REPLY LETTER FOR REVIEWER #1

Anonymous referee

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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*.

This paper compares water mass formation processes occurring in the Southern Ocean in three different data assimilated ocean model results. This is a very important exercise assessing model performance.

The authors related sea ice to the Weddle Sea Polynya and then the Antarctic Bottom Water. They conducted nice analysis on conversion from a water mass to another due to convection using volume percentage of water masses. They reported that in two of the models (ECCO2 and SoSE) AABW is formed through open ocean convection in Weddell Sea, while in other model (My Ocean University of Reading, UR025.4) through dynamically accurate continental shelf convection and exporting of dense water. I found that these processes are well explained in the text, and relationship between sea ice, open ocean convection and the volumetric percentage is consistent.

We would like to thank the referee for the very encouraging and positive comments on the manuscript! We have thanked both referees in the acknowledgments section:

"*We would finally like to thank C. Heuzé and the anonymous referee for the valuable suggestions that improved the manuscript.*"- Page 19, lines 24-25

Following the suggestions, the manuscript was substantially rewritten to convey the ideas in a more robust storyline. Major text changes were made in section 3, and the results are now described as follows:

Section 3.1 – First, we describe the SIC and SIT alterations for all reanalysis products including their similarities and differences.
Section 3.2- The water mass alterations are discussed by sector and then compared between the reanalysis products. We tried to follow this order of description whenever possible: first ECCO2, then UR025.4 and finally SoSE alterations.
Section 3.3 –An analysis of the temperature and salinity anomalies in the three layers of the Southern Ocean was performed for each model. This analysis provides valuable clues on the mechanisms involved in AABW formation in each model and adds to the discussion of the mechanisms of AABW formation.
Section 3.4 –The results of the previous 3 sections are joined in a detailed unifying explanation, which is explained as many times as needed to convey the main idea to the reader.

Finally, the manuscript had the English carefully revised by the American Journal Experts (AJE), with the following certificate verification key: 2643-6C26-AB4A-DF99-D760

The authors argued that the excessive open ocean convection in ECCO2 and SoSE is due to insufficient assimilation of sea ice. I do not agree with the author on this matter. There is no doubt that sea ice is closely related to the open ocean convection, but oceanic processes such as rising of WDW might have initiated open ocean convection and the reduction in sea ice.

We agree with the referee on the fact that both sea ice assimilation and WDW rising played roles in the opening of the polynya. To better convey this idea, some changes were made to the text. In the abstract, the sentence on lines 13 and 14 has been rewritten as follows:

"We found that two of the products create AABW by open ocean deep convection events in the Weddell Sea that are triggered by the interaction of sea ice with the Warm Deep Water, which shows that the assimilation of sea ice is not enough to avoid the appearance of open ocean polynyas." - Page 1, lines 13-16

In the discussion of the AABW formation processes in section 3.4, the following has been added:

"*The trigger of the polynya in SoSE is similar to that in ECCO2and was the heat delivery to the surface level by the WDW. The 100-m integrated oceanic heat content calculated is 5.724x1022 J under the polynya (August 2005), which is higher than the 5.708x1022 J heat content calculated for August 2008 when there are no ice-free areas. Although the difference is two orders of magnitude lower than the OHC value, the difference results in a one degree warmer surface temperature in August 2005 than in August 2008 and crosses the freezing point of seawater."* – Page 14, Lines 11-15

In the summary and conclusions section, the following sentence has been added:

"Furthermore, weak stratification that enhanced WDW heat release to the surface seemed to be one of the main triggers of the Weddell Sea Polynya opening in the ECCO2 and SOSE reanalysis products." - Page 18, Lines 19-20

In addition, what the authors have observed could be initial adjustment. For example, in ECCO2 sudden change occurs in 2004 as explained in the text. How could you show that this is not an adjustment process?

We agree that the polynya opening in the Southern Ocean simulations can generally be due to the adjustments to the initial settings of the model. However, in ECCO2, the polynya opens after twelve years of simulations, and it only increases after opening, so we do not believe the establishment of the polynya in ECCO2 is an expression of an initial adjustment. That is also in agreement with the findings of Azaneu et al. (2014). In the case of SoSE, a one-year spin-up time is applied in 2004 to adjust the reanalysis to its initial settings. The SoSE output is then released only for the period after the spin-up procedure, and hence it is considered that the solution is already adjusted to its initial settings. Therefore, we do not believe the polynya opening in this reanalysis is an adjustment process. Some sentences were added to the text to describe this point of discussion:

"*Finally, although the polynya in SoSE occurs at the beginning of the reanalysis output, we do not believe its opening is a result of an initial adjustment process, since a one year spin-up procedure is conducted in the prior year (2004) to bring the SoSE to its equilibrium conditions…*" – Page 15, Lines 8-10

What is causing the differences between the models? I suppose it may be hard to pinpoint the processes causing the differences, but I suggest the authors to compared circulation patterns and vertical profiles of temperature and salinity more carefully. Except for SoSE (Fig. 3), there is no figure showing temperature and salinity. A related question is why UR025.4 performs better. Is this resolve the coastal geometry better? Is it initialized differently?

We agree with the referee that a better description of the causes of the different hydrographic and ocean dynamic patterns in ECCO2, SoSE and UR025.4 needed to be further explored. A whole section (Section 3.3) discussing the temperature and salinity changes in the surface, intermediate and bottom layers was added to better explain the differences that have led to the AABW formation in each model. The section regarding temperature and salinity values can be found in the revised manuscript.

By analyzing the temperature and salinity patterns, we found that water column stratification might be one of the main reasons why ECCO2 experiences an open ocean polynya and UR025.4 does not. The ECCO2 bottom layer experiences warming prior to the polynya opening, while the intermediate layer seems to cool down. Those changes might have led to a less stratified water column, allowing vertical heat transfer to melt sea ice and open the ECCO2 polynya in the Weddell Sea.

To expand upon those ideas, some other sentences were inserted in the main text. In the new section 3.3, we added the following:

"Cooling and salinity increase in both the surface and intermediate layers of the Weddell Sea sector before 2006 (Figure 8b,e) when considered together with the continuous warming in the bottom layer (Figure 8c), reveal an important feature since it allows for vertical stratification to weaken, thus favoring deep convection." – Page 11, Lines 31-32

Additionally, in section 3.4 we discussed the possible reasons why UR025.4 performs better, while ECCO2 and SoSE create spurious open ocean polynyas:

"Finally, in all three reanalysis products investigated in this study, the AABW formation occurred due to a higher content of warm CDW-derived waters and interaction with sea ice. Why then the mechanism of AABW formation in UR025.4 is different from the other two reanalysis (ECCO2 and SoSE)? One of the possible explanations might be that the advection of CDW-derived waters in UR025.4 originates from the east in the Weddell Sea. There is a region with consistently low sea ice concentrations and thicknesses near the center of the Weddell Sea, which is due to the natural isopycnal uplift inside the Weddell Gyre (de Steur et al., 2007). Hence, the warm CDW waters that flow west along the isopycnals tend to rise when they reach the central Weddell Gyre, while they stay roughly at the same depths when they flow east towards the Indian Ocean sector and only upwell along the coast due to coastal divergence. Thus, the warm water in the deep Weddell Sea layers is expected to exchange heat with the sea ice in the central Weddell Gyre, which can likely lead to the establishment of a polynya. In fact, Timmermann and Beckmann (2004) attempted to accurately reproduce that so-called warm water halo and found an enhanced vertical heat exchange with sea ice, which resulted in the opening of an oceanic polynya in the Weddell Sea. In addition, long-term cooling of the intermediate layers and the warming in the bottom layers of ECCO2 might have played a role in polynya establishment. Those trends decrease Southern Ocean vertical stratification and allow heat to be transported upwards and deep convection to happen. Azaneu et al. (2014) discussed the possible triggers of the ECCO2 polynya and suggested that the long-term warming of the bottom waters was one of the main factors that contributed to the polynya establishment and subsequent expansion. In addition, both ECCO2 and SoSE use the same ocean model and similar modeling frameworks, so we cannot rule out the appearance of the polynya in both models as an expression of similar model features of the reanalysis products." – Page 17, Lines 17-34

It must be explained in the references, but I hope there would a description on the assimilated data over the Southern Ocean. Comprehensive explanation on the initialization is necessary. Difference in the initial states might be the cause of the difference in the convection and water mass formation.

A more detailed description of the assimilated data and the initial conditions in each reanalysis product was added to the manuscript. In the manuscript, while describing the ECCO2 framework, the following paragraph has been added:

"*The data assimilated by ECCO2 includes temperature and salinity profiles from the World Ocean Circulation*

Experiment database, Argo floats, and XBT measurements; sea surface temperature measurements from the Group of High Resolution Sea Surface Temperature (GHRSST); sea level anomaly data from altimetry; temporal mean sea levels from Maximenko and Niiler (2005); sea ice concentrations from passive microwave data; sea ice thickness from Upward Looking Sonar; and finally sea ice motion from the QuikSCAT and RADARSAT-GPS radiometers. A Green's function method is used to calibrate the control variables (Menemenlis et al., 2005) and the initial parameters, which include initial temperature and salinity conditions; background vertical diffusivity; atmospheric surface boundary conditions; critical Richardson numbers; air-ocean, ice-ocean and air-ice drag coefficients; albedo coefficients of ice, ocean and snow; bottom drag and vertical viscosity. ECCO2 is run directly from its initial conditions, without the use of a spin-up period to bring the model to equilibrium (Aksenov et al., 2016)." – Page 3, Lines 16-25.

The data constraints of SoSE were added as follows:

"*The data constraints of SoSE include temperature and salinity fields from Argo floats and instrument-mounted elephant seal profiles; CTD and XBT profiles from the Scripps Institution of Oceanography High Resolution CTD/XBT network and the CliVar and Carbon Hydrographic Data Office; sea surface height from the Radar Altimetry Database System; sea surface temperature from microwave radiometers; sea ice concentrations from the National Snow and Ice Data Center; mean dynamical topography from the Technical University of Denmark; and bottom pressure estimates from the ECCO project. The other measurements used in the assimilations were taken from the Antarctic Marine Living Resources Program, the Long-Term Ecological Research Network and the Diapycnal and Isopycnal Mixing Experiment in the Southern Ocean. The SoSE initialization includes a one-year spin up period using the dataset from the 2004Ocean Comprehensible Atlas (OCCA - Forget, 2010) with adjusted kinetic energy. The optimization method applied in the SoSE changes the initial temperatures and salinities, and a one-week adjustment shock occurs when the model begins to run. Furthermore, neither the OCCA nor the SoSE were optimized to eliminate spurious drifts (M. Mazloff, personal communication)."* – Page 4, Lines 12-23.

The data assimilated by the UR025.4 was also added:

"*UR025.4 data includes temperature and salinity profiles from the EN3 dataset, including Argo floats, XBT, CTD, TAO and PIRATA measurements; sea surface temperature and altimetry data from the International Comprehensive Ocean-Atmosphere Data Set; and sea ice concentration from the Ocean and Sea Ice Satellite Application Facility.UR025.4 uses initial conditions of EN3 climatology to start the simulation. Authors considered that the 3d-Assimilation scheme allowed fast adjustment of surface and subsurface properties, and hence no spin up period is used in this reanalysis (Valdivieso et al., 2014)*" Page 4, Line 3-8.

In several places, ocean current are introduced while explaining water mass formation. There, however, are no figures and it is not easy to follow the explanation. Please added appropriate figures.

We agree that a figure showing the acceleration of zonal velocities around Prydz Bay is necessary since our main conclusions of UR025.4 are based on the enhanced sea ice transport due to the enhanced current velocities in that area. To show that zonal velocity increases in Prydz Bay, we calculated the mean zonal speed profile along 70.125°W between the coast and 64°S. This figure can be found in the supplementary material (Figure S1). It is possible to see in Figure S1 that after 2004, the negative zonal velocities increase especially at the surface. Those strong negative current velocities show the intensification of the westward flow of the Antarctic Coastal Current (ACoC) around Prydz Bay, which is the main velocity alteration that occurs during AABW formation.

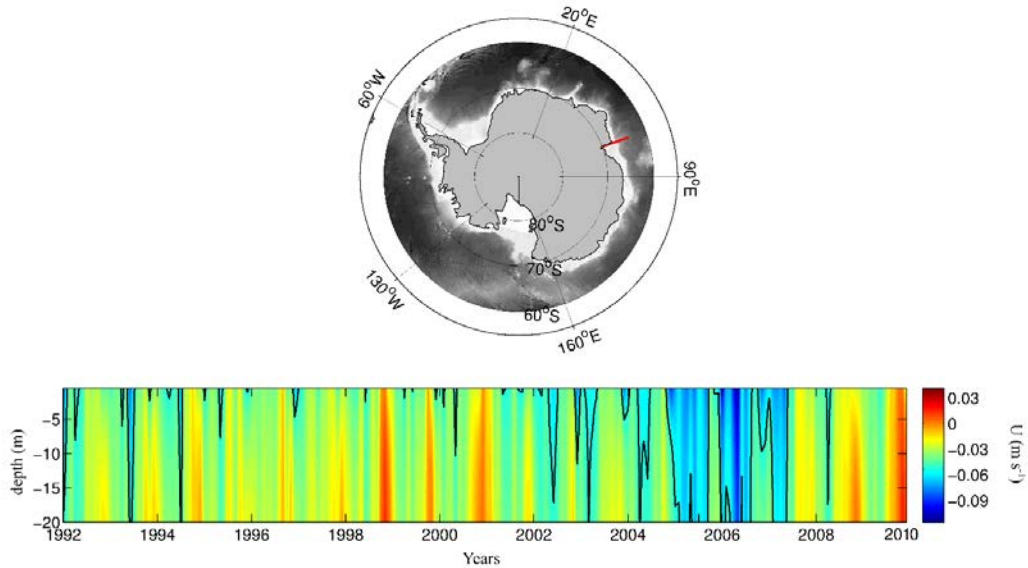

Figure S1. The temporal evolution of a mean current speed profile in UR025.4. The red line at the top shows the transect used to calculate the mean profile (70.125°W)

In addition, the green arrows in Figure 13 show the intensity and direction of the current at 250 m depth, which indicates the intensification of the ACoC and the offshore-directed buoyancy current.

It was concluded that improvements necessary. What kinds of improvement are necessary?

Based on the dynamics of ECCO2 and SoSE, we believe that improvements in the parameters controlling heat exchange between the sea ice and surface water are required. In parallel, understanding the causes of bottom layer warming and intermediate layer cooling in ECCO2 is necessary for future studies to better delineate the mechanisms generating stratification. The following text has been added to the section 4 to convey those ideas:

"Furthermore, weak stratification that enhanced WDW heat release to the surface seemed to be one of the main triggers of the Weddell Sea Polynya opening in the ECCO2 and SOSE reanalysis products. The WDW increase reported here is consistent with the observed results reported by Kerr et al. (2017 - under review), who found a consistent increase of the WDW contribution to the total mixture of deep and bottom waters in the Weddell Sea from 1984 to 2014, despite the high degree of interannual variability. However, since no real open ocean polynya has been reported since the 1970s (Gordon 1978), a critical analysis of the model mechanisms of heat exchange between the surface waters and sea ice is required in the future to efficiently understand the role of WDW in open ocean polynya establishment. In addition, since bottom layer warming and intermediate layer cooling are the possible mechanisms that diminished stratification in ECCO2, further evaluation of the causes of those trends is needed to understand the primary factors leading to the weak ocean surface stratification." – Page 18, Lines 19-27.

Figures 1, 3 and 4 should be improved. The contours lines except for the black ones in Fig. 4 are hard to see. A scale bar is necessary for SIC

As suggested, the quality of the figures was enhanced. The white contour lines were changed to gray lines, and a scale bar was added for the SIC values. Please also notice that the ECCO2 and UR025.4 figures now display both SIC and SIT. Additionally, the following changes were made to the figures:

- Previous Figure 1 is now Figure 11

- Previous Figure 3 is now Figure 12
- Previous Figure 4 is now Figure 14

Those figures are shown below:

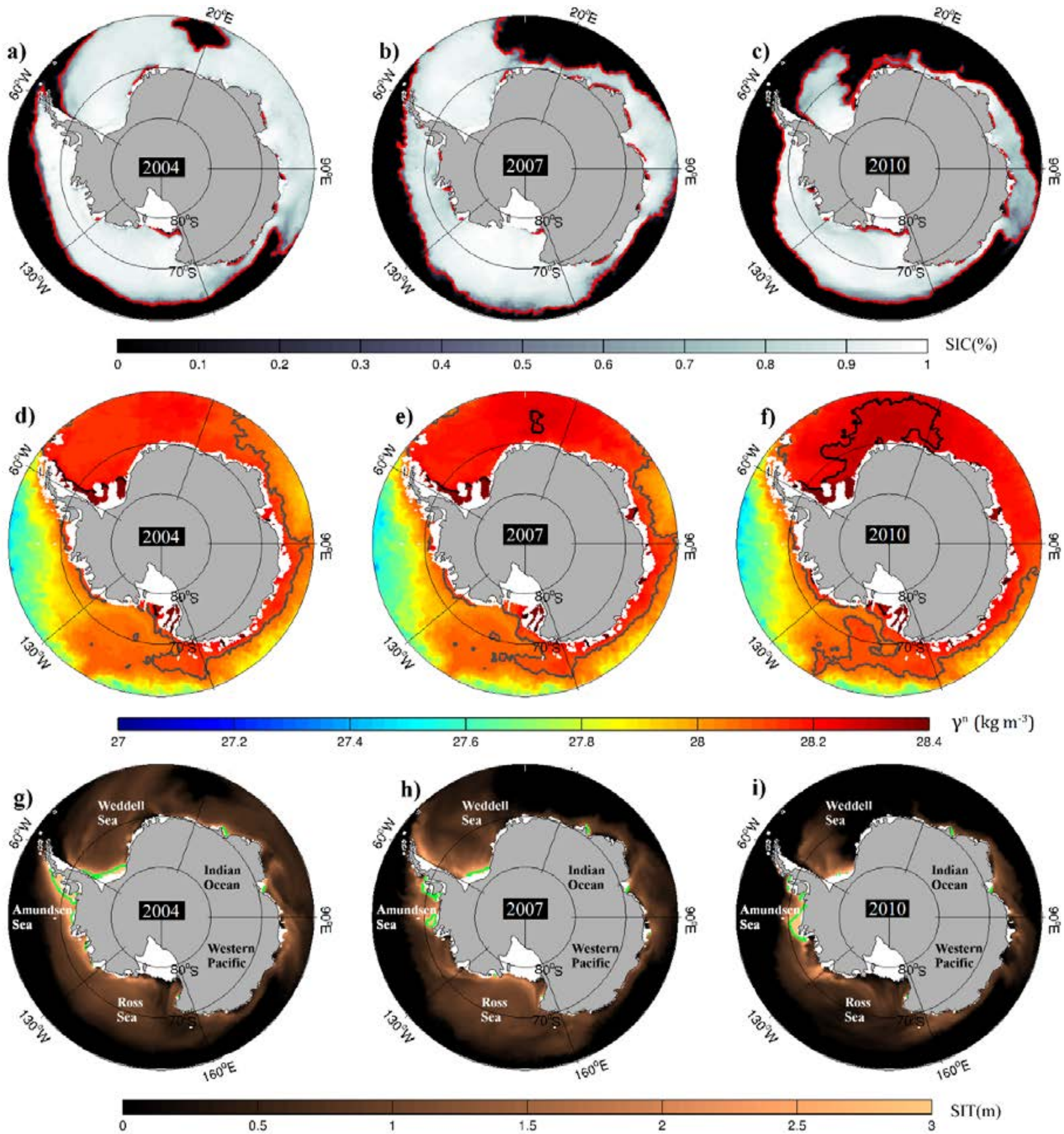

Figure 11: (a), (b) and (c) are the mean ECCO2 sea ice concentrations in November of 2004, 2007, and 2010 respectively. The red contours delineate the 30% sea ice concentration, which is the border of the polynya. The straight black lines separate each Southern Ocean sectors analyzed. (d), (e) and (f) are the mean neutral density filled contours at 700 m for November of 2004, 2007, and 2010, respectively. The gray lines delineate the 28.1 kg m-3neutral density of WDW and the black lines the 28.27 kg m-3 of the WSDW. (g), (h) and (i) are the mean ECCO2 SIT (m) in November 2004, 2007, and 2010, respectively. The green contours delineate areas with SIT greater than 3.5 m.

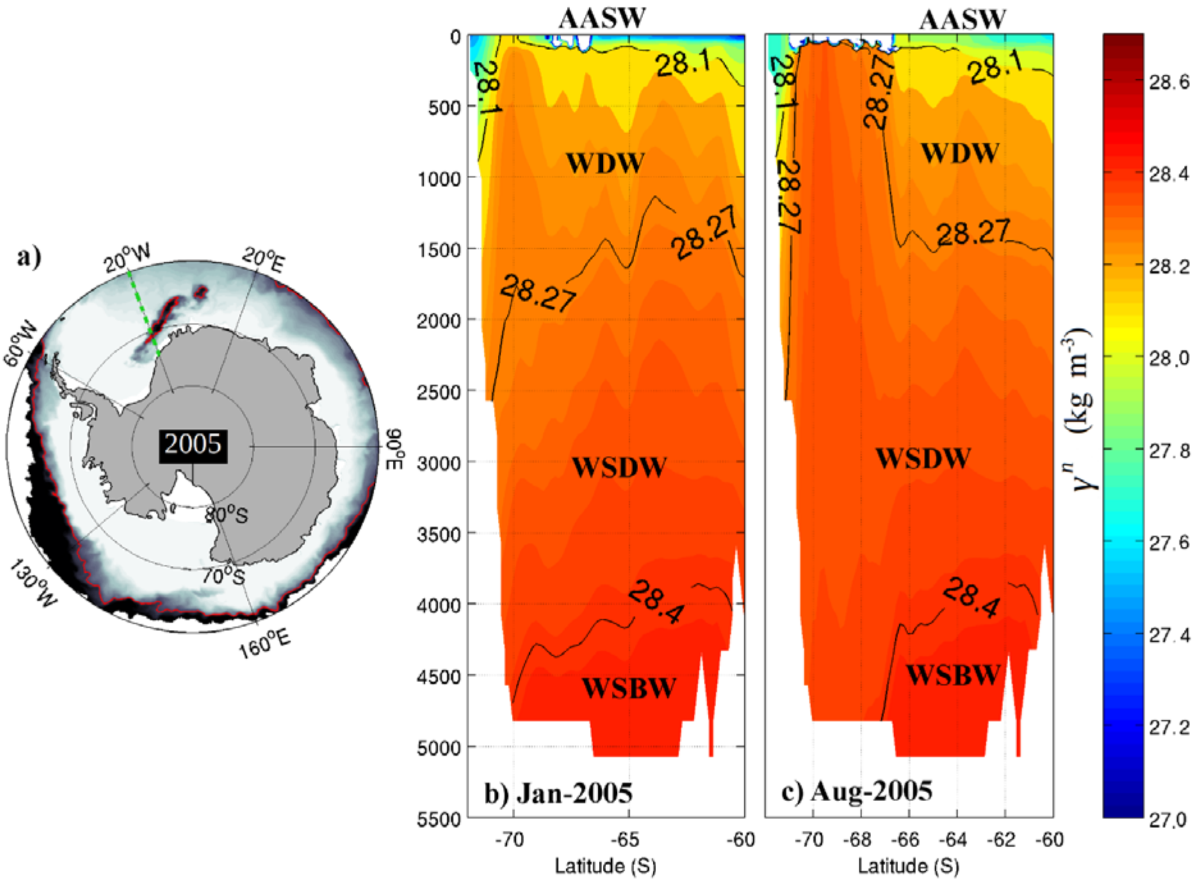

Figure 12: a)A map of the sea ice concentration of SoSE in August 2005 showing the polynya. The transect used is marked by the dashed green line. The black areas are the areas with 0% sea ice concentration. The red line marks the 30% sea ice concentration margin, as the border of the polynya. b) and c) The neutral density contours from a 20 W vertical section in January and August, respectively. The neutral density lines of 28.1 kg m-3, 28.27 kg m-3 and 28.4 kg m^{-3}separate the AASW/WDW, WDW/WSDW and WSDW/WSBW, respectively.

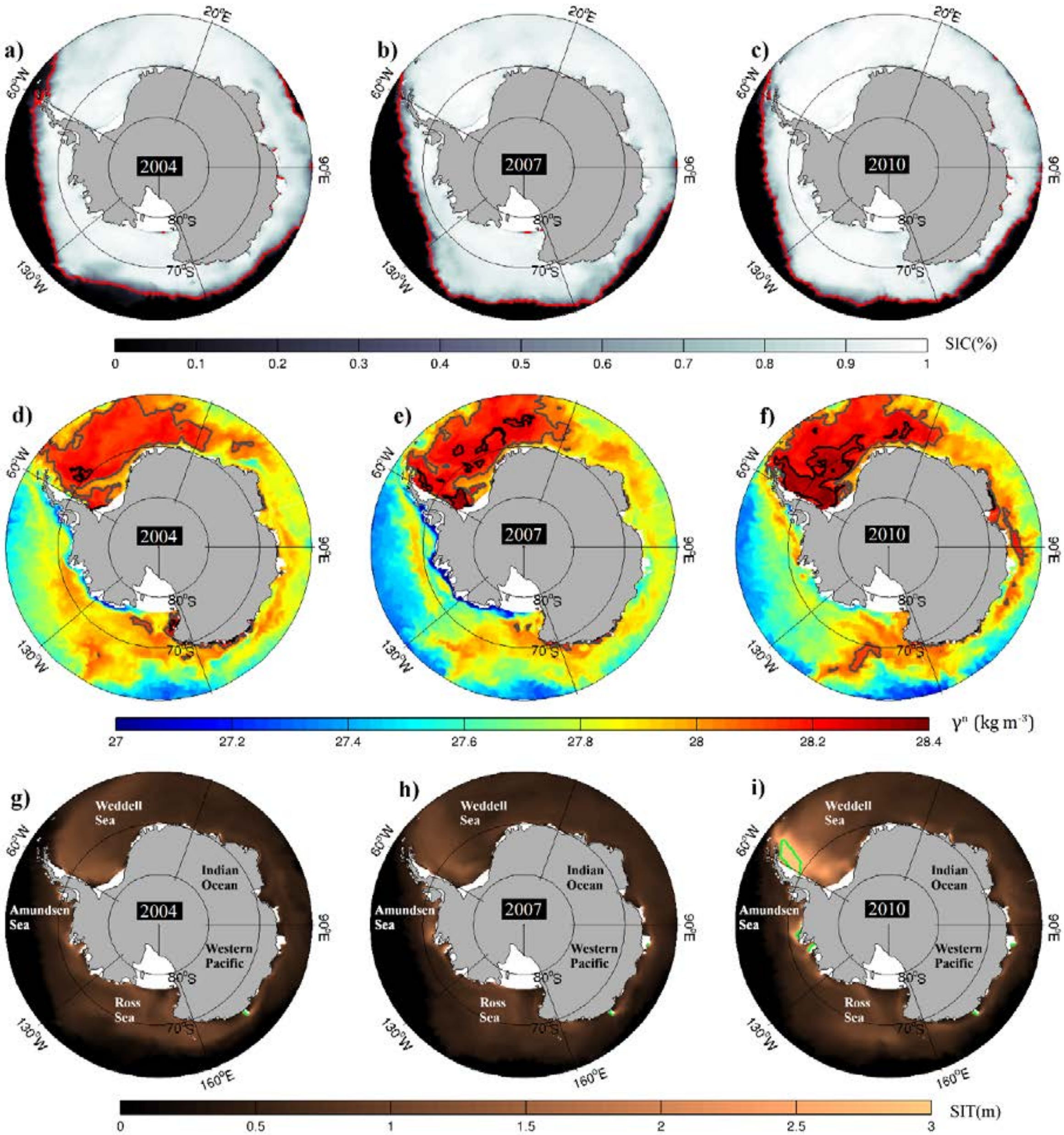

Figure 14: (a), (b) and (c)The mean UR025.4 sea ice concentration in September of 2004, 2007, 2010, respectively. The red line marks the 30% SIC contour. (d), (e) and (f)The neutral density contours at 700 m depth in September of 2004, 2007, and 2010. The gray lines delineate the 28.1 kg m^{-3}neutral density of WDW and the black lines the 28.27 kg m^{-3} of the WSDW. (g), (h) and (i)Monthly sea ice thicknesses of UR025.4 in September of 2004, 2007 and 2010, respectively. The green line marks the 3.5 m sea ice thickness.