

## ***Interactive comment on “On the export of dense water from the Weddell and Ross Seas” by R. Kerr et al.***

**R. Kerr et al.**

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We thank reviewer #2 for suggestions and very constructive comments, which have significantly contributed to improve this m/s. Our reply following the list of the reviewer comments.

Referee 2:

General comments: The authors describe seasonal and interannual variabilities of water mass export from the Weddell and Ross Seas, based on a state-of-the-art ice-ocean coupled model (OCCAM). For the interannual variability, they show spatial and time varying characteristics of dense water export from the basins and shelf water mass, and find a coherent variation between the two, mainly due to the change of the

C731

wind driven ocean circulation. I think the topic is generally interesting and important for Antarctic research. The structure and analysis method of the paper are totally reasonable and all figures are fine. Therefore, I think this paper is basically worth for publishing in Ocean Science.

However, I have one critical concern about the definition for estimating (dense water) export, and my decision for the current manuscript is major revision. In this paper, water export are estimated by calculating the transport across some specified sections. I think that this calculation leads to underestimate or overestimate for the exports. (For example, some changes of the position of density front could easily and largely modify the estimated value.) In particular, I think that the export from dense shelf water formation area should be defined by all export from shallower region to deeper region in continental shelf (i.e. export across shelf break) to take account of all dense shelf water mass formation over the continental shelf. Moreover, for the current AABW estimation, I could not separate the transport over continental shelf (upper layer) or over continental slope and rise (lower layer). I think export in the lower layer should be treated as AABW transport.

AR: We agree with the reviewer in this point that the m/s does not fully explore the issue of dense water export. However, it is, in general, out of the scope of this study to investigate the dense shelf water outflow into the deep ocean using OCCAM model. These results are presented in a more comprehensive way in R. Kerr's PhD thesis. In fact, the model did not reproduce AABW formation very well around the Antarctic margins, which was expected due to the model spatial resolution, lack of tides, lack of ice shelves, and weaknesses in the sea ice model. Therefore, we think that deep ocean convection may also be acting as AABW sources in this particular run. Hence, we present some results in the m/s showing the dense water outflow into the deep ocean through the analysis of NW Weddell Sea formation section, which is the only region in the OCCAM model that displays a satisfactory result related to AABW production near the shelf-break.

C732

To avoid confusion when we are talking about the AABW flow around the continental slope (and consequently export to global ocean) and dense shelf water spilling off the shelf, we have renamed the sections following the reviewer's 2 suggestion. Thus, we have now: (i) Weddell and Ross Sea Export Sections (the same as presented in OSD m/s), (ii) Weddell and Ross Sea Southern Sections (referring to the old "formation" sections in the southern regions), and (iii) Weddell Sea Formation Section (that refers to the old NW Weddell Formation Section). We think that re-labeling the sections as indicated above clarifies that the volume transport in the Export and Southern sections are primarily the lateral transports of recirculating and new AABW varieties in the Weddell and Ross Seas (e.g. WSBW and WSDW in the Weddell Sea). Thus, we would not compare the transport across the Southern Sections with estimates of rates of AABW production in the real ocean, which was a concern pointed out by the reviewer.

Specific Comments: [1. Introduction] I think this introduction is well written. (P1660/L27-28) "..., therefore modelling results ... an alternative way to ...on AABW export." I think the expression is too strong. This sentence is only valid when the model shows perfect performance. I recommend that authors rephrase it.

AR: The sentence was rephrased to "Therefore modelling results are an alternative way to fill those gaps and, in this study, to address the impact of source water variability on AABW export.

[2. Model description and forcing] (P1661/L11-14) Remove the sentences. Why do you describe a different model (NCAR-CCSM) performance in section 2?

AR: The sentence was removed.

(P1661/L24) "explicitly" Does the effect of ice shelves, icebergs, and runoff from ice sheet include implicitly in the model?

AR: We rephrased the sentence to clarify this point. Please see below.

"However, cryosphere processes related to ice shelves, icebergs and ice sheet runoff

C733

are not included in the model."

(P1661/L25) "66 levels" Generally, a Z-coordinate model has difficulty to simulate downslope flow of dense water over continental slope (Wang et. al 2008). Does the model have enough vertical resolution for reproducing AABW formation processes? Reference: Q. Wang, S. Danilov, and J. Schroter (2008), Comparison of overflow simulations on different vertical grids using the Finite Element Ocean circulation Model. *Ocean Modelling* 20, 313-335

AR: We agree with the reviewer's comment and as also highlighted by Reviewer 1 we include a sentence that talk about some deficiencies of the model used in this study to better reproduce AABW formation in the shelf-break zone. Please see below the full paragraph inserted in the m/s.

"It is well known that the shape of the ocean floor and, specially, the seabed corrugations act to steer the main downslope flow of dense shelf waters towards the deep ocean, thus impacting directly the contribution of AABW. This was recently highlighted by Muench et al. (2009) for the Northwestern Ross Sea. They point out that corrugations enhance entrainment and reduce along-slope speed of the dense outflow. Thus, the authors show the importance of considering small-scale local topography when modeling dense outflows. The bathymetry used in OCCAM does not benefit from recent high resolution swath bathymetric surveys around the Antarctic and therefore may be locally incorrect and/or too smooth. However, comparing a latitudinal section of the OCCAM's bottom volume transport spilling off the shelf (not shown) in the Northwestern Weddell Sea with results obtained from Gordon and Muench (1995; see their Fig. 8) in an approximately similar area, the main direction of OCCAM's volume transport in this area agrees with that shown by Gordon and Muench. Additionally, export of deep and bottom water from the Ross Sea is particularly sensitive to tides (Padman et al., 2009), however the model output used here does not allow investigation of this influence. By the way, it is indicated that a Z-coordinate model has some difficulty to simulate downslope flow of dense water over continental slope (Wang et al., 2008)."

C734

(P1662/L9-11) "Sea ice ... in each affected grid cell" Is this description for an initial condition for sea ice field?

AR: Yes. This topic was clarified in the m/s as indicated above when we are answering to Reviewer 1.

[3. Southern Ocean representation] As mentioned above, please consider to redefine the estimation of AABW and shelf water exports. Since this paper is model-based study, the more precise and consistent definition for the exports in the model should be used.

AR: Please see the first answer to Reviewer 2, when we explain the changes made.

[3.1 Modelled hydrographic sections] (P1663/2nd paragraph and Fig. 2) In my reading, HSSW is also missing in Figs. 2a, 2c, and 2e. Therefore, I could not reach the conclusion in L23-L24 ("the water masses ... represented reasonably well in the sections (Fig. 2)")

AR: We have changed the sentence (please see below) and include some additional information that was not present previously in the m/s, but allow us to consider a good representation of HSSW in the model. "The reasons of HSSW absence in some of the  $\sigma_t$ -S diagrams shown (e.g. Fig. 2a) are related to the fact that only a small part of the export and southern sections are over the continental shelf. Model-observation water mass properties statistical comparison through Taylor diagrams (R. Kerr PhD thesis 2010, not shown) also support the good representation of the modelled hydrographical sections used in this study. That is particularly true for those regions with repeat observations (e.g. Weddell Sea export section)."

(P1664/L1-4) "We conclude ..., which provides a high degree of confidence in the analysis of the model time series" There isn't any result of time series of water masses.

AR: We rephrased the sentence. See below. "We show that OCCAM preserves the observed general  $\sigma_t$ -S shape but it also represents the pattern of water mass structure

C735

for both coastal and deep ocean in the Antarctic continental margins (Fig. 2), which provides a high degree of confidence to perform subsequent analysis of the model time series."

[3.2 AABW source layers depth] For discussing water masses which are separated by neutral density surfaces, some more information (e.g. contours of 28.00 and 28.27 of neutral density) should be overlaid in Fig. 3. In alternative way (and its direct way), authors can discuss water masses averaged over the neutral density layer.

AR: This section was included in the m/s only to report how the model is representing the AABW source layers, we have added the neutral density surface isopycnals in Fig. 3 as suggested by the reviewer.

(P1664/L26-27) "the highest salinity plume .." Is there any result or reference that supports this sentence?

AR: We have added the reference below that discuss about the plumes over the western Ross Sea continental slope. Gordon, A. L., Zambianchi, E., Orsi, A., Visbeck, M., Giulivi, C. F., Whitworth III, T., and Spezie, G. (2004). Energetic plumes over the western Ross Sea continental slope, *Geophysical Research Letters*, 31, L21302, doi:10.1029/2004GL020785.

[4. Cross-section volume transport] [4.1 Full-depth volume transport] The volume transport of the gyre should be described by one value (e.g. maximum value of barotropic stream function). I think that the difference between export and formation sections indicates missing flow branches of the gyre in the estimation.

AR: We have added this information, please see below. "The gyre transports at the two locations are not the same because the sections as shown do not include the whole of the Weddell/Ross Gyre transports, which can be indicating missing flow branches of the gyre in that estimation."

(P1666/L6-9) "Nevertheless, the OCCAM model ..." Judging from the mean, the vari-

C736

ance, and the trend (Fig. 4 a-b), the sentence could not be a reason for underestimation of full-depth volume transport.

AR: The OCCAM values show transports of a similar magnitude of the ADELIE summer measurements only during winter months. So, we include this information in the paragraph to clarify the sentence. Please see below. "Nevertheless, although OCCAM simulation show winter transports (Fig. 4a) of a similar magnitude of that reported by ADELIE summer observation, the OCCAM model transports represents an average over 17-year period and one might expect them to be less than some observed values from snapshot cruises or short time series (< 3 years), which are subject to short-term variability and/or long-term trends."

[4.2 Bottom layer definition] (P1666/L19-20) "Moreover, OCCAM model.." Add some references that show the model performance for reproducing bottom waters around Antarctica.

AR: We have added the reference of Renner et al. (2009).

(P1666/L20-22) "This can be clearly seen ..." A figure based on observation (temperature and density) is needed for the comparison against the model result (Fig. 5).

AR: We have cited the reference of the Southern Ocean Atlas (below) for comparison with the figure. However, considering the benefit to the whole m/s, we do not think that an observed climatology Figure is essential in this case. Orsi., A. H., T. Whitworth III, Hydrographic Atlas of the World Ocean Circulation Experiment (WOCE). Volume 1: Southern Ocean (eds. M. Sparrow, P. Chapman and J. Gould), International WOCE Project Office, Southampton, U.K., ISBN 0-904175-49-9. 2004.

[4.3 bottom layer volume transport] (P1667/2nd paragraph and Fig. 7) Instead of performing normalization, I recommend that authors use the right vertical axis (different scale from the left axis) to show the counterpart timeseries. I think that the difference of absolute value is important information when comparing the model result with ob-

C737

ervation.

AR: Done. Figure 7 now show the absolute values instead of normalized ones.

(P1668/L1) "slightly" It seems that the modeled mean transport of 0.5 Sv is much lower than the observed one (1.95 Sv). It is not a "slightly" difference.

AR: The word was removed.

(P1669/L15-16) Why does the variability export from the Ross Sea formation section show low?

AR: As previously reported the model has some deficiencies to reproduce the AABW production in the shelf-break zones. This is particularly true for the Ross Sea, where the model AABW production is generally below 0.5 Sv. Thus, this could be reflecting in low energy associated with AABW export variability in this region. On the other hand, although the model transports was validated with observations in the Weddell Sea, we cannot find AABW export time series available for comparison of the AABW export in the Ross Sea. We assume in this case that there is no reason to consider that the AABW export variability is not represented, as good as presented in the Weddell Sea, in other areas around the continent. We added the comments in the m/s. Please, see below.

"This low energy can be related to the model deficiencies to reproduce the AABW production in the shelf-break zones, probably due to resolution issues. This is particularly true for the Ross Sea, where the model AABW production is generally below 0.5 Sv. On the other hand, although the simulated AABW transport was validated with observations in the Northwestern Weddell Sea, we cannot find available time series for comparison of the AABW export in the Ross Sea"

(P1669/L16-22) Although a reference (Venegas and Drinkwater 2001) is cited for the explanation of the export variability shown in Fig. 9, I think that some results are needed to show dynamical link between dense water export and surface variables

C738

(wind, temperature, sea ice production, and so on).

AR: As explained above and following both the reviewer's suggestions we inserted a sentence in the m/s that talk about lagged correlations between the wind and AABW export time series in the Weddell Sea. Please see below.

"To show dynamical link between AABW export and surface variables we performed a lagged correlation between zonal wind stress (defined here as the annual mean between 60°S and 65°S - 040°W and 020°E) and AABW export time series in the Weddell Sea export section. The result (not shown) unveils the highest correlations with a five months lag (36%) and around lag-0 (25-35%). The former was the same period of influence previously reported by Jullion et al. (2010) study, which revealed that the variability in the wind stress field over the Weddell Sea leads changes in AABW properties in the Eastern Drake Passage by approximately five months. Moreover, the same study suggested that the variability in AABW properties over that same area could be controlled by AABW export from the Weddell Sea."

[5. Correlations between AABW sources properties and deep ocean export] In my reading, judging from timeseries in Fig. 10, the high correlation in the section 5 is achieved by decadal variability (a low state in 1990-1994, and high states in 1988-1989 and 1999-2005). Is the discussion/timescale of correlation analysis in this section consistent with those in the previous sections?

AR: Yes, it is. The previous analysis, based on wavelet power spectrum, shows high energy during periods of 1 and 2-4 yr, but also it is present high variability of a period of 8 yr (that is not shown, as it lays out of the cone of influence). The total span of OCCAM time series used (i.e. 17 yr) does not allow us to see and to discuss more about decadal changes in AABW volume transport.

(P1671/L4-5) "faster or slower phase of the wind-driven Weddell Gyre" What does this phrase mean?

C739

AR: We clarified this sentence in the text, please see below. "...probably because both are associated with faster or slower periods of the wind-driven Weddell Gyre."

(P1671/L16-18) "Finally, another positive feedback ..." I didn't understand the sentence at all. If it is important, please add more explanation.

AR: To avoid confusion the sentence was removed.

(P1672/L11-15) "Thus, the correlation maps are" In Hellmer et al 2011, there is a freshening trend (0.09 psu / 17 years) over the northwestern Weddell Sea continental shelf. In timeseries of salinity anomaly in Fig. 10, however, there is a significant increasing trend in the salinity over the northwestern Weddell Sea continental shelf. Is it possible to discuss the phenomena associated with observed freshening trend?

AR: Ours findings reveal a phase correlation between AABW volume export and shelf waters salinity in the NW Weddell Sea time series, thus evidence that freshening trends could be used as a proxy to determine variations (decreasing in this case) of AABW export. We are not interested at this time to determine properties trends from the model outputs, but to relate possible properties changes and variability with AABW export. In addition, Hellmer et al. (2011) show the steepest freshening trend between 1989 and 1997, a period that agrees with the highest OCCAM salinity anomaly found between 1989 and 1994 in the model. The observed freshening trend between 1997 and 2006 is not so intense as in the previous years, and the model show alternating periods of freshening also not so intense after 1997. We added this comment in the m/s. Please, see below.

"Additionally, Hellmer et al. (2011) show the steepest freshening trend in the tip of the Antarctic Peninsula between 1989 and 1997, a period that agrees with the highest OCCAM salinity anomaly found between 1989 and 1994 (Fig. 10). The observed freshening trend between 1997 and 2006 is not so intense as in the previous years, and the model show alternating periods of freshening also not so intense after 1997 (Fig. 10)."

C740

(P1672/L21-23) "In general, bottom water export ...' Add some references.

AR: As we are talking about our results we include the reference of figure 11 to be checked. (P1673/L13-15) "We have shown that ..." What kind of change of wind are observed in the forcing dataset? Does the change of wind forcing explain the variability of AABW export?

AR: Please, see the answer above for a similar question. We have included a sentence talking about correlations between zonal wind stress and AABW export.

(P1673/L21-P1674/L4) Does the model reproduce the absence of the AABW cold pulse in the Northwestern Weddell sea in 2000?

AR: Yes, during the year 2000 potential temperature anomaly dropped to mean levels (near zero) in the NW Weddell Sea; however the potential temperature anomaly remains negative in this region after 1997 in the model. We have added this sentence in the m/s. Please see below.

"As well, potential temperature anomaly in the model (not shown) dropped to mean levels (near zero) in the Northwestern Weddell Sea during 2000; however it remains negative in this region after 1997."

Technical corrections: There are different expressions for deep ocean in the manuscript (deep regime/ deep ocean regime/ open ocean regime/ oceanic regime), and they are very confusing.

AR: We agree with the reviewer and changed all different expressions cited above to "deep ocean" in the m/s.

[Fig.2 and its caption] The line for 28.27 of neutral density should be drawn.

AR: The caption was wrong, the neutral density line corresponds to 28.27 instead of 28.26. We have corrected it.

[Reference] (P1679/L32) Validation of \*\*\*three\*\*\* global ocean models in the Weddell

C741

Sea

AR: Done.

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Interactive comment on Ocean Sci. Discuss., 8, 1657, 2011.