly explained the idea, and hence, that was changed from

"The temperature and salinity decreases described in section 3.3 in the bottom layer of ECCO2 after 2006 are related to the polynya appearance. The AABW varieties formed under the Weddell polynya retain the distinct low salinity and low temperature signals due to heat loss at the surface." - Page 13, Lines 4 to 6.

to "*The temperature and salinity decreases described in section 3.3 in the bottom layer of ECCO2 after 2006 are related to the polynya appearance and AABW formation, since the bottom layer of the Weddell Sea in this reanalysis essentially contains AABW. Hence, since cooling and freshening is present in bottom layer of Weddell Sea sector in ECCO2, we suggest that AABW varieties formed under the Weddell polynya retain the distinct low salinity and low temperature signals due to heat loss at the surface."* – Page 13, Lines 13 to 17.

P14, first paragraph: again, please give the values. What is the "very shallow depth"? What do you mean l10 by "a much smaller scale"? Give depth / volume values.

Thank you again. The suggestions were added as following:

-In page 14, lines 2 and 3, it was added the depth requested (10 m). The phrase now is written as "*From January to May, before the polynya opens, the presence of WDW at 10 m at approximately 70°W is noticeable in the SoSE neutral density transects.*" in lines 25 and 26.

-In page 14, lines 9 and 10, we also added the volume change described by the smaller scale. Now the sentence is written as "*WSDW formation also occurs during the following two winters, but with volumes less than half of the 6% production in 2005."* in lines 32 to 33.

P14: so you seem to say that the polynya opening in SoSE is the consequence of WDW upwelling. What is causing it? You don't need to formally prove it, but check if someone has looked at that already or suggest potential mechanisms.

Thank you for the suggestion. We agree that is necessary to point out which processes could be leading to WDW uplift in the reanalysis. Hence, the following paragraph was added to the text:

"It seems that WDW uprising is the main mechanism responsible for melting the sea ice, and creating the Weddell polynya in both ECCO2 and SoSE. Although out of the scope of this study, some processes can cause isopycnal uplift in Weddell Sea, creating the open ocean polynya. An experiment with global ocean-sea ice model performed by Hirabara et al., (2012) has suggested that a saline surface layer and persistent cyclonic wind stress are necessary to lower vertical stratification and allow WDW uplift over the Maud Rise. In a recent attempt to reproduce the Weddell Polynya, Cheon et al. (2015) has found that the establishment of strong negative wind stress curl in Weddell Sea accelerates the Weddell gyre, causing WDW to upwell in the center of the gyre and melting sea ice. Furthermore, a simulation with the Kiel Climate Model (KCM) has shown that warm waters built-up in Weddell Sea deep layer during non-convective periods, and after decades the heat buffered interact with sea ice opening the Weddell Polynya (Martin et al., 2013)." – Page 15, Lines 15 to 23.

P15, l1: this comment is the one reason I waived my anonymity already in the previous round of reviews: No, this is not what Heuzé et al. (2013) says! As said during the previous review, please change to Kjellsson et al. (2015) or Heuzé et al. (2015). Note that your author response document says you did change it to Heuzé et al. (2015).

You are right. Sorry for the typo. As requested, the reference was changed to Heuzé et al. (2015).

P16, l1: where can that "be seen"?

The use of “be seen” is also misplaced. We changed for “hence”. Now the phrase reads:
“Hence, UR025.4 rather accurately represents both the warm water entrance into Prydz Bay and the density increase along the circulation present in the real world.” – Page 17, Lines 1 to 3.

P16, l6: likewise, where do you show that it is colder and with lower salinity?

Thank you for the comment. We analyzed maps of temperature and salinity anomaly throughout the time series, and through the maps it was possible to see the low temperature and salinity anomalies propagating from Indian Ocean Sector towards Weddell Sea Sector. However, those maps were not shown in the final manuscript. We hence changed the sentences to:

“*Thoroughly inspecting monthly maps of salinity and temperature anomalies (not shown) revealed that UCDW originating from the Indian Ocean entering the Weddell Sea in UR025.4 is colder and with lower salinity than the local WDW in the Weddell Sea, especially due to the melting episode that occurred in Prydz Bay in early 2004.”* – Page 17, lines 7 to 9.

P17, l17: “a higher content” than what?

Thank you. We agree this sentence is confusing. For clarity, we changed to:

“*First, the real AABW formation in the Indian Ocean sector occurs after the modified Circumpolar Deep Water (mCDW) circulates deeper under the ice shelves surrounding Prydz and Vincennes Bays, mixing with the DSW created in the coastal polynyas and increasing its salt content as well as lowering its temperatures (Williams et al., 2016).” - Page 18 , Lines 7 to 10.*

P17, l31: the long-term warming of the bottom waters has been found by other people with other models (although related to your reanalyses). Cite for example Martin et al. (2012) https://link.springer.com/article/10.1007/s00382-012-1586-7 or Dufour et al. (2017) http://journals.ametsoc.org/doi/abs/10.1175/JCLI-D-16-0586.1

Thank you for the suggestions. As requested, we added the reference of both studies mentioned:

“Long term warming of bottom waters have been pointed as a trend also in other non-assimilatory models, such as the Kiel Climate Model (Martin et al., 2013) and Climate models CM2.5 and CM2.6 (Dufour et al., 2017), and in both studies the heat buffered has opened a polynya in Weddell Sea.” – Page 19, Lines 11 to 13.

Figure 8: typo in caption, this figure shows ECCO2, not UR025.4

Thank you for noticing. The typo was fixed.