<u>RESPONSE LETTER</u>

Dear Dr. Matthew Hecht (Editor, Ocean Science)

Please find enclosed a revised manuscript based on submission #OS-2014-12**,** which was originally titled **"ASSESSMENT OF THE ECCO2 REANALYSIS ON THE REPRESENTATION OF ANTARCTIC BOTTOM WATER PROPERTIES"** by M. Azaneu et al. The manuscript has been carefully revised in response to the reviewers' comments and suggestions. The reviewers considered the study an important tool to improve modeling accuracy in the Southern Ocean and of interest to the community. The reviewers indicated that the article presents a careful comparison, being commendably complete. However, their suggestions differ on some important issues. Referee 1 requested to develop the discussion, focusing on the model progression prior to 2004, which preempted the large polynya in the Weddell Sea, and also the effects of this event. In contrast, referee 2 suggested splitting the article and evaluating the reanalysis by considering only the period before the polynya. As previously discussed with the editor, we followed the suggestion of referee 1 and extended the discussion on the polynya event. We sought to accommodate both reviewers' opinions throughout the text. Detailed responses (**R**) to the reviewers' comments are shown in *italics* below. Revised sentences are indicated with blue font. We thank the reviewers for their suggestions, which substantially improved the manuscript. Additionally, the manuscript was carefully revised by a professional English language editing service.

Sincerely,

Marina Azaneu

(Corresponding author)

Authors Responses (R) to Reviewers:

<u>Referee 1:</u>

General Comments

This manuscript discusses compares water properties (theta, salinity, and neutral density), velocities, and AABW transports from the ECCO2 reanalysis against observations within the Southern Ocean. The manuscript is reasonably well written, and the material is probably of interest to the community. However, there are a number of flaws. First, while the manuscript is commendably complete, it is long and difficult to wade through. It lacks a unifying story, but the good news is that there is one which could be told. Second, the manuscript has way too many tiny little figures. These are so small that they appear to be jokes. Many of them must be magnified to 3x their nominal size to be able to read them. This deficit needs to be fixed by reducing the number of panels in many figures and arranging them so they use more of the page. Third, paragraphs are often rambling, and lacking topic sentences. Repetition of figure captions within the text adds unnecessarily to the rambling and the length. Fourth, the manuscript is full of vague and unqualified assessments like "adequate", "fair", or "good". The reader is left asking "good for what"? Very frequently the comparison shows persistent biases or large discrepancies between data and observation, yet the reanalysis output are deemed good in the end. The conclusions often seem divorced from the careful comparisons that proceed them. Specific comments follow, indexed by page and line number as appropriate.

R. *We thank the reviewer for his/her valuable review of our manuscript. Following the reviewer's suggestions, the manuscript was reorganized and rewritten to eliminate unnecessary text and enhance the flow of the text. The article's discussion was extended to include the "unifying story", which was necessary to improve the article. We also reevaluated the conclusions to better represent the results obtained from the careful comparisons performed in this study. Moreover, we followed the reviewer's and editor's opinion and gave more attention to the polynya events and the model progression prior to the event. Unqualified assessments were removed from our evaluations; these statements were replaced with quantified comparisons when appropriate. We agree with the reviewer that some figures had too many panels, which made it difficult to visualize the information. In some cases, we have originally submitted the different panels (i.e., a, b,…) on separated pages; however, the figures were presented in grouped in Ocean Science Discussion. We sought to decrease the number of figure panels, rearrange them when possible and improve the figures. In addition, figures considered as complementary information were moved to the supplemental material.*

Specific comments:

1. The title might be better written: "Assessment of the representation of Antarctic Bottom Water properties in the ECCO2 reanalysis."

R. *We thank the reviewer for this suggestion. The title was changed accordingly.*

2. The authors might find Wunsch and Hemibach (in press J. Phys. Oceanogr.) of interest, since it attempts to use ECCO2 output to look at global deep ocean temperature changes in recent decades.

R. *We thank the referee for suggesting the additional study for inclusion in the present work. The suggested reference is now included in Lines 124–133 (see below). However, the added reference uses the ECCO product, not the ECCO2 product (which was used in our study). The products differ in several ways, such as the resolution, the numerical algorithm for fitting and the surface forcings.*

"The original ECCO project was established in 1998 as part of the World Ocean Circulation Experiment (WOCE), with the intent of generating a quantitative reproduction of the time-evolution of ocean states (Menemenlis et al., 2008); this project has focused on decadal and long-term climate changes (Wunsch, 2009). For example, Wunsch and Hemibach (2014) used an updated ECCO product to describe temperature and heat content changes primarily in the abyssal ocean. The authors found a linearly decreasing trend in the integrated global heat content below 2000 m. Moreover, they also found an important regional heterogeneity that was most evident with respect to a warming in the western Atlantic and sectors of the deep Southern Ocean. However, previous ECCO solutions were limited by the coarse resolution and absence of sea ice representation."

3. There does seem to be a unifying story here that could be used. It seems that the coarse resolution and lack of ice shelf processes make AABW formation weak in the first part of the reanalysis period, until a Polynya opens up and floods the Weddell Sea with AABW. This is highly reminiscent of work by Martin and Latif over the past few years, and more recently a 2014 article in Nature Climate Change by some other authors. In these works, which analyze coarse resolution models, it is argued that heat builds up in the Southern ocean until it melts sea ice and a polynya opens, cooling the ocean interior and forming bottom water the only way these models can. Perhaps something similar is happening here, since the model does not allow much AABW to be formed on the shelf. Thus the AABW properties are too warm and velocities and transports are weak early on in the reanalysis period, and then the polynya opens up, flooding the deep Southern Ocean with a very unrealistic amount of very dense AABW.

R. *We acknowledge the reviewer for the valuable comments. The studies of Martin et al., 2013 and de Lavergne et al. 2014 contributed to improving the basis of the article's discussion and broadened the* *understanding of the possible process and modifications occurring in the ECCO2 reanalysis. Please see an example of a passage that was added to the revised manuscript (Lines 843–854):*

"We believe that the difficulty in reproducing the export of dense waters along the continental slope in the reanalysis, which produces less dense deep and bottom layers, results in a less stratified Southern Ocean, as suggested by de Lavergne et al. (2014). The warming trend of AABW and the pronounced seasonality of sea ice are also important contributors to decreases in the stability of the water column and create favorable conditions for the initiation of deep convection. Thus, warmer waters in the deep and bottom layers and saltier waters at the surface should be the determinant factors for convective mixing and the homogenization of the water column in the ECCO2 reanalysis. The heat transported to the surface melts the sea ice and hinders the formation of new ice, leading to the opening and the maintenance of the large oceanic polynya after 2004. Deep waters become colder due to heat loss at the surface, leading to the production of dense waters at deeper levels (typically below 2000 m) in the Weddell Sea after 2004."

4. P1024, L14. A reanalysis produces output, not data. Please fix this error throughout the manuscript.

R. *When referring to the reanalysis, "data" was replaced with "output".*

5. P1024, L19. Change "deep" to "bottom".

R. *The text was changed accordingly.*

6. P1025, L11-12. The amount and distribution of AABW in the global ocean is quantified in Johnson (2008, J. Geophys. Res.).

R. *The following was added to the revised manuscript on Line 42:*

"Antarctic Bottom Water (AABW) covers ca. 58% of the ocean's abyssal layer and fills and ventilates the deepest basins of the global ocean (Johnson et al. 2008)."

7. P1026, L11. Change "Eventually" to "Occasionally".

R. *The text was changed accordingly.*

8. P1026, L21-22. Change "Most of . . . up to 80%" to "Antarctic Sea Ice area undergoes a large seasonal cycle, varying by up to 80%." Also, surely there are more recent works on this than Zwally et al. (1979), Cavalieri and Parkinson (2008, J. Geophy. Res.) takes advantage of many years of satellite data, for instance.

R. *The sentence was changed and the reference was updated in the revised manuscript as follows (Lines 77–78):*

"The Antarctic Sea Ice area undergoes a large seasonal cycle, varying in extent by approximately 83% *(Parkinson and Cavalieri, 2012)."*

9. P1027, L9-11. Recent AABW salinity changes are described around Antarctic in Purkey and Johnson (2013, J. Climate).

R. *The suggested reference was added to Lines 94–96:*

"Freshening of the deep Amundsen–Bellingshausen, Australian–Antarctic and Weddell Basins between 1991 and 2008 was also identified in WOCE data; the latter basin exhibited the smallest trend (Purkey and Johnson, 2013)."

10. P1027, L19. Huhn et al. (2013, Deep-Sea Res. I) should also be of interest here regarding recent reductions in Weddell Sea deep and bottom water ventilation.

R. *We agree. We added the following sentence regarding the suggested reference (Lines 104–109):*

"Reduced AABW volume can result from changes in the properties of the produced dense water or from a decrease in its formation rate. The latter can be one of the factors linked to the aging and reduced ventilation rate of WSBW and WSDW at the Prime Meridian between 1984 and 2011 (15% and 21% reductions in the ventilation rates, respectively); larger reductions in the ventilation rates of WSBW near the bottom water sources (26–30%) occurred during the period 1992–2011 (Huhn et al., 2013)."

11. P1027, L23. Change "Ocean modeling powered . . . products" to "Assimilation of data into ocean models".

R. *This sentence was modified accordingly (Lines 112–113).*

12. P1029, L10. Change "ARGO" to "Argo" throughout.

R. *The text was changed accordingly.*

13. P1030, L15 and throughout the manuscript. Sentences like "Figure 1 shows . . ." or "are presented in Fig. 2", or "Table 1 lists" generally duplicate figure or table captions, wasting space. Always try to start paragraphs with a topic sentence, then devote the rest of that paragraph to supporting that topic. Try to refer to figures and table parenthetically as they support that topic, describing them only as that description advances an argument. Doing this for each paragraph will make the manuscript shorter, better focused, and much more readable.

R. *We thank the referee for the recommendation. We modified the manuscript to follow this structure.*

14. P1034, L20. Change "seek" to "sought".

R. *The text was changed accordingly.*

15. P1035, L11. Change "closer" to "closest".

R. *The text was changed accordingly.*

16. P1035, L4-7. This is a great example of tuning a metric to accommodate a model failure. Because the model fails to make a sufficiently cold water mass, but also makes it much too salty, just switch to density and then it is possible to say it is "adequate", because the errors in temperature and salinity partly compensate in density.

R. *The choice of γ^n= 28.27 kg m^{-3} as the threshold for comparing AABW transport with the results of Fukamachi (2010) was not intended to accommodate a model failure. In recent studies, AABW is often defined as water mass with neutral density $\gamma^n \geq 28.27$ kg m^{-3} south of the Subantarctic Front (e.g., Whitworth et al., 1998; Orsi et al., 1999; Talley et al., 2011; Kerr et al., 2012; Azaneu et al., 2013; Huhn et al., 2013; Ohshima et al., 2013; van Sebille et al., 2013; Jullion et al., 2013), which is generally coincident with the 0°C isotherm in the open ocean. We used the typical neutral density threshold for the evaluation of hydrographic properties and variability of AABW (e.g., Sections 2.3 and 2.4.3) and decided to maintain the same definition throughout the manuscript for consistency. The absence of the* *threshold used by Fukamachi (2010) for defining AABW (Θ=0°C) in the ECCO2 product is indicated in the text and reinforces the fact that the reanalysis product is warmer than expected (which is noted in our results). Moreover, the AABW hydrographic properties, as temperature, salinity and density, are properly compared and discussed in Sections 3.1 and 3.2. Section 3.3 focuses on the transport and variability of AABW. We believe that the choice of a commonly used definition for AABW is acceptable for the presented comparisons. We modified the sentence to more clearly convey the reasons for choosing the AABW definition and also to highlight the model deficiency as follows:*

*"*The AABW definition used for the volume transport calculation follows our previously defined threshold (i.e., $\gamma^n = 28.27$ kg m^{-3}) for consistency throughout the manuscript. However, in this section, it is important to notice that the AABW produced by the reanalysis is warmer than expected. Consequently, the isotherm limit used by Fukamachi (2010) (i.e., waters colder than 0°C) is not present in the reanalysis section during the comparison period.*"* (Lines 313–318)

17. P1040. Wouldn't it be better to describe the formation of the polynya immediately, then proceed with the rest of the analysis, discarding the polynya period for most time averaged analyses and retaining it as appropriate to show its effect in some of the time-series analyses?

R. *We agree with the referee's suggestion. We moved the polynya description to the beginning of the results section (Section 3.1). We also discarded the polynya period for most of the time-averaged analyses.*

18. P1043, L16 and following. Should "narrow" be replaced with "thin"?

R. *The word "narrower" was replaced by "thinner".*

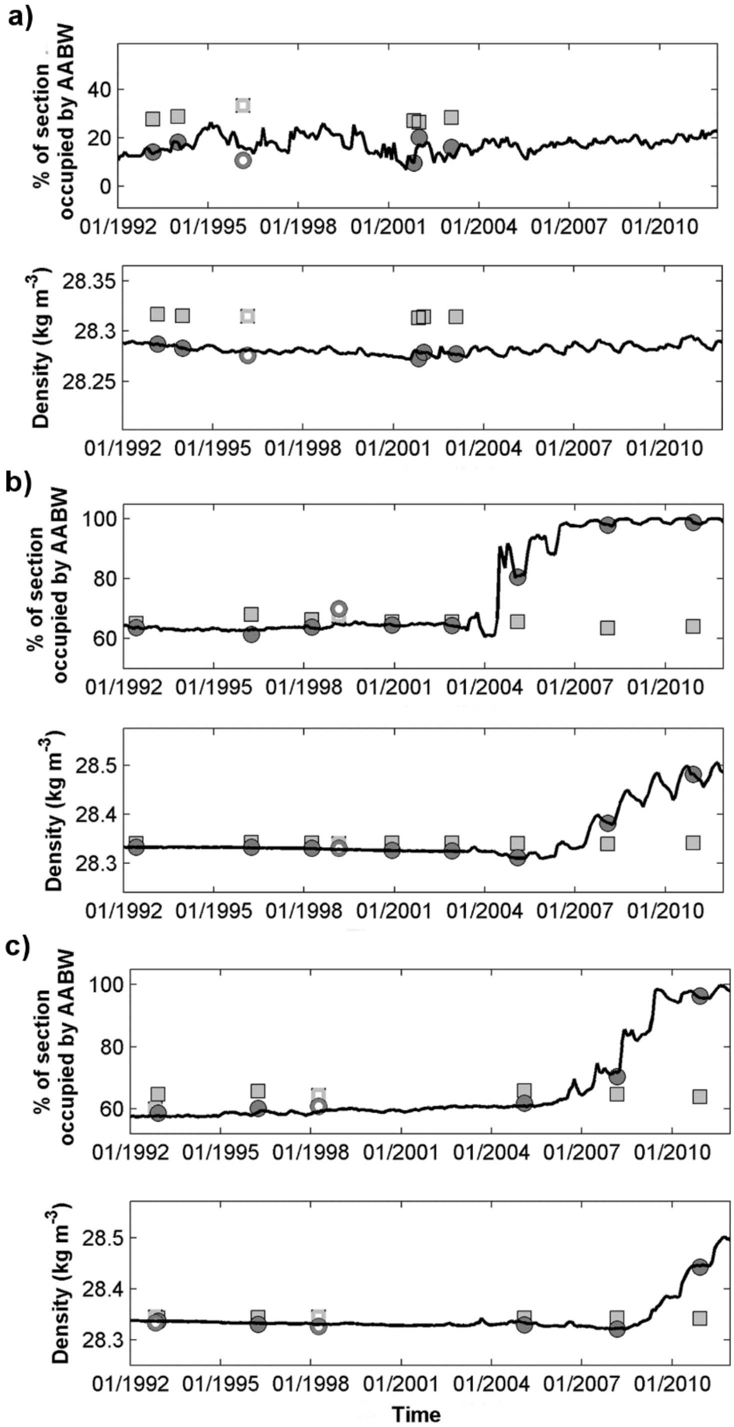
19. P1045, L3-14. This paragraph seems important, but it is unclear. Please rewrite it.

R. *We agree. The paragraph was rewritten for clarity as follows:*

"The property fields of the sections within the Weddell Sea and along the Prime Meridian are consistent between the reanalysis and in situ data, which is indicated by the highly coincidental 0°C isotherm and 34.64 isohaline (Figs. 10 and 11). The major regional features are represented by the reanalysis output, e.g., the characteristic doming of the Weddell Sea cyclonic gyre (Fahrbach et al., 2004) and the signature of the Antarctic slope front, which is a boundary between the shelf waters and the Circumpolar Deep Water over the Antarctic continental slope (Jacobs, 1991). The warm core of the WDW that is adjacent to the continental shelf is represented in the reanalysis for both sections. Despite the coincident 0°C isotherm, the bottom waters do not reach the low temperatures of the WSBW (-0.7°C). Consequently, the bottom waters are lighter than expected in both sections in the reanalysis product (Figs. 10 and 11, panel γ^n_{rea}–γ^n_{obs}); however, there is good agreement in the AABW upper limit. Therefore, in the sections within the Weddell Sea, the absence of the denser AABW variety (WSBW) is compensated for in terms of volume by the WSDW. However, for section WOCE SR3, the 28.27 kg m^{-3} isopycnal is deeper and, consequently, the dense water layer is thinner. The density overestimation at the western end of WOCE SR4 is not associated with a dense downward flow along the continental slope. Instead, this overestimation is a result of the combination of waters that are saltier (~100 to 400 m) and colder (~400 to 1500 m) than suggested by the in situ data. The downward flow is not identifiable in any of the cross-slope sections." (Lines 528–545)

20. P1045, L24 and following. Aren't the cross-sectional area of AABW and the depth of its upper limit closely related? Why not just use one or the other?

R. *We agree. The estimation of the upper AABW limit is not included in the revised version of the manuscript. Please refer to the modified figure below (which is included in the revised manuscript as Fig. 12).*



The percentage of the section area occupied by the AABW (upper panels) and AABW (bottom panels) layer average density for the WOCE repeat sections (a) SR3, (b) SR2, and (c) SR4. Squares denote the observed estimates. The reanalysis estimates restricted to in situ data availability are represented by circles. Open markers denote incomplete section occupation. Black lines refer to estimates based on the complete spatial and temporal ECCO2 data.

21. P1047, L11 and following. Again, the bottom water is much too warm and salty, so just consider density so the two errors compensate and agreement is good. This is not convincing.

R. *As discussed in question 16, we believe that the choice of the 28.27 kg m^{-3} isopycnal threshold for defining AABW is reasonable for determining its transport and thickness. In addition, to call attention to this issue in the methodology section, we also modified the sentence highlighted by the reviewer to emphasize the problems related to the reanalysis product (Lines 592–595):*

"Based on the 28.27 kg m^{-3} γ^n isopycnal, the AABW layer exhibits a thickness of approximately 1500 m in the ECCO2 reanalysis, which coincides with F10 estimates (see the supplemental material; Fig. S3). However, it is important to notice that the AABW layer is warmer in the reanalysis than in the observations presented by F10."

22. P1057, L25 and following, Purkey and Johnson (2013) estimate basin-averaged rates of salinity change for AABW in recent decades that might be useful here.

R. *We agree and added the suggested reference in Lines 94–96:*

"Freshening of the deep Amundsen–Bellingshausen, Australian–Antarctic and Weddell Basins between 1991 and 2008 was also identified in WOCE data; the latter basin exhibited the smallest trend (Purkey and Johnson, 2013)."

23. P1058, L5-7 and elsewhere. Considering the volume-averaged properties of AABW below an isopycnal is not a good choice, as the convoluted discussion here and elsewhere shows. The size of the control volume and the volume-averaged density both change with time, which leads to results that are difficult to interpret. It is better to stick to changes on pressure surfaces, density surfaces, or in Theta-S space.

R. *We agree with the referee that the volume-averaged properties of AABW around the entire Southern Ocean can cause misleading interpretations. We decided to exclude the rate of change for the entire Southern Ocean, providing only estimates for the individual ocean sectors. We also performed sensitivity tests using area-weighted averages for determining the temporal trends (as performed by Heuzé et al., 2013); however, no significant changes were found.*

24. P1061, L11-12. Is a reanalysis that first fails to make enough AABW and has overly warm and salty varieties until a polynya opens up to flood the abyss with huge volumes of unrealistically dense AABW of "good quality".

R. *After modifying the structure and discussion topics in the article, we carefully reevaluated our conclusions to provide a fairer depiction of the results and discussion. Please see the "Summary and Conclusions" section.*

25. P1064, L5-15. If one just read this paragraph, one would think ECCO2 was great in the Southern Ocean, yet the manuscript details so many deficiencies in physics and discrepancies in water properties and transports.

R. *We agree with the referee. The conclusions were modified accordingly to represent the new discussion directions.*

26. Figure 2 is horrible. The brown blobs almost completely cover the grey blobs, making meaningful comparison impossible. Also, isn't the focus here on AABW? Skip the full water column T-S, and show the deep T-S diagrams. Just use two colors, one for the data and one for the reanalysis output. Lay approximate neutral density contours over the top.

R. *We agree with the referee. Considering that the focus is on AABW, we maintained only the* θ–S *diagram for the water column below 500 m. The markers were reduced in size to provide a better visualization of the information. We used only two colors to distinguish between the datasets and added the proximal neutral density surfaces.*

27. **Figure 3** is also pretty bad. The maps are tiny. Only data-output density differences are shown, making it hard to see what the reanalysis compares to data in temperature or salinity.

R. *For better visualization, we split Fig. 3 into Figs. 5, 6 and 7. We also increased the size of the numbers in the color scale. The color scales were also adjusted to coincide with the text. Complementary figures for the temperature and salinity difference fields were added to the supplemental material.*

28. **Figure 4.** Is there some better way to show the changes than with 20 tiny postagestamp size maps? How about two time series near Maude Rise? If the postage stamps are absolutely necessary, please get rid of the longitude labels and make the maps bigger.

R. *Following the reviewer's suggestion, we omitted part of the maps' coordinates. We also reduced the number of maps presented and increased their sizes. Fig. 4 is now Fig. 3 in the revised text.*

29. **Figure 5.** Note the time-period compared on this Taylor Diagram in the figure caption.

R. *We improved the figure by increasing its resolution and also by replacing the sector labels with numbers, as suggested. The time period used for the comparison was also added to the caption of Fig. 5 (which is Fig. 8 in the revised manuscript).*

30. **Figure 6.** Again, these sections are tiny. At least get rid of the maps and just refer to Fig. 1, but could these maybe be redone to show the difference in properties as colors with the properties of the observations overlaid as contours. Then you would only need to squeeze 9 sections and 3 T-S diagrams onto one page!

R. *For better visualization, we split Fig. 6 into Figs. 9, 10 and 11. Moreover, the panels referring to the observed averages, TS diagrams and the map were removed. The color scale for salinity was modified according to the suggestions. Complementary information regarding temperature and salinity differences was added to the supplemental material.*

31. **Figure 7.** The top and middle panels, while not quite duplicates, show similar information. Why not **get rid of the middle panels**, allowing a bit more room for the remaining plots?

R. *We agree. The middle panels were removed from Fig. 7 (which is Fig. 12 in the revised manuscript).*

32. **Figure 13.** More tiny postage-stamp sized maps! Get rid of the longitude labels, consider getting rid of the top 5 maps on the right side, and figure out a lay-out that uses the page and allows for much bigger maps. Alternately, devise time series plots (either for the entire region or for a few sectors).

R. *To improve the figures, the longitude information was decreased and the panels referring to the AABW volume anomaly were removed. Fig. 13 is Fig. 18 in the revised manuscript.*