1 Dense shelf water formation and brine-driven circulation
2 in the Adélie and George V Land region

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8 **Abstract**

9 The formation and outflow of Dense Shelf Water (DSW) from the Adélie and
10 George V Land region and the seasonal variation in the ocean circulation
11 therein are investigated using a global ice-ocean model with fine resolution
12 around East Antarctica. The model reproduces key elements of the overall
13 system described by previous observational studies: modified Circumpolar
14 Deep Water intrusions into the Adélie Depression, enhanced sea-ice produc-
15 tion in the coastal polynya regime, and seasonal variation in the export of
16 DSW through the Adélie Sill. We find two distinct seasonal circulation pat-
17 terns in the Adélie Depression. The first is a vertical circulation formed over
18 the southwestern flank of the Mertz Bank in winter, with a southeastward
19 inflow of light water in the upper layer and a northwestward outflow of dense
20 water in the lower layer. The second is a surface-intensified clockwise cir-
21 culation trapped in the Adélie Depression during summer. This seasonal
22 variation is attributed to the spinning-up and down of the haline circulation
23 which is driven by the brine-rejection from enhanced sea ice formation in the
24 coastal polynyas. In the model a similar haline circulation also develops in

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25 the Mertz Depression. Assuming a critical density of 27.88 (27.80) kg m^{-3}
26 for outflowing DSW, the annual mean export from the Adélie and Mertz Sills
27 are 0.21 (0.37) Sv and 0.12 (0.32) Sv, respectively. The model clearly shows
28 a dual-system for DSW formation and export from the Adélie and Mertz De-
29 pressions, consistent with recent observational analysis over the continental
30 slope and rise.

31 *Keywords:* Dense Shelf Water, brine rejection, Adélie and Mertz
32 Depressions

33 1. Introduction

34 Antarctic Bottom Water (AABW) is the cold, dense water mass in the
35 abyssal layer of the the World Ocean that is critical to the global climate sys-
36 tem, composing the lower limb of the global thermohaline circulation in the
37 southern hemisphere (Orsi et al., 1999). AABW is produced in key source
38 regions of the Antarctic margin by the overflows of Dense Shelf Water (DSW)
39 formed on the continental shelf by regionally varying combinations of coastal
40 polynyas and ocean-ice shelf interaction. In the Weddell Sea and eastern
41 sector of the Ross Sea (see Fig. 1a), the cooling and freshening influence of
42 melting beneath the large continental ice shelves in these regions is integral
43 to the export of DSW for AABW production (Schlosser et al., 1990; Foldvik
44 et al., 2004; Smethie Jr. and Jacobs, 2005; Orsi and Wiederwohl, 2009). In
45 other areas removed from the continental ice shelves the primary mechanism
46 for DSW formation is brine-rejection from enhanced sea-ice production in
47 coastal polynyas (western Ross Sea, East Antarctica). AABW is typically
48 formed by overflows of DSW mixing with Antarctic Surface Water (AASW)
49 and modified Circumpolar Deep Water (mCDW), as it is transported downs-
50 lope to the abyssal layer.

51 In the Australian-Antarctic Basin sector of East Antarctica, the dominant
52 source region is Adélie and George V Land (AGVL) continental shelf (Gordon
53 and Tchernia, 1972; Rintoul, 1998), in particular the coastal polynya regime
54 over the Adélie and Mertz Depressions west/east of the Mertz Glacier Tongue
55 (MGT) (Williams et al., 2010). These depressions (sometimes referred to as
56 troughs) are suitable for the formation and export of DSW for the following
57 reasons. Firstly, there are persistent coastal polynyas in winter with high

58 sea ice production (Tamura et al., 2008; Williams et al., 2010). Secondly,
59 the depressions provide storage for the accumulation of salinity from brine-
60 rejection and insulate newly-formed DSW under the coastal polynya from
61 lateral mixing with the mCDW that penetrates southwards across the shelf
62 break. Thirdly, both regions have bathymetric export pathways through sills
63 in the shelf break.

64 Direct sea-ice/oceanic measurements in coastal polynyas around Antarc-
65 tica are temporally and spatially limited due to geographical and climatic
66 difficulties. The first wintertime oceanographic observations of the Adélie
67 Depression during the 'Mertz Polynya Experiment' (July-September 1999)
68 described the water mass properties and general circulation, confirming the
69 formation of DSW and provided an estimate of the corresponding sea-ice
70 growth rates (Bindoff et al., 2001; Williams and Bindoff, 2003). Williams
71 et al. (2008) described the seasonal formation and export of DSW from
72 moored instruments in the Adélie Depression and Adélie Sill between 1998-
73 2000. Williams et al. (2010) extended this analysis to moored instruments
74 and ship-based measurements from the austral summer of 2001 and spring
75 of 2004 on the upper continental slope and lower continental rise, describing
76 a dual-system of DSW export from Adélie (primary) and Mertz (secondary)
77 Depressions.

78 Numerical modeling, that can reproduce the observed water masses and
79 circulation, offers to improve our understanding of the processes in the AGVL
80 region. To achieve this, suitable models must explicitly resolve coastal polynyas,
81 whose typical horizontal scale is from a few to 100 km, and the associated
82 physical processes therein. Previous modeling in the Antarctic and Southern

83 Ocean region has not employed such high resolution, with a few exceptions
84 (Marsland et al., 2004, 2007; Kushahara et al., 2010). Moreover, to resolve the
85 bottom topography of the coastal region (*e.g.* sill, depression, shelf break,
86 etc.) which strongly controls water mass exchange into and out of the conti-
87 nental shelf region, a spatial resolution of a few kilometers is required. The
88 purpose of this study is to investigate the formation and outflow of DSW
89 and the seasonal variation of the ocean circulation in the AGVL region us-
90 ing an ice-ocean model of regionally high resolution. Section 2 describes the
91 ice-ocean model. In section 3, we validate the model results against direct
92 observations in the Adélie Depression. In section 4, we describe the modeled
93 ocean circulation and water mass formation in the AGVL region. In section
94 5, we examine the mechanisms of ocean circulation in the Adélie Depression
95 by idealized numerical experiments. Summary and discussion are presented
96 in section 6.

97 2. Ice-ocean model

98 We use the ice-ocean model COCO (Hasumi, 2006). The sea ice model
99 adopts a two-category thickness representation (Hibler, 1979). Its thermody-
100 namics is based on Bitz and Lipscomb (1999), with one layer for ice and a no-
101 heat-capacity layer for snow. Prognostic equations for momentum, mass and
102 concentration are taken from Mellor and Kantha (1989). Internal ice stress
103 is formulated by the elastic-viscous-plastic rheology (Hunke and Dukowicz,
104 1997). The model domain is global (Fig. 1a for the Southern Ocean). To
105 achieve high resolution in the focal region (Fig. 1b), two singular points
106 of the horizontal curvilinear coordinate are placed on East Antarctica (70°E
107 70.5°S and 143°E 68°S). The horizontal grid size over the coastal area in East
108 Antarctica is between a few kilometers and 15 km and that in the Adélie and
109 Mertz Depressions is within a few kilometers (Fig. 1b). The vertical coor-
110 dinate system of the ocean model is a hybrid of σ (normalized depth) and
111 z . There are 69 vertical levels: σ coordinate is applied to the five upper-
112 most levels between the free surface and 50 m below the mean surface level,
113 and the z coordinate is applied below. The vertical grid spacing in the z
114 coordinate region is 50 m (29 grids) and 100 m (35 grids) above and below
115 1500 m, respectively. A partial step representation is adopted for the bottom
116 topography (Adcroft et al., 1997).

117 The ocean model includes a uniformly third order polynomial interpola-
118 tion algorithm for tracer advection (Leonard et al., 1993), isopycnal diffusion,
119 isopycnal layer thickness diffusion (Gent et al., 1995), and a surface mixed
120 layer parameterization based on turbulence closure (Noh and Kim, 1999).
121 The isopycnal diffusion coefficient is $1.0 \times 10^2 \text{ m}^2\text{s}^{-1}$ and the thickness dif-

122 fusion coefficient is $1.0 \text{ m}^2\text{s}^{-1}$. The background vertical diffusion coefficient
 123 is $1.3 \times 10^{-5} \text{ m}^2\text{s}^{-1}$ at the surface and gradually increases with depth up to
 124 $2.9 \times 10^{-4} \text{ m}^2\text{s}^{-1}$ (case III of Tsujino et al. (2000)). The background ver-
 125 tical viscosity coefficient is $1.0 \times 10^{-4} \text{ m}^2\text{s}^{-1}$. Horizontal eddy viscosity is
 126 parameterized by a Laplacian form, and its coefficient spatially varies so as
 127 to resolve the Munk layer. The bottom friction is parameterized by a simple
 128 quadratic law with a constant drag coefficient of 1.3×10^{-3} . Convection is
 129 represented by a simple convective adjustment scheme.

130 The ice-ocean drag coefficient is 3.0×10^{-3} , and the associated turning
 131 angle is -10° relative to the direction of the uppermost layer velocity in
 132 the ocean model. To parameterize subgrid-scale leads, the maximum sea
 133 ice concentration is set to 0.98. Sea ice salinity is fixed at 5 psu. In the
 134 framework of a two-category sea ice model, the open/newly-formed ice area
 135 and the consolidated sea ice area coexist in one grid, and a minimum thickness
 136 for the consolidated sea ice (demarcation thickness) must be specified. A
 137 demarcation thickness of 10 cm is used in this study. It should be noted
 138 that sea ice production is a key factor controlling the ocean circulation in an
 139 Antarctic coastal polynya system, and that the ice model used in this study
 140 successfully reproduces the sub-regional locations of the coastal polynyas and
 141 high sea ice production around the AGVL region (Kusahara et al., 2010).

142 The model bathymetry, as shown in Fig. 1, is derived from GEBCO (IOC,
 143 IHO, BODC, 1994) and the data around the Adélie Sill (142.0°E - 145.0°E ,
 144 66.2°S - 65.7°S) is updated by shiptrack data prior to 2002 (Porter-Smith,
 145 2003). To realistically reproduce the horizontal topography, the coastline
 146 around Antarctica incorporates the summertime ice shelf and iceberg tongue

147 edges identified by the MODIS Mosaic of Antarctica Image Map (Haran
 148 et al., 2005). Observations indicate that coastal polynyas are formed in the
 149 downwind/downstream or 'lee' side of grounded icebergs and floating ice
 150 tongues, as well as in continental bays (Massom et al., 1998). To incorporate
 151 the blocking effect of sea ice advection by such grounded icebergs into the
 152 model, we set the sea ice velocity to zero at the corresponding grid points
 153 (Kusahara et al., 2010). In reality, there are spatial gaps among grounded
 154 icebergs, which allow sea water to pass through. Therefore in the model,
 155 oceanic flows are permitted below the grid points of grounded icebergs. In
 156 this study grounded icebergs are placed in the northern region of the Mertz
 157 Glacier tongue (sometimes referred to as 'the dagger'), along 149°E , and
 158 along 149.75°E (Fig. 1b).

159 The surface boundary conditions for the model include: surface wind, air
 160 temperature, specific humidity, downward shortwave, downward longwave,
 161 fresh water flux, and sea level air pressure. Daily data are utilized for all
 162 components. To calculate the wind stress and sensible and latent heat fluxes,
 163 we use the bulk formula of Kara (2000). When the surface air temperature is
 164 below 0°C , precipitation is treated as snow. Outside of the area within 100
 165 km from the coast of East Antarctica between 50°E and 160°E , sea surface
 166 salinity is restored to the monthly mean climatology with a 10 day damping
 167 timescale to suppress the bias towards overly deep convection in the offshore
 168 region. In the northern hemisphere, temperature and salinity are restored
 169 to the monthly mean climatology (Steele et al., 2001) throughout the water
 170 column. We perform an 18-year integration with the surface air climatology
 171 of Röske (2006) to obtain a quasi-steady state and continue the integration for

172 three years by switching from the forcing data to 1979 of the NCEP/NCAR
173 reanalysis (Kalnay, 1996) to avoid an initial shock to modeled system. After
174 initialisation, we perform a simulation from 1979 to 2008. The model results
175 for the thirty years 1979 - 2008 are utilized for the following analysis. In
176 some of the analyses for the ocean, we use monthly climatologies averaged
177 over the above period.

3. Validation of model results against observations in the Adélie Depression

Here we validate the model results against hydrographic and mooring observations in the Adélie Depression (Williams and Bindoff, 2003; Williams et al., 2008). The wintertime hydrographic sections ('Shelf-Break' and 'Loop' sections of Williams and Bindoff, 2003) are shown in Fig. 2a, together with the areas over which the modeling results are averaged for comparison with the mooring data (Williams et al., 2008). Major place names and small scale seamounts over the Mertz Bank (mb1, mb2, mb3, and mb4) are also labeled in Fig. 2a.

For the convenience of quantitative comparison, we use potential density (σ_θ) of 27.88 kg m^{-3} as a lower limit of DSW in the Adélie Depression for two reasons. Firstly, this potential density corresponds to the lower limit of modeled DSW when DSW is defined by a dense water which outflows from the Adélie Depression and whose outflow ceases in summer. Secondly, a number of previous observational studies in the Adélie Depression (Bindoff et al., 2001; Williams and Bindoff, 2003; Williams et al., 2008) suggest this is a conservative estimate of the minimum potential density for exported DSW to produce AABW (hereafter referred to as the critical density). While a detailed discussion about the best water mass definition of DSW is beyond the scope of this paper, we note that defining the critical density of DSW, i.e. the density at which there is sufficient negative buoyancy for downslope AABW production to begin, is problematic due to its dependence on the spatio-temporal variability of the ambient offshore density field (Williams et al., 2010). It is also problematic for models to use rigid water mass definitions

203 determined from observations when systematic biases are present.

204 We also use neutral density (γ^n , Jackett and McDougall, 1997), which is
205 frequently used for defining water masses in the Southern Ocean. Neutral
206 density surfaces of 28.00 and 28.27 kg m⁻³ correspond to the highest density
207 (deeper limit) of AASW and the lowest density (shallower limit) of AABW,
208 respectively (Orsi et al., 1999; Bindoff et al., 2000; Orsi and Wiederwohl,
209 2009). The layer between these two neutral density surfaces is defined as
210 mCDW. Note that in the potential temperature-salinity space the potential
211 density surface of 27.80 kg m⁻³ roughly traces the neutral density surface of
212 28.27 kg m⁻³ for cold temperatures.

213 3.1. Shelf-Break section

214 The modeled vertical profiles of potential temperature, salinity, and po-
215 tential density along the Shelf-Break section in August are shown in Figure 3.
216 Near-freezing temperatures are found in the surface 50-m-thick layer and the
217 bottom 400-m-thick layer in the Adélie Depression (Fig. 3a). The maximum
218 potential temperature is at intermediate depths (between 100 and 300 m)
219 over the whole section. The warmest intrusion, with potential temperature
220 around -0.8°C, is found between stations 59 and 60 (to the north of mb2)
221 at depths around 300 m.

222 The near-freezing water at the base of the Adélie Depression has high
223 salinity, up to 34.7 psu (Fig. 3b). There is another salinity maximum near
224 the bottom between stations 61 and 63 whose value (34.6 psu) is slightly
225 lower than in the Adélie Depression. The water from the surface to 300 m is
226 fresher, with a minimum value of about 34.35 psu centered between stations
227 59 and 60. Isohaline contours are slanted in the eastern half of the Shelf-

228 Break section, and they outcrop between stations 62 and 63. The potential
229 density has a similar pattern to salinity, as the temperature dependence of
230 density at this temperature is weak.

231 The modeled features of potential temperature and salinity are broadly
232 consistent with the observational results (Williams and Bindoff, 2003, col-
233 ored circles in Fig. 3). However, there are three notable differences. Firstly,
234 the modeled intrusion at 200-300 m depths is wider and warmer than the ob-
235 served one (Figs. 3a and 4a-b). Secondly, the modeled salinity in the surface
236 150-m-thick layer and the corresponding potential density are lower than the
237 observed one (Figs. 3b and 4a-b). Finally, the modeled salinity and poten-
238 tial density at depths from 200 to 400 m are higher than observed. These
239 observed properties are outside the standard deviation of the interannual
240 variability in the model, implying that there are systematic biases in the
241 model.

242 A strong vertical velocity shear is found just to the east of station 57, with
243 a southeastward surface flow of lighter waters and a northwestward bottom
244 flow of denser waters. The velocity shear is consistent with a potential density
245 front which is formed over the southeastern flank of the Mertz Bank (Fig.
246 3c). There are four separate southward flows across this section between
247 stations 59 and 63: the first between stations 59 and 60, the second to
248 the east of station 60 (over the western flank of the northward protruding
249 topography from mb3), the third to the east of station 61, and the fourth
250 between stations 62 and 63 (over the western flank of mb4). These flows have
251 a vertically coherent structure with the maximum velocity near the surface.
252 The second and fourth flows have relatively large velocity from 100 m depth

253 to the bottom, suggesting that there is net inflow into the Adélie Depression.
254 The first and third flows are along topography (see horizontal velocity fields
255 shown later).

256 Characterizing the water masses using density, the features along the
257 Shelf-Break section are briefly summarized as follows. AASW of 100-200
258 m-thick flows into the Adélie Depression over the whole section across the
259 shelf break. The water of mCDW, which is positioned below AASW, flows
260 into the Adélie Depression along the strong density front formed over the
261 southwestern flank of the Mertz Bank and bottom topography. The waters
262 in the densest classes (DSW) have a bottom intensified structure and flow
263 northwestward to the Adélie Sill.

264 *3.2. Loop section*

265 Figure 5 shows the modeled vertical profiles of potential temperature,
266 salinity, and potential density along the Loop section in August. The Loop
267 section consists of sections 1, 2, and 3 (Fig. 2a).

268 Potential temperature is a maximum of about -1.4°C at around 300 m
269 over the southwestern flank of the Mertz Bank (Figs. 4 and 5a). Waters of
270 near-freezing temperatures are found at the surface over the whole section
271 and over the full water columns in the coastal areas. The potential temper-
272 ature maximum in the Loop section is linked with that of the mCDW inflow
273 in the Shelf-Break section.

274 There are salinity and density fronts over the southwestern flank of the
275 Mertz Bank (Fig. 5b and 5c), with fresher, less dense water in the surface
276 layer around the boundary between sections 1 and 2. Higher salinity waters
277 are found in the coastal areas of sections 1 and 3, indicating brine rejection

278 from coastal polynyas. The position and slope of the 27.88 kg m^{-3} isopycnal
279 are in reasonable agreement with observations (Williams and Bindoff, 2003).
280 Again, there are some model biases as well as in the Shelf-Break section (Fig.
281 4c-d).

282 In section 1 there is a southeastward surface flow and a northeastward
283 bottom flow over the southwestern flank of the Mertz Bank, while there is a
284 weak inflow into the interior of the Loop section over the whole of section 2. In
285 section 3, there is a southeastward flow at depths between the surface and 200
286 m, which is directed towards the Mertz Glacier Tongue, and a northwestward
287 inflow in the bottom layer. Once again characterizing the water masses
288 by density, we find AASW and mCDW flowing towards the Mertz Glacier
289 Tongue along the southwestern flank of the Mertz Bank and the densest shelf
290 waters flowing northwestwards to the Adélie Sill.

291 Williams and Bindoff (2003) estimated the absolute velocity along the
292 Loop section based on data from the shipboard ADCP and geostrophic shear
293 from hydrography. The velocity normal to the section (Fig. 5) does not
294 agree well with the observation (Fig. 11 of Williams and Bindoff, 2003).
295 However, it should be noted that the observational estimate includes tides
296 and short-term variability due to eddies. It is difficult to directly compare
297 the climatological average of the modeled velocity with the observational
298 estimate. Overall the good agreement of the tracer fields between the model
299 and the observation indicates model's ability to reproduce the time-average
300 velocity field.

3.3. Seasonal variation in the Adélie Depression and at the Adélie Sill

Figure 6 shows the seasonal variations of potential density in the areas near the Mertz Glacier Tongue (A in Fig. 2a, hereafter referred to as the 'depression' region) and just south of the Adélie Sill (B in Fig. 2a, hereafter referred to as the 'sill' region). The seasonal variation of potential density in the Adélie Depression is closely linked to the sea ice production there, whose seasonal variation is displayed in Fig. 7 (see an area enclosed by dashed line in Fig. 2a, hereafter referred to as the 'control volume'). Sea ice production within 30 km from the coast accounts for about 60% of the total ice production in the Adélie Depression (Figs. 2b and 7).

In the depression region (Fig. 6a), a strong stratification forms near the sea surface in summer, which is then eroded in March due to sea ice production and the associated brine rejection. From July to August, when sea ice production reaches its maximum, deep convection occurs in the coastal area and the potential density over the whole water column increases. The potential density at the surface and bottom reaches a maximum in August and September, respectively. Subsequently, the surface layer starts restratify from December after the cessation of sea ice production.

The strong near-surface stratification in the sill region also begins to erode in March, as in the case of the depression region (Fig. 6b). Sea ice production is relatively smaller in this area, due to its distance from the coast (Figs. 2b and 7). There is no deep convection increasing the potential density over the whole water column, but there is limited convection from April to May. At depths deeper than 200 m, the potential density starts to increase in June and is a maximum in October. Subsequently, the potential density decreases

326 gradually from November to April.

327 Figure 6c shows the seasonal variations at 425 and 575 m for the two
328 regions, in both the model and the observations. The observed monthly
329 values are calculated from the available mooring data in the period from
330 April 1998 to April 1999 (Williams et al., 2008). In the model, potential
331 density starts to increase in May at 425 m in both regions. Potential density
332 in the sill region reaches a maximum in October, which is a month after the
333 peak in the depression region, and the maximum value in the sill region is
334 higher than in the depression region. These modeled features are similar to
335 those observed (Williams et al., 2008).

336 The model reproduces the observed seasonal variations at the four moor-
337 ing depth/locations in terms of the amplitude and phase. The modeled
338 potential density, on the other hand, is biased toward higher density. The
339 largest bias is found at the depth of 575 m in the depression region. There
340 are several possible reasons for the model bias. Firstly, there is no interac-
341 tion between ice shelves and the ocean in this model. Williams et al. (2008)
342 showed the existence of Ice Shelf Water (ISW) at the depth of 587 m near
343 the Mertz Glacier Tongue and described the classic 'ice-pump' mechanism by
344 which the densest shelf water at the base of the Adélie Depression migrates
345 to the grounding line at the back of the Mertz Glacier, ultimately producing
346 colder, fresher Ice Shelf Water that re-enters the Adélie Depression at mid-
347 depths in the southern half of the MGT that is intensified near Buchanan
348 Bay. The lack of ISW in this model is consistent with the largest bias found
349 at 575 m in the depression region. Secondly, no flow is permitted under the
350 Mertz Glacier Tongue in the model. The water mass exchange under the

351 Mertz Glacier Tongue from the Mertz Depression may influence the water
352 mass properties in the Adélie Depression. The third is uncertainty in the
353 forcing data set. Tamura et al. (2008) reported that the sea ice production
354 estimated from the NCEP/NCAR reanalysis surface air data is larger by 26%
355 than that estimated from the ECMWF reanalysis. Since the current model
356 is driven by the NCEP/NCAR reanalysis, it is likely that the current model
357 tends to be biased toward larger DSW production. This model bias is an
358 important consideration when estimating the formation of DSW based on
359 water mass definitions derived from observations.

360 4. Circulation and water mass budget

361 4.1. Adélie Depression

362 4.1.1. Winter regime

363 Sea ice production in the Adélie Depression starts in March, and the
364 coastal areas exhibit active sea ice formation from May to September (Fig.
365 7). The potential density in the Adélie Depression reaches the maximum
366 in September (Fig. 6). Isopycnal surfaces corresponding to $\gamma^n = 28.00$ and
367 28.27 kg m^{-3} and $\sigma_\theta = 27.88 \text{ kg m}^{-3}$ are outcropped at the surface (Figs.
368 8a and 10a). In the surface layer (top 50 m), there are flows across the shelf
369 break toward the coastal areas which exhibit high sea ice production. In
370 the subsurface (125 m) and middle (275 m) layers, there are three routes of
371 southward flow across the shelf break into the Adélie Depression (Fig. 10a):
372 to the west of mb1, between mb2 and mb3, and to the west of mb4. These
373 southward flows merge into one stream over the southwestern flank of the
374 Mertz Bank and the merged flow is directed to the Mertz Glacier Tongue
375 (Fig. 8b and 8c). The potential temperature is a maximum in the subsurface
376 and middle layers along this flow, which extends from the shelf break to the
377 edge of the Mertz Glacier Tongue.

378 In the middle layer, there is a strong density front which runs parallel
379 to the southwestern flank of the Mertz Bank. To the north of the density
380 front there is a merged southeastward flow coming from shelf break (fig. 8b
381 and 8c). An opposing flow exists to the south of the front in the middle
382 and lower (425 m) layers, which flows from the Mertz Glacier Tongue to the
383 Adélie Sill (Fig. 8c and 8d). The water as dense as 27.88 kg m^{-3} extends to
384 the north of the Adélie Sill, indicating a pronounced outflow of DSW that

385 has a bottom-intensified structure (Figs. 8c-d and 10a).

386 Along the density front, a warmer water mass, corresponding to AASW
387 and mCDW, intrudes across the shelf break in the middle layer (Fig. 8g).
388 The potential temperature maximum in the intermediate depths of the Shelf-
389 Break and Loop sections discussed in the previous section corresponds to this
390 intrusion. The flow patterns in the formation periods of DSW, from June
391 to August, are similar to Fig. 8, except that the density contrast and flow
392 speed are smaller (not shown).

393 4.1.2. *Summer regime*

394 Sea ice production decreases rapidly in October and ceases in December
395 (Fig. 7), the surface layer in the Adélie Depression becoming strongly strat-
396 ified by February (Fig. 6). There is a surface-intensified clockwise (cyclonic)
397 circulation trapped in the Adélie Depression (Fig. 9), as indicated by the
398 dome of dense water at the center of the circulation in the middle and lower
399 layers. In the surface and subsurface layers, fresher waters caused by sea ice
400 melting exist in the coastal area, and a strong westward flow is formed along
401 the coast. The coastal current flows out from the western end of the region
402 in the surface layer and from the northern end in the subsurface and middle
403 layers (Figs. 9a-c and 10). The intrusion of AASW and mCDW from the
404 shelf break extends around the slope of the Adélie depression in a clockwise
405 manner.

406 4.1.3. *Water mass budget*

407 Figure 11 shows the seasonal variation of the net transport across the
408 boundaries of the control volume and across the Adélie Sill (along the north-

409 ern end of the control volume west of 143.75°E) in each 0.02 kg m^{-3} potential
 410 density bin. Throughout the year, there are inflows of relatively light wa-
 411 ters into the control volume and outflows of relatively dense waters (Fig.
 412 11e). The seasonal variation of the outflowing DSW across the Adélie Sill
 413 is almost the same as that across the northern end of the control volume.
 414 It indicates that the outflow of DSW predominantly occurs at the Adélie
 415 Sill. The outflow volume flux of DSW from the Adélie Sill reaches the max-
 416 imum of 0.54 Sv in September and becomes zero in May. The annual mean
 417 DSW outflow from the Adélie Sill and from the whole Adélie Depression
 418 is 0.21 Sv and 0.26 Sv, respectively. From June to December, the volume
 419 loss for the outflow of DSW is balanced by the inflow of less dense waters
 420 across the northern boundary. In this study, we use the cutoff potential
 421 density of 27.88 kg m^{-3} as the critical density for DSW. Figure 12 shows a
 422 dependence of the estimated DSW outflow transport on the selected cutoff
 423 potential density. Since the dependence on density at 27.88 kg m^{-3} is not
 424 small, our estimate is sensitive to the prescribed cutoff density and will be
 425 addressed further in the discussion section.

426 To examine the potential temperature-salinity characteristics of water
 427 masses exchanged across the northern boundary, the net transport is calcu-
 428 lated in the potential temperature-salinity space with bin intervals of $0.1 \text{ }^{\circ}\text{C}$
 429 and 0.02 psu (Fig. 13). The outflow of DSW denser than $\sigma_{\theta} = 27.88 \text{ kg m}^{-3}$
 430 becomes notable from July to November. From December to March, the
 431 main component of the outflow is in the areas corresponding to modified
 432 Shelf Water (mSW), indicating that remnant DSW in the Adélie Depression
 433 mixes with the mCDW penetrating from the shelf break and the resulting

434 water mass flows out through the Adélie Sill. From April to June, there is
 435 no notable outflow of DSW, only mCDW/mSW.

436 Figure 14 shows the seasonal variation of ratio of waters classified by
 437 potential density bins of 0.02 kg m^{-3} width in the control volume. The ratio
 438 of DSW reaches the maximum of about 55% in September and a minimum
 439 of about 5% in June. The amount of remnant DSW in the Adélie Depression
 440 in June is smaller by one order of magnitude than outflow volume of DSW
 441 from the Adélie Depression in the year. This fact indicates that the newly-
 442 formed DSW in the Adélie Depression is depleted by outflow and mixing
 443 with mCDW within the year, i.e. there is little storage or accumulation of
 444 DSW from year to year.

445 4.2. Mertz Depression

446 As in the case of the Adélie Depression, there are two distinct seasonal
 447 flow patterns in the Mertz Depression: a vertical circulation formed in the
 448 depression during winter and a surface-intensified clockwise horizontal circu-
 449 lation trapped over the depression during summer (Figs. 8 and 9). Coastal
 450 polynyas form in lee side of a near-meridional line of grounded icebergs, in-
 451 cluding iceberg B9-b, along $148\text{--}149^\circ\text{E}$ and show high sea ice production
 452 (Fig. 2b). Sea ice productions over the Adélie and Mertz Depressions (sums
 453 over areas enclosed by solid lines and coastline/grounded icebergs in Fig.
 454 2b) are 219 km^3 and 120 km^3 , respectively. The sea ice production in the
 455 Mertz Depression accounts for about 35% of total sea ice production in the
 456 AGVL region, consistent with observational analysis (Williams et al., 2010).
 457 There are intrusions of AASW and mCDW from shelf break into the Mertz
 458 Depression along the western flank of the Ninnis Bank (Fig. 8). Along these

intrusions, potential temperature is maximum at intermediate depths. The slope of the density front formed over the western flank of the Ninnis Bank is weaker than that formed over the southwestern flank of the Mertz Bank in the Adélie Depression. The densest waters ($\sigma_\theta > 27.90 \text{ kg m}^{-3}$) are found along the southern and western flanks of the Mertz Depression. Along the weak density front, bottom dense water flows toward the Mertz Sill against the western side of the Mertz Depression.

There is a distinct outflow of DSW from the Mertz Depression. The density of outflowing DSW from the Mertz Depression is lighter than that from the Adélie depression (Fig. 12). Outflowing waters denser than 27.88 kg m^{-3} in the Mertz Depression are found from August to December, and the period of outflowing DSW is shorter than in the Adélie Depression (Fig. 15). Annual mean export of waters denser than $\sigma_\theta = 27.88 \text{ (27.80) kg m}^{-3}$ from the Mertz Sill is 0.12 (0.32) Sv . The model demonstrates the dual-system for DSW formation and export from the Adélie and Mertz depressions described by observations (Williams et al., 2010) and confirms that the Mertz Depression produces less DSW, over a shorter period of time.

476 5. Mechanism of the ocean circulations

477 5.1. Idealized experiments

478 In the initial simulation (hereafter referred to as CTRL), the ocean cir-
479 culations in the Adélie and Mertz Depressions are characterized by two distinct
480 patterns for winter and summer. In the Adélie Depression in winter, a verti-
481 cal circulation developed over the southwestern flank of the Mertz Bank and
482 consists of a southeastward flow in the upper layer toward the Mertz Glacier
483 Tongue and a northwestward flow in the lower layer toward the Adélie Sill. In
484 summer there is a surface-intensified clockwise horizontal circulation which
485 is trapped over the Adélie Depression. In this section, we focus on the Adélie
486 Depression and perform a series of idealized numerical experiments to inves-
487 tigate the mechanisms driving the two distinct seasonal circulations.

488 The setup of the idealized experiments is summarized in Table 1. The
489 coastline and topography is the same as in CTRL. For simplicity, a stand-
490 alone ocean model is used for these experiments, and idealized surface fresh-
491 water flux and wind stress are imposed. EXP1 is driven only by surface
492 freshwater flux which corresponds to sea ice production of 10 cm s^{-1} . The
493 forcing area is between 140°E and 146.2°E and within 30 km distance from
494 the coast. After a 1-year integration a quasi-steady state in the Adélie De-
495 pression is achieved. EXP2 and EXP3 are driven only by the surface wind
496 stress of winter and summer, respectively, calculated from the climatology of
497 Röske (2006). In these cases a quasi-steady state is obtained after a 90-day
498 integration. The initial condition for the three experiments has a uniform
499 tracer distribution (potential temperature at -1.0°C and salinity at 34.0 psu)
500 and zero velocity over the entire model domain. The initial condition for

EXP4 and EXP5 is the final state of EXP1. No surface forcing is imposed in EXP4, and only the summertime wind stress is imposed in EXP5.

5.2. Results of idealized experiments

Figure 16 shows the results (potential density anomaly referenced to the initial condition and velocity) of EXP1 and EXP4, which are averaged over the last 60 days. In EXP1 (Fig 16a-d), there is a density front between a dense water mass formed in the coastal area and the lighter water mass over the southwestern flank of the Mertz Bank that comes from the shelf break. In the subsurface layer, there is flow toward the Mertz Glacier Tongue. There is a flow of dense water from the Mertz Glacier Tongue to the Adélie Sill along the density front in the middle and lower layers, and a dense water mass flows out from the Adélie Sill. These features are similar to wintertime in the CTRL.

There are two qualitative differences between EXP1 and CTRL. Firstly, Antarctic Slope Front (ASF) and Current (ASC) does not exist over the continental slope, and thus the strong westward flow along the ASC is lacking in EXP1. Secondly, the light water in the surface layer in EXP1 flows eastward with the dense water formed in the coastal area on the right. These differences are caused by the difference in stratification between the initial conditions. In EXP4 (Fig 16e-h), there is a surface-intensified clockwise circulation in the Adélie Depression, i.e., there is a dome of positive density anomaly at the center of circulation. These features are similar to the summertime situation of CTRL. Velocities in the Adélie Depression for EXP2 and EXP3 are smaller by one order of magnitude than those in EXP1, and there is no pronounced circulation (not shown). The flow pattern in EXP5

526 is similar to that in EXP4. This implies that wind stress is not the main
527 driving force for the circulation in the Adélie Depression.

528 These results indicate that the vertical circulation in winter is driven by
529 the brine rejection in the coastal polynyas and that the surface-intensified
530 clockwise circulation in summer results from the cessation of sea-ice produc-
531 tion. The seasonal variation in the circulation in the Adélie Depression can
532 be understood as spinning-up and down of the haline circulation driven by
533 brine rejection, a phenomenon that has been documented for the large-scale
534 global thermohaline circulation (e.g., Kawase, 1987; Suginohara and Fuka-
535 sawa, 1988). While the haline circulation presented here is more localized,
536 the basic physics are the same. The same mechanism is also valid for the
537 seasonal variation of circulation in the Mertz Depression.

538 6. Summary and Discussion

539 In this study we used a global ice-ocean model to investigate the formation
540 and export of DSW from Adélie and George V Land. The model reproduces
541 the observed features of winter hydrography in the Adélie Depression such as
542 a warm mCDW intrusion at intermediate depths and a low salinity AASW in
543 the surface layer (Figs. 3 and 5). The model also reproduces the amplitude
544 and phase of the seasonal variation of potential density observed at mooring
545 sites near the Mertz Glacier Tongue and just south of the Adélie Sill (Fig.
546 6a).

547 The modeled circulations in the Adélie and Mertz Depressions are char-
548 acterized by two distinct flow patterns during winter and summer (Figs. 8
549 and 9). In the two depressions, a vertical circulation develops in winter and
550 a surface-intensified clockwise circulation is formed in summer. From a se-
551 ries of idealized experiments (Table 1 and Fig. 16), these circulations in the
552 depressions are shown to be the result of a spinning-up and down of haline
553 circulation driven by brine rejection at coastal polynyas, unrelated to the
554 surface wind stress.

555 In the Adélie Depression, the vertical circulation consists of a southeast-
556 ward flow in the upper layer towards the Mertz Glacier Tongue and a north-
557 westward flow in the lower layer toward the Adélie Sill (Figs. 3, 5, and 8).
558 These flows are associated with a density front along the southwestern flank
559 of the Mertz Bank. The density front is formed between dense waters formed
560 in the coastal area and lighter waters that originated from the shelf break.
561 The wintertime northwestward bottom flow is connected to the outflow of
562 dense waters from the Adélie Depression.

563 The outflow of DSW from the Adélie Depression is predominantly through
 564 the Adélie Sill. The outflow of the densest classes of shelf water (DSW) has
 565 a bottom intensified structure under the density front at the Adélie Sill. The
 566 wintertime outflow of dense water from the Adélie Sill is compensated by the
 567 inflow of AASW and mCDW across the shelf break (Fig. 11). AASW flows
 568 into the Adélie Depression across the shelf break over a wide zonal extent and
 569 with a thickness of 100-200 m (Fig. 10a). The inflow of mCDW is confined
 570 in the strong density front formed over the southwestern flank of the Mertz
 571 Bank and bottom topography (Figs. 3 and 10a).

572 The model clearly shows a dual-system for the formation and export of
 573 DSW from the Adélie and Mertz Depressions (Fig. 12), consistent with recent
 574 observational analysis over the upper continental slope and lower continental
 575 rise (Williams et al., 2010). Assuming a critical (cutoff) potential density
 576 for DSW of 27.88 (27.80) kg m^{-3} , the annual mean transport to the open
 577 ocean across the Adélie and Mertz Sills are estimated to be 0.21 (0.37) Sv
 578 and 0.12 (0.32) Sv, respectively. This modeled DSW export from Adélie Sill
 579 is consistent with previous observational and model studies (Table 2).

580 However, the DSW export in this study is likely to be overestimated
 581 because the modeled potential density of outflow is biased to the higher
 582 density. Assuming the bias of potential density is 0.04 kg m^{-3} (Figs. 4 and
 583 6), the above DSW exports from Adélie and Mertz Sills are re-estimated to
 584 be 0.12 (0.30) Sv and 0.05 (0.22) Sv, respectively (Table 2).

585 The property of outflowing dense water through the Adélie Depression
 586 corresponds to DSW from July to November, and mSW from December to
 587 March, indicating that DSW in the Adélie Depression is mixed with the pen-

etrating mCDW from the shelf break and the mixed water outflows through
the Adélie Sill (Figs. 13 and 14). The density of the DSW outflow from the
Mertz Depression is lighter than that from the Adélie Depression and has a
shorter export season (Figs. 13 and 15).

Marsland et al. (2004) showed the wintertime overturning circulation in
the Adélie Depression linked with coastal polynya processes using an ice-
ocean model. Their medium horizontal resolution over the Adélie Depression
was not enough to resolve key features of bottom topography for reproducing
the ocean circulation there, where a horizontal resolution as high as a few
kilometers is needed to realistically reproduce the observed features in the
AGVL region. In this study, we demonstrate for the first time that a high
resolution model can realistically reproduce the observed features across the
entire AGVL region and can be a powerful tool for studying Antarctic coastal
polynya systems.

In this study, the grid points for ice shelves are treated as land. However,
in reality there is an interaction between the ocean and the ice shelves. This
interaction is considered to lead to melting ice shelves and adding freshwater
into the ocean, which could modify sea ice distributions and water mass
formations (Hellmer, 2004). Losch (2008) proposed a new ice shelf cavity
model for z coordinate ocean models. Such an ice shelf cavity model is
currently under development for use in COCO.

In the present model, the downslope mixing of dense shelf water over
the slope is not well reproduced (Wang et al., 2008), due mainly to the
coarse vertical resolution (grid thickness is 50 - 100 m over the continental
slope). To effectively reproduce downslope flows over the continental slope

613 and the reciprocal ascending plumes of ice shelf water beneath ice shelves,
614 much higher vertical resolution (about 20 m) is required to explicitly resolve
615 the boundary layers between the ocean and solid boundaries.

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Table 1: Summary of idealized experiments.

	Initial Condition	Freshwater Flux	Wind Stress	Period
EXP1	T=-1.0°C, S=34.0 psu	$\sqrt{^*}$	-	360
EXP2	T=-1.0°C, S=34.0 psu	-	JJA	90
EXP3	T=-1.0°C, S=34.0 psu	-	DJF	90
EXP4	Final state of EXP1	-	-	180
EXP5	Final state of EXP1	-	DJF	180

*: Freshwater flux corresponding to a sea ice production of 10 cm/day.

Table 2: Comparison with previous studies

Source	Water mass	DSW export (Sv)
Adélie Sill		
Williams et al. (2008)	$\sigma_\theta > 27.88$	0.1 - 0.5
Marsland et al. (2004)	$\sigma_\theta > 27.88$	0.15
This study	$\sigma_\theta > 27.88$	0.21 ± 0.05
	$\sigma_\theta > 27.88 + 0.04$	0.12 ± 0.05
	$\sigma_\theta > 27.80$	0.37 ± 0.04
	$\sigma_\theta > 27.80 + 0.04$	0.30 ± 0.05
Mertz Sill		
This study	$\sigma_\theta > 27.88$	0.12 ± 0.07
	$\sigma_\theta > 27.88 + 0.04$	0.05 ± 0.05
	$\sigma_\theta > 27.80$	0.32 ± 0.07
	$\sigma_\theta > 27.80 + 0.04$	0.22 ± 0.08

725 **Figure 1** Bathymetry of the model (a: Southern Ocean, b: around the
 726 AGVL region). In b), horizontal grid spacing is shown by red dashed lines
 727 and grounded icebergs are shown by the crosses. See the caption of Fig. 2
 728 for the abbreviations of place names.

729 **Figure 2** Topography around the AGVL region. a) The blue dashed and
 730 solid lines indicate the Shelf-Break and Loop sections, respectively. The
 731 green boxes labeled by A (depression region) and B (sill region) indicate
 732 areas used for averaging model results. The red dashed line is the bound-
 733 ary of the control volume. Crosses show the locations of grounded icebergs.
 734 Abbreviations of the place names are as follows: Adélie Bank (AB), Adélie
 735 Depression (AD), Adélie Sill (AS), Mertz Bank (MB), Commonwealth Bay
 736 (CB), Watt Bay (WB), Buchanan Bay (BB), Mertz Glacier Tongue (MGT),
 737 Mertz Depression (MD), Mertz Sill (MS), Ninnis Bank (NB), and B9b ice-
 738 berg (B9b). b) Net sea ice production (m/year). The area of net sea ice
 739 production smaller than 2 m is masked out. The orange lines define areas
 740 for calculating sea ice production.

741 **Figure 3** Vertical sections of (a) potential temperature ($^{\circ}\text{C}$), (b) salinity
 742 (psu), and (c) potential density (kg m^{-3}) in August along the Shelf-Break
 743 section (see blue dashed line with circles in Fig. 2a). Colored circles indicate
 744 observed values of potential temperature and salinity (Williams and Bindoff,
 745 2003). Black contours in panel c) show the velocity normal to the section
 746 (cm/s). Positive (negative) velocity indicates offshore (onshore) direction
 747 and the negative values are hatched. Distance in the horizontal axis is mea-

748 sured from station 58. Dashed blue and red lines indicate the neutral density
749 surfaces of 28.00 and 28.27 kg m^{-3} , respectively. The solid blue line indicates
750 the potential density surface of 27.88 kg m^{-3} .

751

752 **Figure 4** Vertical profiles of potential temperature, salinity and potential
753 density at stations 57, 59, L4 and L9 (see the locations in Fig. 2a) in August.
754 The solid line and gray shading shows the modeled mean and standard de-
755 viation, respectively, and the dashed line shows the modeled value in 1998.
756 Circles indicate the observed value of Williams and Bindoff (2003).

757 **Figure 5** As in Figure 3, but along the Loop section. Positive (negative)
758 velocity indicates outward (inward) direction. Averaged values over three
759 Loop transects are used for the observed potential temperature and salinity
760 (Williams and Bindoff, 2003).

761 **Figure 6** Seasonal variation of potential density near the Mertz Glacier
762 Tongue (area A, depression region) and just south of the Adélie Sill (area B,
763 sill region). The contour interval in a) and b) is 0.02 kg/m^3 and the values
764 larger than 27.88 kg/m^3 are shaded. The horizontal dashed lines indicate
765 depths of 425 m and 575 m. c) Timeseries of the potential density at 425 m
766 and 575 m, averaged over areas A and B in the model (thick lines), and from
767 the observations (thin lines with dots).

768 **Figure 7** Seasonal variation of sea ice production in the Adélie Depression.
769 Gray colors indicate distance from the coast (km).

770 **Figure 8** Potential density, temperature, and velocity fields at surface (0 -
771 50 m), subsurface (125 m), intermediate (275 m), and lower (425 m) layers in
772 September. Dashed blue and red lines indicate the neutral density surfaces of
773 28.00 and 28.27 kg m^{-3} , respectively. Solid blue lines indicate the potential
774 density surface of 27.88 kg m^{-3} . Gray lines show the depth contours, with
775 100 m (500 m) intervals in the regions shallower (deeper) than 500 m. Some
776 vectors are thinned out for clarity. Numbers with red circles indicate mb1,
777 mb2, mb3, and mb4.

778 **Figure 9** As in Figure 8, but in February.

779 **Figure 10** Vertical sections of potential density (kg m^{-3}) along the bound-
780 aries of the control volume in (a) September and (b) February. Black contours
781 show the velocity normal to the section (cm/s). Positive (negative) velocity
782 indicates outward (inward) flow. Negative values are hatched. Dashed blue
783 and red lines indicate the neutral density surfaces of 28.00 and 28.27 kg m^{-3} ,
784 respectively. Solid blue line indicates the potential density surface of 27.88 kg m^{-3} .

785

786 **Figure 11** Seasonal variation of net transport across control volume bound-
787 ary in 0.02 kg m^{-3} potential density bins. Positive values indicate out-

788 flow from the control volume. Blue lines indicate the potential density of
789 27.88 kg m^{-3} . In b), the vertical blue bars show the standard deviation of
790 interannual variability for $\sigma_\theta = 27.88 \text{ kg m}^{-3}$.

791 **Figure 12** Dependence of annual mean DSW transport from the Adélie (cir-
792 cles) and Mertz (squares) Sills on the cutoff density. Error bars indicate the
793 standard deviation of interannual variability and are only shown for the DSW
794 transport from the Adélie Depression for clarity.

795 **Figure 13** Seasonal variation of water exchange across the northern bound-
796 ary of the Adélie Depression in potential temperature-salinity space. Dashed
797 blue and red lines show the neutral density of 28.00 and 28.27 kg m^{-3} , re-
798 spectively. Blue thick and thin lines show the potential density of 27.88 and
799 27.80 kg m^{-3} , respectively.

800 **Figure 14** Ratio of water masses in the control volume. The total volume
801 of the control volume is $8.82 \times 10^6 \text{ km}^3$. Dashed blue and red lines indi-
802 cate the neutral density surfaces of 28.00 and 28.27 kg m^{-3} , respectively.
803 The solid blue line indicates the potential density surface of 27.88 kg m^{-3} .
804 Vertical blue bars show the standard deviation of interannual variability for
805 $\sigma_\theta = 27.88 \text{ kg m}^{-3}$.

806 **Figure 15** As in Figure 13, but across the Mertz Sill.

807 Figure 16 Potential density anomaly (relative to the initial density) and
808 velocity fields at surface (0 - 50 m), subsurface (125 m), intermediate (275
809 m), and lower (425 m) layers for (a-d) EXP1 and (e-h) EXP4.

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812

Figure 1:

Figure 2:

Figure 3:

Figure 4:

Figure 5:

Figure 6:

Figure 7:

Figure 8:

Figure 9:

Figure 10:

Figure 11:

Figure 12:

Figure 13:

Figure 14:

Figure 15:

Figure 16: