

## Reply from authors on comments from Reviewer #2

General comment on the first statements: Rev#2 wishes to see a more detailed water mass description. The revised version includes a more extensive description of the frontal systems encountered along the track. This is part of the hydrography section where we use definitions by Moore et al., 1999 and Dong et al., 2006. They use surface expressions of SST. We define the location and changes observed in the SAF and the APF.

We have also added 8 more figures surface ODV plots on SST and salinity in the Amundsen Sea and Ross Sea (new Figure 3). This will make the variability clearer to observe.

Table 3 has been revised (now Table 4) and we calculated mean values of the carbonate system parameters in the Amundsen Sea (100 to 130W) and Ross Sea (150W to 180E).

The multivariate analysis has been described more thoroughly and also included a table which summarize the statistical output from the model runs (correlation, error and more, new Table 2).

Several comments are based on a misconception that the data has large seasonal variability. This is not the case since measurements/samples were performed in December to beginning of January (except 2006 which ended 26<sup>th</sup> December). This is clearly stated in Table 1 in the previous version. In the revised version this has been clarified further in the text and figure captions and figures.

Comments on abstract comments:

We have now re-written the abstract and hope that it is now more conclusive with the results. The abstract is also shorter and less speculative. We have also added information on the years we highlight as especially interesting.

The Introduction has been re-written and somewhat shortened (moved parts to discussion and conclusion, that have also been extensively rewritten)

**Page 7781, L5:** We clarified the sentence that [H<sup>+</sup>] has increased by 30%.

**Page 7881, L6-8:** Since we explain more about effects of OA later in the manuscript we added that there are large unknowns on the effects from OA since many organisms have adapted to pH changes through evolution on Page 7884 L8 (after the Ref Gattuso and Hansson). Added the following text” However, most organisms experience substantial diurnal (Fransson et al., 2004) and seasonal changes in the carbonate system, larger than the change caused by anthropogenic CO<sub>2</sub> uptake. This implies that they have ability to adapt to pH changes.” This was also asked for Ref#1.

**Page 7882, L3-4:** changed “Southern Polar Ocean” to “western Antarctic seas”.

**Page 7884, L8-10:** Added reference Shi et al., 2010

**Page 7884, L15:** Here we refer to carbonate system data, which is unique in the AmSea during that time of year. However, we added the Lee et al study in the introduction (L7883). Dolan et al is interesting but not directly relevant for the aim or results for our study.

**Page 7886, L10-13:** The calibration described in Chierici et al., 2012 was performed in December 2007 to January 2008 (OSO 07/08 expedition) on the same instrument/sensor that was as used on all four expeditions. The Amundsen Sea was studied in December 2007, December 2008 and December 2010. The Ross Sea was covered for all four expeditions during end of December and beginning of January. That means that we have little temporal variability during the four expeditions. (The timing and study area of each cruise have been clarified in Table 1). In December 2010, we took five samples from the seawater supply and used conventional extraction technique (same as in 2007) to have a spot check on the performance on the chl a sensor to investigate deviations from the 2007/2008 calibration. These 5 data points agreed with the fit found in 2007 (unpublished), hence the same equation was used for all four expeditions. We added text "Changes in phytoplankton composition could induce different fluorescence response and give rise to large interannual variability in chl a levels, which was not taken into account in our study".

We have also added a figure using remotely sensed chl a data for all years. The remotely sensed chl a data show high chl a in the same area as in 2010 (64S-68S), which was not present in December in 2007 and 2008. In 2006, the high chl a patch was present, but the ship ventured further north and we did not measure chl a in that area.

**Page 7887, L14-15.** That was a misunderstanding and unclear abbreviations in Figure captions and figures and has now been clarified. The cruise dates for all expeditions are (were) noted in Table 1, we also follow the same abbreviations as stated in Table 1. For clarification: all expeditions started in December and ended in January (except 2006 that ended 26<sup>th</sup> of December), the abbreviations the reviewer#2 refer to is an abbreviation for the expedition that took place from December 2007 and ended January 2008 (= 2007/08 as an example). This has been clarified in the legends and Figure captions and is now referred as 2007/2008 (exemplified). We have also clarified this in Table 1

**Page 7888, line 6:** It is correct that the Ross Sea and RSP was visited all four years (as can also be observed in Figure 1. In Table 1 we referred to the Main Study area. However, this column was removed in the revised version since it is redundant information.

**Page 7888, lines 8-10:** We explained the location of fronts for all years, thus the comment is not relevant any longer. The other years, the route was along north-to south direction and passed quickly resulting in large changes on small area, thus the fronts were passed more clearly. This has been added in the text Page 7888 after Line 21.

**Page 7888, Lines 10-15:** we added figures and information on the SST and salinity changes while entering the AmS and RS. New Figure 3, blow up on AmS and RS.

**Page 7888, lines 18-19:** Yes, the salinity increased. This has been added in the text.

**Page 7888, lines 26-27:** The freezing point is between -1.83 and -1.86 for the salinities at the ice edge. This has been corrected in the text and -1.2 C has been removed.

**Pages 7889, lines 11-13:** Sentence has been removed in revised version since it has no relevance.

**Results: general comment to Ref#2:** all data are from December to beginning of January and are thus taken within the same months every year meaning that seasonal variability is small. Table 3 (now table 4) has been revised and include mean values in AmSea and RS. It makes more sense (less spatial variability) and the data are more useful for interpretation.

**Discussion and conclusions:** Discussion has been rewritten and speculative comments have been removed. The discussion is based on the actual data both from the presented data in the figures and the multivariate analysis. For an objective approach to investigate the controls on the carbonate system we used the data in multivariate analysis. We have restructured the section (more details in method section than in discussion) and included more information on the multivariate analysis and the interpretation of results are directly linked to the presented data in figures. Table 2 shows the statistical summary of the PCA analysis and OPLS-DA analysis.

**Comment on organisms and most important  $\Omega_{Ar}$  window at Page 2469:** Not completely clear what Ref#2 is aiming at in this comment. Our study is the first showing  $CaCO_3$  saturation in the surface waters in the AmSea during this time of year and during four years. We do not have data to discuss the magnitude and duration of the period when  $\Omega_{Ar}$  falls below 1. On the other hand, the critical level of  $\Omega_{Ar}$  is different for different organisms and as mentioned before they have means to adapt.

Subsurface data of aragonite saturation (Chierici et al., in prep and presented on conferences) show that subsurface values are generally lower than surface waters. This is likely due to the effect of CDW which contains large amounts of  $CO_2$  (thus low pH and Omega). Pteropods have a lifecycle of 1-2 years in Antarctic waters. However as discussed in Chierici et al., 2011 where we performed a seasonal study in the Arctic, shows that omega values are lowest in winter and fall, which is the same time as juveniles of pteropods resides in the polar mixed layer (<60 m).

**Page 7893, line 26:** This is based on estimates on the decadal change in anthropogenic CT in in the Southern Pacific sector in the Southern Ocean from Sabine et al., 2008. Based on the oceanic anthropogenic  $CO_2$  uptake rates from 1991 to 2006, CT was determined to increase by 5-10  $\mu mol kg^{-1}$  per decade in the western Antarctic waters (Sabine et al., 2008). Here we use their estimates on the increase rate in CT of 10  $\mu mol kg^{-1}/decade$  in (no changes in AT and SST) in the western Antarctic waters and constant AT, SST and salinity to project the changes in  $\Omega_{Ar}$  in the next 50 years.

**Page 7894, lines 18-19:** we added text about this in the discussion section and added reference to the Lannuzel study where they found high concentrations of Fe in sea ice melt water. The Bathmann study is less unclear regarding the effect of melt water and iron on PP.

**Figures and tables:** changed the fonts on axis and figure text on 2, 5, 6 and 12. However, we also ask the production office at BGS to have less figures/sheet. Figure 6 is not meant to be 6 figures on one page. The original file is one figure on each A4 page with high resolution file. The font is now TNR font 15 on A4 format.

**Table 1:** removed start location in revised Table 1.

**Table 3** changed, now it is mean values from Amundsen Sea and Ross Sea for each year. TNew revised version this is Table 4.

**Page 7904:** Figure 2, missing labels have been added (a,b)

**Page 7906:** Fig 4: labels have been added (a,b,c, d)

**Page 7907, Fig 5:** Added in Figure captions that the sensor is out of range in RSP and AmP.

**Page 7909-7912 7-10:** Changed numbers to black and increased font. All numbers in bold. It was only 2007 and 2010 plotted since that was where we found largest difference in December sea ice concentration and carbonate system variables.

**Page 7914, Fig 12:** changed accordingly

**Technical comments: all technical comments have been changed accordingly**

**Page 7881, line 5,** changed accordingly

**Page 7882, line 3:** Since the Southern Ocean is a vast area ranging from tropical oceans to polar, we wished to make a clear distinction by naming our study area Southern Polar Ocean for the area south of 60 S. This was already described at page 7881 in previous version and now we have clarified this further by adding (>60°S) in the text at page 7881.

**Page 7882, lines 14-17.** Has been rephrased

Page 7884, line 3: changed

**Technical comments: all technical comments have been changed accordingly**

**Table 2:** Statistical summary of the principal component analysis (PCA) and the two models from the OPLS-DA on the Amundsen Sea (AmS) and the Ross Sea (RS).

Name	Type	Components	Observations	R2X	R2Y	Q2
Interannual	PCA-X	2	219	0.808	---	0.708
AmS	OPLS-DA	1+1+0	69	0.554	0.99	0.99
RS	OPLS-DA	1+2+0	52	0.885	0.99	0.99

\* OPLS-DA loading;  $\Omega_{Ar}(y)$ , 7 variables (x): AT/CT/pH/ pH<sup>15</sup>/Chl a/SST/salinity; **1+1+0**, **1** correlates to y, *1* orthogonal to x, 0 orthogonal to y.

**Table 4.** Summary of the mean values and standard deviation of the carbonate system parameters, total alkalinity ( $A_T$ ), total dissolved inorganic carbon ( $C_T$ ), pH on total scale at 15 °C ( $pH^{15}$ ), pH on total scale at *in situ* temperature ( $pH_{in situ}$ ), aragonite saturation ( $\Omega_{Ar}$ ), and calcite saturation ( $\Omega_{Ca}$ ) in the Amundsen Sea (AmS, grey shade) and Ross Sea (RS) for each year. N denotes number of data points used in the study for each year. Minimum and maximum values are denoted min and max, respectively. \* *In 2006, samples are located in northern Amundsen Sea (~68 °S) and not in the polynya or coastal Amundsen Sea, thus intercomparison is irrelevant.*

Expedition (region)	$A_T$ ( $\mu\text{molkg}^{-1}$ )	min/ max	$C_T$ ( $\mu\text{molkg}^{-1}$ )	min/ max	$pH^{15}$ min/ max	$pH_{in situ}$ min/ max	$\Omega_{Ar}$ min/ max	$\Omega_{Ca}$ min/ max	N				
OSO2006 (AmS)*	2303±12	2287/ 2316	2170 ±14	2147 /2192	7.846 ±0.017	7.819/ 7.871	8.106 ±0.016	8.082/ 8.130	1.54 ±0.05	1.46/ 1.63	2.45 ±0.09	2.33 2.61	16
OSO2006 (RS)	2305±12	2289 /2331	2192 ±9	2181/ 2216	7.793 ±0.035	7.733/ 7.859	8.060 ±0.032	8.004/ 8.121	1.37 ±0.12	1.18/ 1.60	2.19 ±0.19	1.89/ 2.55	25
OSO2007/2008 (AmS)	2295±12	2270/ 2322	2190 ±22	2141/ 2225	7.771 ±0.063	7.675/ 7.900	8.038 ±0.067	7.932/ 8.179	1.30± 0.19	1.03/ 1.71	2.07 ±0.30	1.64/ 2.73	34
OSO2007/2008 (RS)	2313±19	2285/ 2343	2196±18	2153/ 2213	7.794 ±0.074	7.730/ 7.969	8.053 ±0.075	7.994/ 8.235	1.40± 0.27	1.18/ 2.05	2.23 ±0.43	1.88/ 3.27	9
OSO2008/2009 (AmS)	2288±11	2275/ 2315	2182 ±32	2094/ 2202	7.771 ±0.100	7.710/ 8.030	8.041 ±0.103	7.976/ 8.304	1.32± 0.36	1.11/ 2.26	2.10 ±0.58	1.77/ 3.61	13
OSO2008/2009 (RS)	2321±13	2299/ 2344	2185 ±20	2005/ 2205	7.876 ±0.109	7.780/ 8.180	8.101 ±0.067	8.039/ 8.443	1.58 ±0.25	1.34/ 3.02	2.52 ±0.40	2.13/ 4.82	20
OSO2010/2011 (AmS)	2293±14	2263/ 2313	2173 ±25	2137/ 2211	7.817 ±0.067	7.730/ 7.930	8.084 ±0.071	7.968/ 8.184	1.45 ±0.22	1.19/ 1.80	2.31 ±0.35	1.90/ 2.87	12
OSO2010/2011 (RS)	2309±11	2289/ 2326	2071 ±51	1989/ 2129	8.070 ±0.100	7.910 8.220	8.327 ±0.092	8.184/ 8.471	2.50 ±0.50	1.75/ 3.28	3.98 ±0.79	2.79/ 5.23	10
Mean AmS	2295±6		2179±9		7.801 ±0.037		8.067 ±0.033		1.40 ±0.11		2.23 ±0.18		
Mean RS	2312±7		2180±6		7.883 ±0.130		8.135 ±0.130		1.71 ±0.53		2.73 ±0.85		

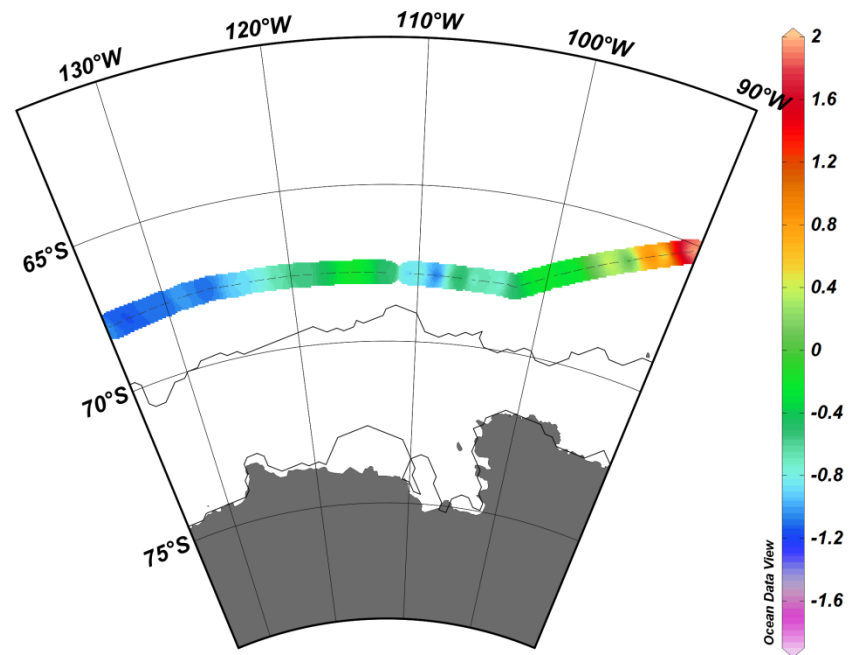
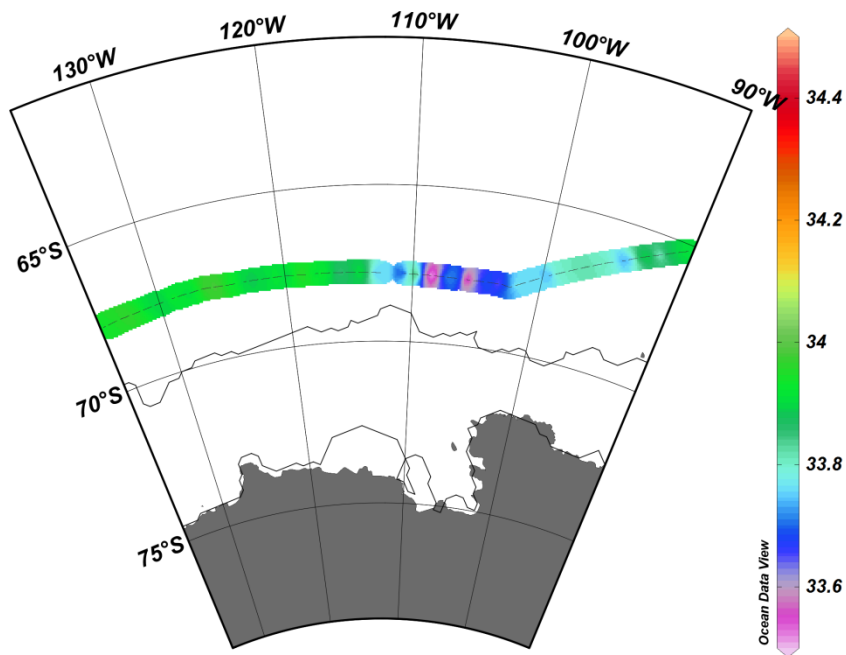


Figure 3: Variability of a) salinity and b) SST in the Amundsen Sea in 2006. The grey thin lines mark the December sea-ice edge.

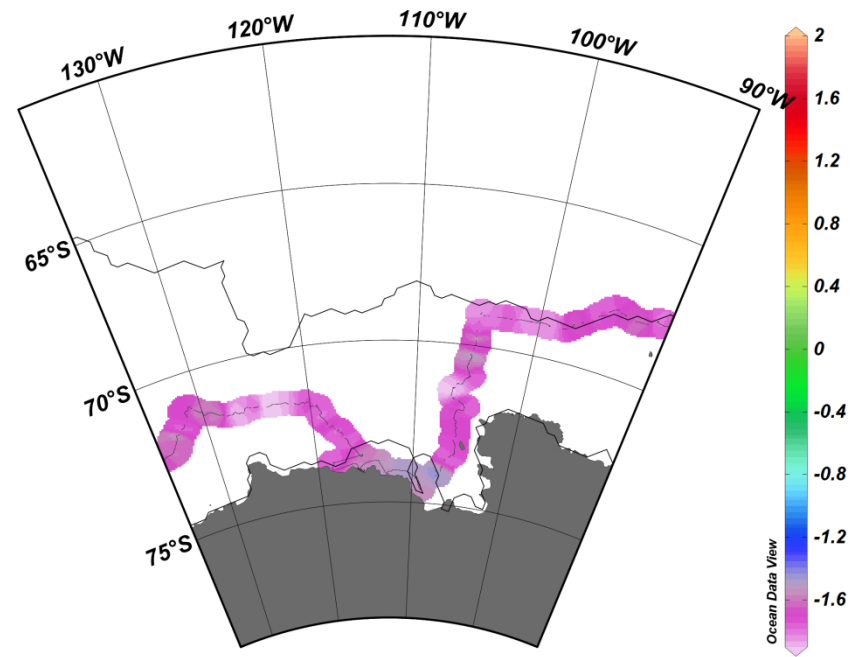
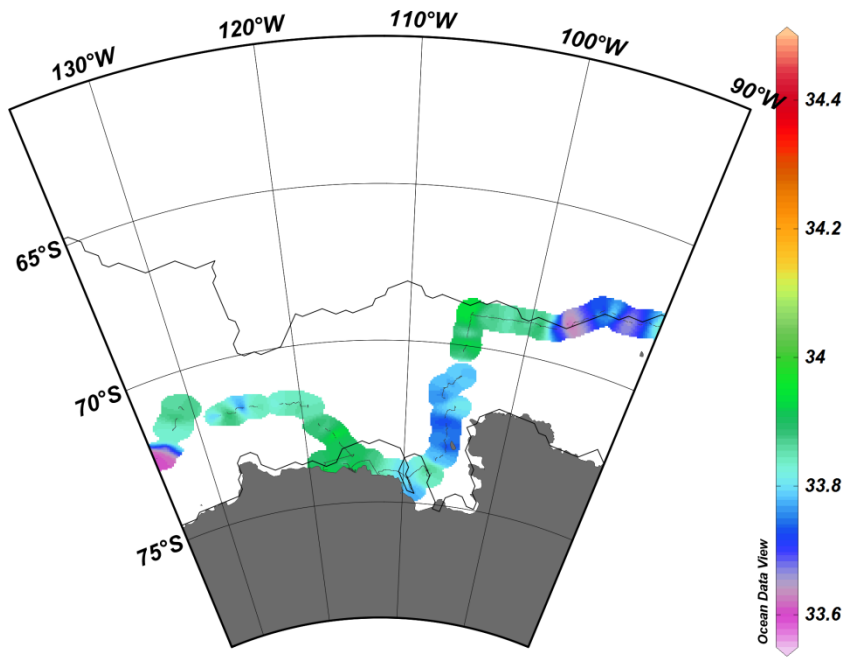


Figure 3: Variability of c) salinity and d) SST in the Amundsen Sea in 2007. The grey thin lines mark the December sea-ice edge.



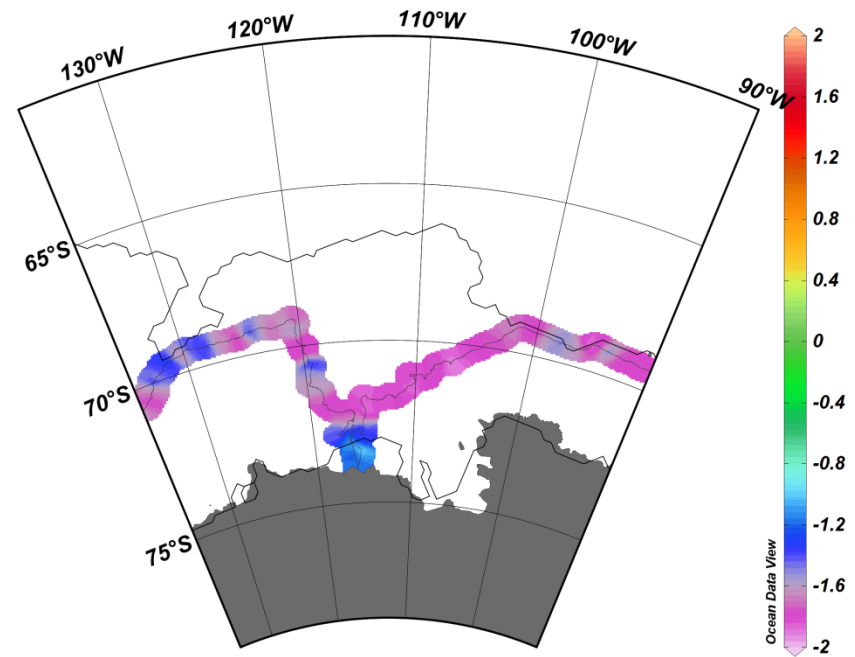
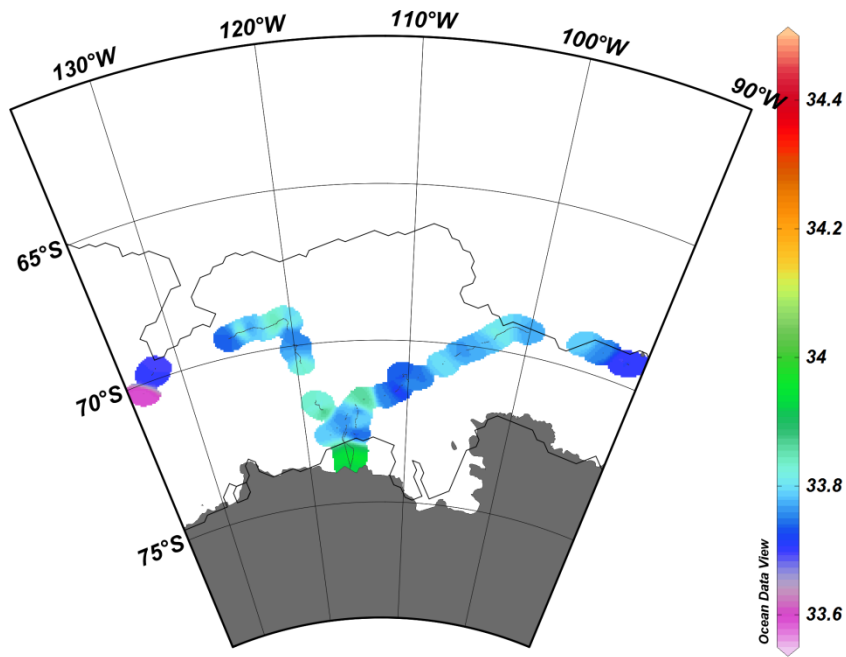


Figure 3: Variability of e) salinity and f) SST in the Amundsen Sea in 2008. The grey thin lines mark the December sea-ice edge.

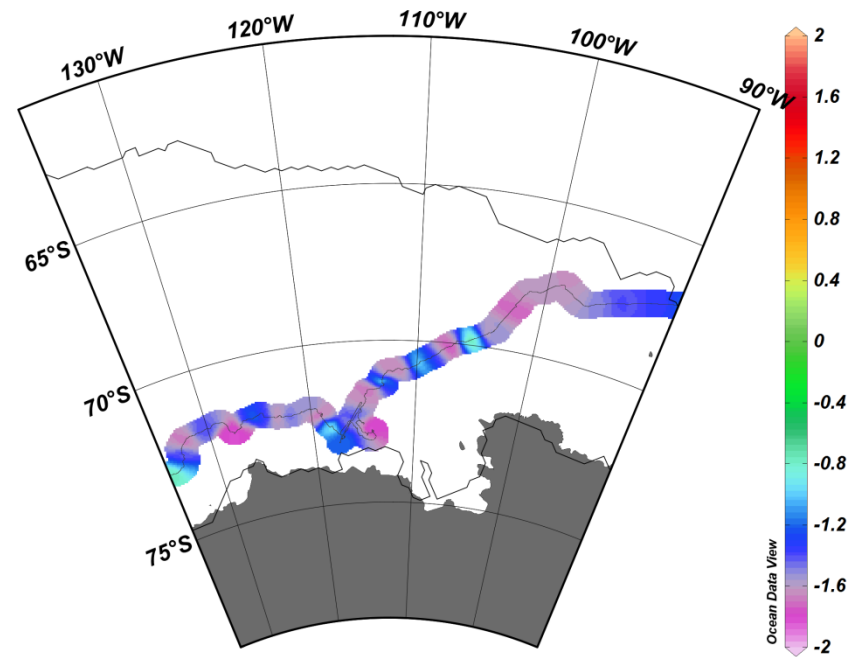
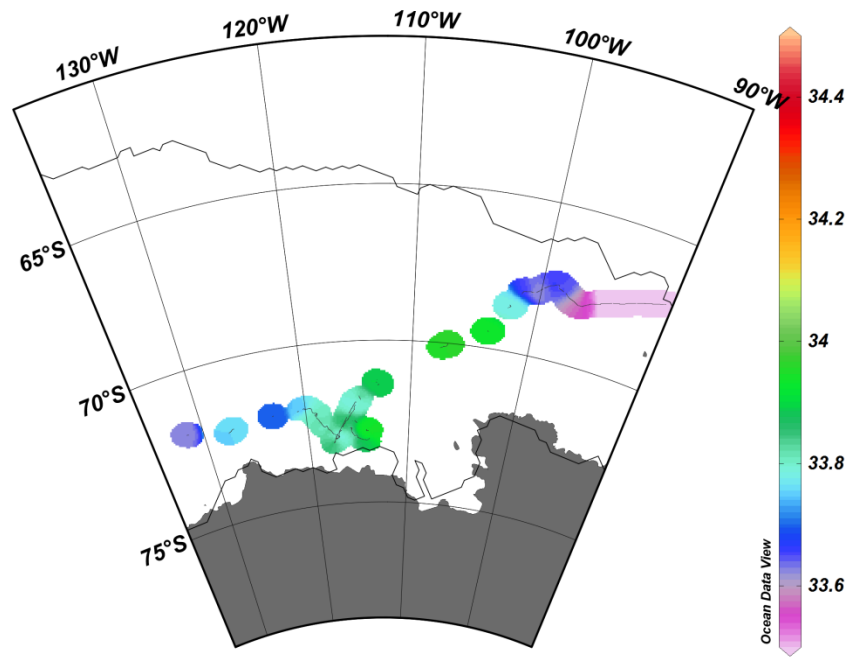


Figure 3: Variability of g) salinity and h) SST in the Amundsen Sea in 2010. The grey thin lines mark the December sea-ice edge.

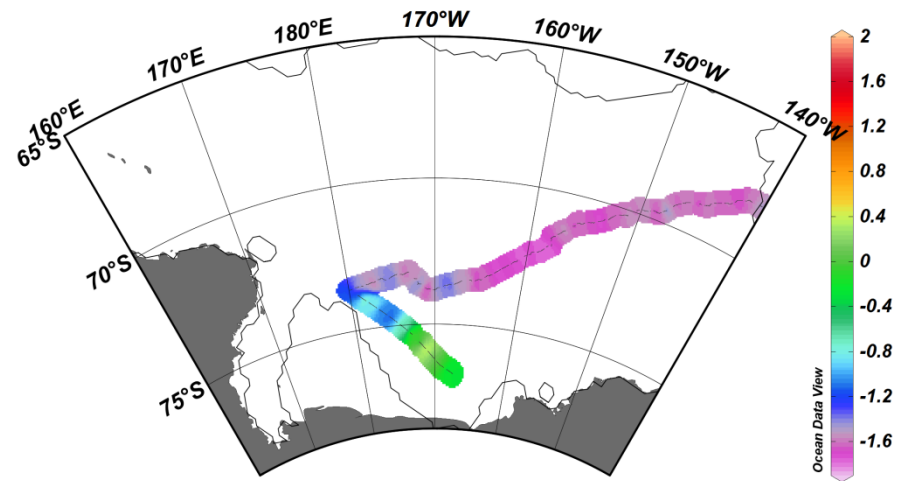
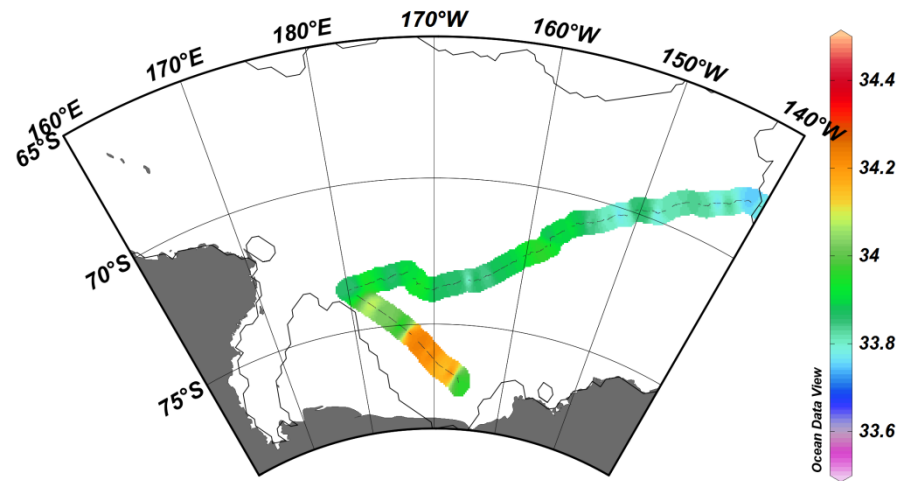


Figure 3: Variability of i) salinity and j) SST in the Ross Sea in 2006. The grey thin lines mark the December sea-ice edge.

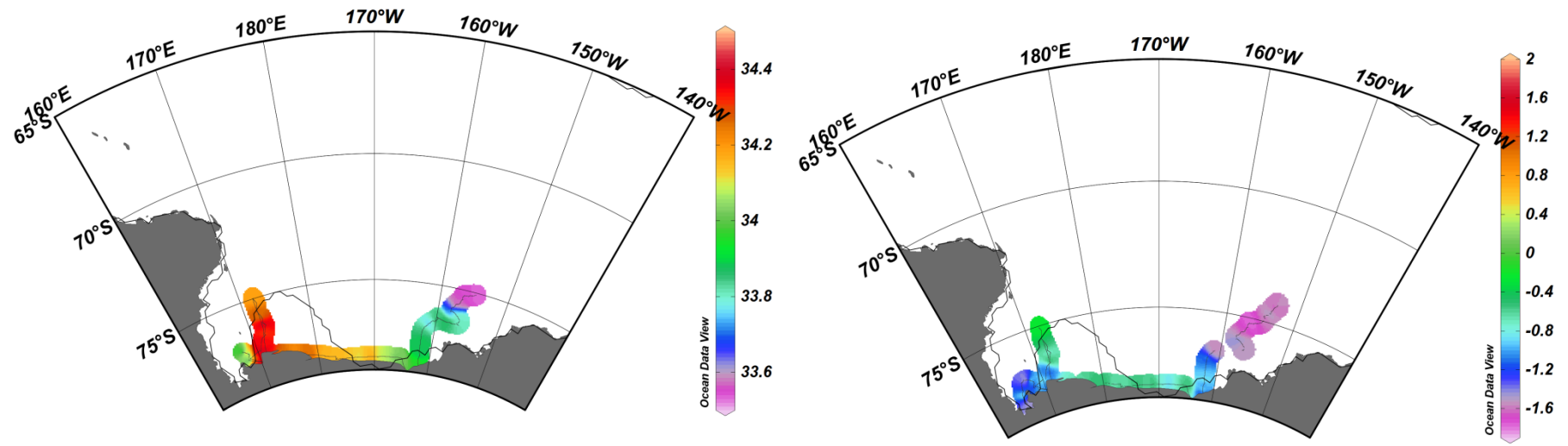


Figure 3: Variability of k) salinity and l) SST in the Ross Sea in 2007/2008. The grey thin lines mark the December sea-ice edge.

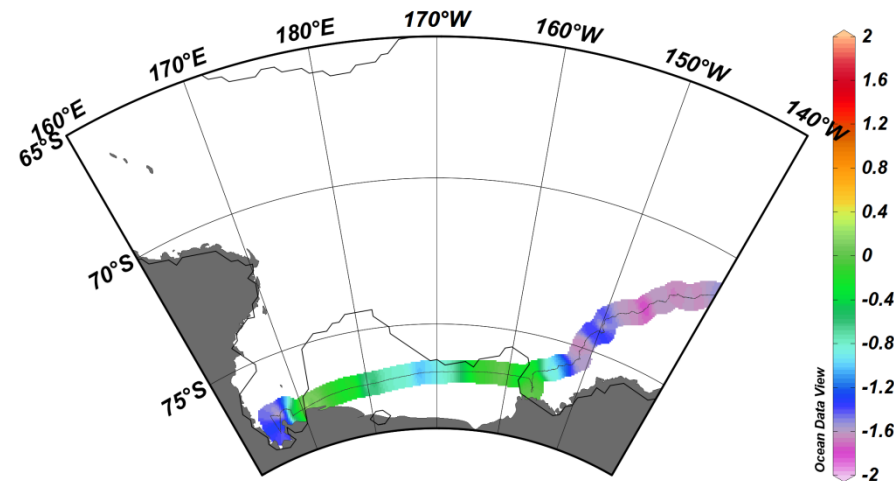
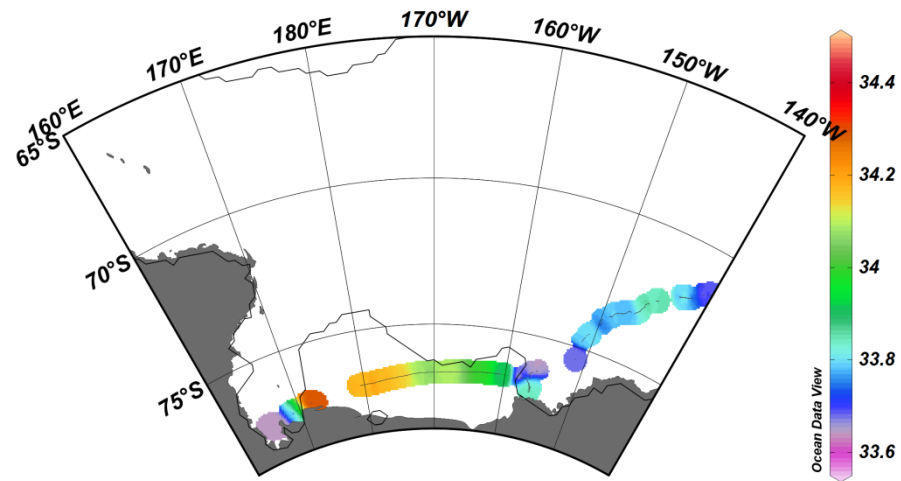


Figure 3: Variability of m) salinity and n) SST in the Ross Sea in 2008/2009. The grey thin lines mark the December sea-ice edge.

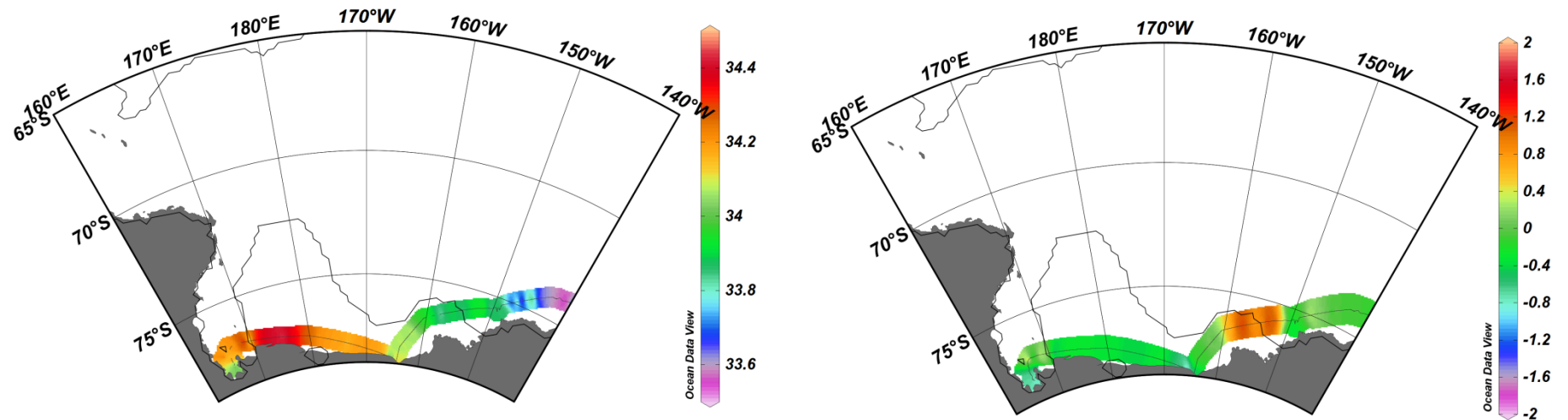


Figure 3: Variability of o) salinity and p) SST in the Ross Sea in 2010/2011. The grey thin lines mark the December sea-ice edge.