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► To cite this version:

Loïc Jullion, Alberto C. Naveira Garabato, Sheldon Bacon, Michael P. Meredith, Peter J. Brown, et al.. The contribution of the Weddell Gyre to the lower limb of the Global Overturning Circulation. *Journal of Geophysical Research. Oceans*, 2014, 119 (6), pp.3357-3377. 10.1002/2013JC009725 . hal-01255764

HAL Id: hal-01255764

<https://hal.science/hal-01255764>

Submitted on 13 Jan 2016

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1 The contribution of the Weddell Gyre to the lower
2 limb of the Global Overturning Circulation

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Abstract. The horizontal and vertical circulation of the Weddell Gyre
is diagnosed using a box inverse model constructed with recent hydrographic
sections and including mobile sea ice and eddy transports. The gyre is found
to convey 42 ± 8 Sv ($1 \text{ Sv} = 10^6 \text{ m}^3 \text{ s}^{-1}$) across the central Weddell Sea

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7 and to intensify to 54 ± 15 Sv further offshore. This circulation injects $36 \pm$
8 13 TW of heat from the Antarctic Circumpolar Current to the gyre, and ex-
9 ports 51 ± 23 mSv of freshwater, including 13 ± 1 mSv as sea ice to the
10 mid-latitude Southern Ocean. The gyre's overturning circulation has an asym-
11 metric double-cell structure, in which 13 ± 4 Sv of Circumpolar Deep Wa-
12 ter (CDW) and relatively light Antarctic Bottom Water (AABW) are trans-
13 formed into upper-ocean water masses by mid-gyre upwelling (at a rate of
14 2 ± 2 Sv) and into denser AABW by downwelling focussed at the western
15 boundary (8 ± 2 Sv). The gyre circulation exhibits a substantial through-
16 flow component, by which CDW and AABW enter the gyre from the Indian
17 sector, undergo ventilation and densification within the gyre, and are exported
18 to the South Atlantic across the gyre's northern rim. The relatively mod-
19 est net production of AABW in the Weddell Gyre (6 ± 2 Sv) suggests that
20 the gyre's prominence in the closure of the lower limb of global oceanic over-
21 turning stems largely from the recycling and equatorward export of Indian-
22 sourced AABW.

1. Introduction

23 The Southern Ocean plays a pivotal role in the global ocean circulation. The absence
24 of continental barriers in the latitude band of Drake Passage permits the existence of the
25 eastward-flowing Antarctic Circumpolar Current (ACC), which is supported geostrophically
26 by sloping isopycnals and serves as a conduit for oceanic exchanges between the three
27 major ocean basins [*Rintoul and Naveira Garabato, 2013*]. Coupled to this intense zonal
28 flow, a meridional circulation exists in which Circumpolar Deep Water (CDW) upwells
29 along the southward-shoaling isopycnals of the ACC [*Speer et al., 2000*]. Whereas the
30 lighter classes of CDW reach the upper-ocean mixed layer within the ACC and are re-
31 turned northward near the surface, the denser classes of CDW are transported southward
32 and enter the system of cyclonic gyres and westward-flowing slope frontal jets encircling
33 Antarctica. There, CDW replenishes and mixes with Antarctic surface waters and water
34 masses found over the Antarctic continental shelves, ultimately resulting in the formation
35 of Antarctic Bottom Water (AABW). The production and northward export of AABW is
36 an integral component of the southern closure of the global overturning circulation (GOC,
37 *Talley [2013]*), gives rise to its lower cell [*Lumpkin and Speer, 2007*], and is an important
38 driver of deep global ocean ventilation [*Orsi et al., 2002*] and marine biogeochemical cy-
39 cling [*Marinov et al., 2006*].

40 Traditionally, the Weddell Gyre (Figure 1) has been regarded as by far the primary
41 region of AABW formation, accounting for upwards of 60 - 70% of all AABW produc-
42 tion [*Orsi et al., 1999, 2002*]. Through several decades of oceanographic measurements,
43 a picture of the gyre has been built in which CDW enters the gyre's southern limb near

44 30°E [*Orsi and Whitworth, 1993; Gouretski and Danilov, 1993; Park et al., 2001*] and
45 is gradually cooled and freshened by mixing with ambient waters as it flows westward
46 near Antarctica. Further downstream, CDW interacts with dense, relatively saline wa-
47 ters cascading off the broad continental shelves of the southwestern and western Weddell
48 Sea, resulting in the production of AABW [*Gill, 1973; Foster and Carmack, 1976*]. The
49 regional variety of AABW is made up of two water masses: Weddell Sea Bottom Wa-
50 ter (WSBW), produced primarily near the Filchner-Ronne ice shelves, is the coldest and
51 densest AABW in the Weddell Gyre ($\theta < -0.7^\circ\text{C}$, $\gamma^n > 28.40 \text{ kg m}^{-3}$, see *Orsi et al.*
52 [1999]). The warmer and lighter Weddell Sea Deep Water (WSDW; $0 > \theta > -0.7^\circ\text{C}$,
53 $28.27 < \gamma^n < 28.40 \text{ kg m}^{-3}$) may be formed directly by mixing between shelf waters
54 and CDW, or indirectly by entrainment of CDW into WSBW as the shelf water plume
55 cascades down the continental slope. A distinct variety of WSDW is formed near the
56 Larsen ice shelves (LIS) in the western Weddell Sea that is lighter and fresher than deep
57 water formed further south [*Fahrbach et al., 1995; Gordon et al., 2001; Huhn et al., 2008;*
58 *Gordon et al., 2010*]. The reader may refer to *Nicholls et al. [2009]* for a detailed review
59 of AABW in the Weddell Sea.

60 The newly formed AABW is conveyed northeastward by the Weddell Gyre and exported
61 to the mid-latitude Southern Ocean and beyond through openings in the topographic
62 barriers bounding the gyre to the north, most conspicuously along the South Sandwich
63 Trench near 25°W [*Orsi et al., 1999*]. In spite of the presumed high-ranking status of the
64 Weddell Gyre in AABW formation, present estimates of AABW production in the gyre
65 are unsatisfactorily wide-ranging (Table 1). These differences represent a combination of
66 inconsistencies between different estimation techniques, AABW definitions or regional flow

67 regimes; and temporal variability [*Naveira Garabato et al.*, 2002a]. This large uncertainty
68 in the quantification of water mass transformation and ventilation in the Weddell Gyre
69 has historically posed a significant obstacle to determining its standing in the closure of
70 the GOC.

71 There are now several pieces of evidence that challenge this traditional view of the Wed-
72 dell Gyre. Most fundamentally, the long-held notion of the gyre as a largely hermetic bowl
73 with a few, well defined inflow and outflow pathways is inconsistent with observations.
74 *Klatt et al.* [2005] point out the existence of a substantial inflow of CDW into the gyre
75 along its northern rim, while *Gordon et al.* [2001] and *Naveira Garabato et al.* [2002a]
76 suggest that AABW may be exported from the gyre across a wider zonal swath than
77 previously thought, including the major topographic barrier of the South Scotia Ridge.
78 A most unexpected finding in this context relates to the observation of a prominent flow
79 of AABW from the Indian Ocean sector entering the southern Weddell Gyre across its
80 eastern rim [*Meredith et al.*, 2000; *Hoppema et al.*, 2001; *Couldrey et al.*, 2013], which has
81 led to the (as yet untested) proposition that the role of the gyre in AABW formation has
82 been historically overstated [*Jacobs*, 2004].

83 Here, we seek to characterise the contribution of the Weddell Gyre to the closure of
84 the lower limb of the GOC by diagnosing the gyre’s three-dimensional circulation and
85 water mass transformations with a box inverse model. The model is articulated around
86 four hydrographic transects (Figure 1) spanning the gyre’s inner reaches and outer rim,
87 conducted over a 5-year period centered on the 2007-2008 International Polar Year (Table
88 2). The data sources and model design are described in sections 2 and 3, respectively.
89 Results are presented in sections 4 and 5, where the former addresses the gyre’s lateral

90 circulation and thermodynamical budgets, and the latter describes the vertical circulation.

91 Section 6 discusses the implications of our results for the present paradigm of the Weddell

92 Gyre circulation. Our main findings are synthesized in section 7.

2. Data

2.1. Hydrographic data

93 Four hydrographic transects spanning 5 years (2005 - 2010) were analysed in this study

94 (Table 2). The configuration of the inverse model box, which incorporates two complete

95 coast-to-coast sections, allows us to differentiate between the water mass transformations

96 and overturning circulation occurring in association with shelf-slope processes in the vicin-

97 ity of the continental shelves and ice shelves of the southwestern Weddell Sea, and the con-

98 tributions to transformations and overturning by gyre interior processes. CTD profiles of

99 temperature and salinity were measured during the cruises, as well as velocity with vessel-

100 mounted and lowered acoustic Doppler current profilers. All four hydrographic cruise data

101 sets were subjected to secondary quality control testing by performing crossover analyses

102 with CARINA [Key *et al.*, 2010] and GLODAP [Key *et al.*, 2004] regional data products

103 (following [Hoppema *et al.*, 2009]) to analyse for systematic biases inherent in individual

104 cruise measurements. In this work, crossover analyses were performed for salinity only;

105 as occurred during GLODAP, CARINA and PACIFICA [Key *et al.*, 2004, 2010; Tanhua

106 *et al.*, 2010] temperature was not analysed as it is considered by far the most accurately

107 measured parameter and it is assumed that its random and systematic errors are negligi-

108 ble. All four salinity data sets used in the Weddell region inversion were found to be of

109 high quality, with derived data offsets being below the adjustment threshold of 0.005.

110 **The I6S section**, a quasi-meridional line along 30°E between South Africa and Antarc-
111 tica, was occupied under the auspices of CLIVAR in February - March 2008 by the RV
112 Roger Revelle (cruise 33RR20080204). 106 CTD stations with a characteristic spacing
113 of 30 km were collected during the cruise [*Speer and Dittmar, 2008*], and 54 of them are
114 used in this study.

115 **The ANDREX section**, extending quasi-zonally from the tip of the Antarctic Penin-
116 sula to 30°E, 55°S (station 90 on Figure 1), was originally scheduled to be occupied in
117 one single cruise in January 2009 (Table 2). However, after 27 stations (corresponding
118 to station 73 on Figure 1 near 19°W, 61°S), the JC30 cruise [*Bacon and Jullion, 2009*]
119 was aborted due to a medical evacuation. A second cruise, JR239 [*Meredith, 2010*], was
120 conducted approximately one year later (March - April 2010) to complete the section. 68
121 stations were occupied during this cruise, including a repeat of the ALBATROSS transect
122 (Mar-Apr 1999) over the South Scotia Ridge [*Naveira Garabato et al., 2002b*]. West of
123 the South Orkney Islands, heavy sea ice conditions precluded an exact repeat of the AL-
124 BATROSS line, and stations were placed on a more northerly sector of the South Scotia
125 Ridge. The JC30, JR239 and I6S transects were merged into one section extending from
126 the tip of the Antarctic Peninsula to the Antarctic coast at 30°E. We refer to this merged
127 section as ANDREX / I6S.

128 **The SR4 section**, between Kapp Norvegia and Joinville Island (Figure 1), was due to
129 be occupied in full in January-February 2008 by cruise ANTXXIV of the PFS Polarstern.
130 However, the slope current near Kapp Norvegia could not be sampled during this transect
131 due to heavy sea ice conditions and a tragic medical evacuation. We therefore chose to

132 use the previous occupation of the section (cruise ANTXXII in January - February 2005)
133 in our analysis [*Fahrbach, 2005*].

2.2. Sea Ice

134 Daily means of sea ice concentration were derived from the Special Sensor Microwave /
135 Imager (SSM/I) Passive Microwave sensor using the NASA Team algorithm for the period
136 2005-2010 [*Cavalieri et al., 1996*]. The daily ice motion data were derived from the same
137 sensor and period using the Fowler algorithm. These data were provided as a personal
138 communication by Chuck Fowler and Mark Tschudi [*Fowler, 2003*].

139 Sea ice thickness data are extremely scarce, due to the difficulty in accessing ice-covered
140 areas, particularly during winter. We estimated a climatological sea ice thickness from the
141 ASPeCt data set (<http://aspect.antarctica.gov.au/>), which archives data from 83 voyages
142 and 2 helicopter flights for the period 1980 - 2005 [*Worby et al., 2008*]. To calculate sea ice
143 volume fluxes, the 6-year mean of the daily products of sea ice concentration and velocity
144 across each section are multiplied by the climatological sea ice thickness distribution and
145 the array of distances between data points.

2.3. Southern Ocean State Estimate (SOSE)

146 SOSE is a high-resolution ($1/6^\circ$ grid) numerical model of the Southern Ocean with data
147 assimilation covering the 2005-2010 period [*Mazloff et al., 2010*]. Comparison with our
148 observations showed the model to suffer from a cold ($0.01 - 0.02^\circ\text{C}$) and fresh (0.01-0.02)
149 bias, resulting in an abyssal stratification that is stronger than observed in the center
150 of the gyre across the SR4 section. Further north, the performance of SOSE improves,
151 likely as a result of an increase in the abundance of observations used in constraining

152 the model. Despite these discrepancies, the temporal variability of the modelled flow
153 reflects our understanding of the regional circulation, with elevated variability over the
154 continental slopes around the Antarctic Slope Front (ASF), within the ACC and over the
155 South Scotia Ridge, and reduced variability in the interior of the Weddell Gyre. We use
156 SOSE to assess the uncertainties in the reference velocities across the rim of the model
157 box, and to estimate the contribution of the time-varying (eddy) circulation to the volume,
158 potential temperature and salinity budgets of the model domain.

3. A box inverse model of the Weddell Gyre

159 We combine the four transects described in the preceding section in a box inverse model
160 of the Weddell Gyre (Figure 1). The box is constructed as follows, from the Antarctic
161 Peninsula going clockwise: stations 1 to 66 correspond to the JR239 cruise, stations 67 to
162 90 to the JC30 cruise, stations 91 to 125 to the I6S cruise, and stations 126 to 178 to the
163 SR4 cruise (Table 2). In the following, we will refer to the region encompassed by the outer
164 sections as simply the main box, and the smaller region enclosed by SR4 and the continent
165 as the Southwest (SW) box. Box inverse modelling [*Wunsch, 1996*] provides an effective
166 technique to estimate the large-scale ocean circulation by combining observations in a
167 theoretical framework in which conservation of mass, heat, salt (or, equivalently, volume,
168 potential temperature and salinity) and other tracers may be enforced.

3.1. Hydrographic setting

169 Figure 2 shows the vertical distribution of potential temperature and salinity along
170 the rim of the main box. In the northeastern corner, the ACC is visible in potential
171 temperature and salinity maxima near stations 85 - 97 and extends nearly all the way to

172 the continental slope, as evidenced by the southward-shoaling isopycnals along the I6S
173 section. Near the continental slope, the ASF (stations 111-125) is marked by a southward
174 deepening of isopycnals and a thick layer of cold and fresh WW.

175 Along the SR4 transect, a section-wide doming of isopycnals denotes the cyclonic Wed-
176 dell Gyre. Near Kapp Norvegia, the ASF (stations 128 - 132) conveys relatively warm
177 and saline CDW and a thick layer of WW toward the Filchner-Ronne ice shelves (Figure
178 2). Near Joinville Island (near station 172), the presence of newly formed, dense WSBW
179 against the continental slope leads to the characteristic “V” shape of the ASF in that
180 sector. The thick layer of cold WW observed near Kapp Norvegia is eroded in the SW
181 main box and flows back into the box considerably thinner near Joinville Island. *Thomp-*
182 *son and Heywood* [2008] provide a more detailed description of the frontal structure of
183 the SR4 section near Joinville Island, identifying several frontal jets which, for the sake
184 of simplicity, we collectively refer to as the ASF in this study.

185 Over the South Scotia Ridge, several deep passages provide a direct route for deep
186 waters of Weddell Sea origin to enter the Scotia Sea (see *Naveira Garabato et al.* [2002b]
187 for a detailed description of the water masses and their pathways over the ridge). East of
188 the ridge, the Weddell Front (between stations 60 and 61) separates relatively warm and
189 saline CDW to the north from colder and fresher CDW in the inner Weddell Gyre, and
190 is associated with a pronounced northward flow.

3.2. Model set up

The ANDREX - I6S and SR4 sections are divided vertically into 10 layers separated by neutral density interfaces [*Jackett and McDougall*, 1997], as indicated in Table 3. The interfaces are selected to correspond with the boundaries of the major water masses in the

region. Within the main box bounded by the sections, we enforce conservation of mass, heat and salt, represented in the model as volume, potential temperature anomaly and salinity anomaly, in each layer and full depth. Full details of the model implementation (including initialization, solution procedure, choice of weights, and calculation of posterior uncertainties) are given in the Auxiliary Material and are summarized here. We write the full-depth conservation statement for any given tracer as

$$\sum_{j=1}^m \left[\sum_{i=1}^n [\delta_i L_i D_{ij} (V_{ij} + b_i) \rho_{ij} C_{ij}] + \nu_j(C) - [A \overline{\rho C \omega_c^*}]_{\gamma_j}^{\gamma_{j+1}} + F_j^{A-S}(C) + F_j^{SI}(C) \right] = 0, \quad (1)$$

191 where n is the number of station pairs; m is the number of layers; δ_i adopts the value +1 or
 192 -1 depending on whether flow is directed into or out of the box; L_i and D_{ij} are the distance
 193 between successive stations and the layer thickness at each station pair, respectively; V_{ij}
 194 is the baroclinic velocity at the station pair i and layer j ; b_i is the barotropic velocity
 195 at station pair i ; ρ_{ij} is *in situ* density; A is the area of the layer interface within the
 196 box; ω_c^* is the diapycnal velocity for tracer C [McIntosh and Rintoul, 1997; Sloyan and
 197 Rintoul, 2000]; $F_j^{A-S}(C)$ and $F_j^{SI}(C)$ are the fluxes of tracer C associated with air-sea
 198 interactions and sea ice, respectively; $\nu_j(C) = \rho_j [\overline{v' C' h^t} + \overline{v' h^t C^t}]_j$ is the eddy-induced
 199 flux of tracer C for the layer j , which consists of advective (the first) and diffusive (the
 200 second) components; v' and h' are the deviation from the time-averaged mean velocity
 201 and isopycnal layer thickness calculated from SOSE (see below); $\overline{(\cdot)}^\gamma$ and $\overline{(\cdot)}^t$ denote the
 202 area-mean operator over a layer interface and the time-mean operator, respectively (see
 203 Auxilliary Material section 2a). We note that the model incorporates two sets of terms
 204 (sea ice-mediated and eddy-induced transports) that are not normally represented in box
 205 inverse models, but that are important in the context of the Weddell gyre (see Auxiliary
 206 Material section 2a). The model is underdetermined, having a total of 238 unknowns (175

207 barotropic velocities; 27 diapycnal velocities; 30 eddy flux terms; 2 sea ice transport terms,
 208 across ANDREX/I6S and SR4; 2 air-sea heat flux terms, one in the box and one south
 209 of SR4; and 2 air-sea freshwater terms, one in the box and one south of SR4) and only
 210 40 equations (conservation of volume, potential temperature and salinity in 10 isopycnal
 211 layers and full depth). Further to conservation within the main box, we include additional
 212 constraints on the volume and salinity anomaly transports across the two coast-to-coast
 213 sections (Figure 1) and within the ACC (Table 4).

214 As the underdetermined nature of the system allows an infinite number of solutions,
 215 we specify an a priori solution based on observations in order to guide the model. The
 216 initial geostrophic transport is calculated by fitting the geostrophic shear to lowered-
 217 ADCP (when available) or shipboard-ADCP data (see Auxiliary Material, section 2b, for
 218 the initialization of the other variables). The set of equations (1) may be reduced to

$$E\mathbf{x} + \mathbf{n} = \mathbf{y}, \quad (2)$$

219 where E is the matrix of conservation statements, $\mathbf{x} = [b_i, \omega_C^*, F_j^{A-S}(C), F_j^{SI}(C), \nu_j(C)]$
 220 groups the unknowns, \mathbf{y} contains the observation-based prior imbalances in the conser-
 221 vation equations, and \mathbf{n} is the noise term, which amalgamates the prior uncertainties in
 222 each of the unknowns and conservation statements. Row and column weighting are ap-
 223 plied to the model (Eqn. 2) in order to weight constraints and unknowns, respectively.
 224 The weighted system (2) is solved using singular value decomposition [*Wunsch, 1996*].

3.3. The standard solution

225 In solving (2), a solution rank of 28 (out of 40 model equations) is selected. This choice
226 corresponds to the lowest rank that provides a dynamically acceptable solution, for which
227 posterior equation residuals are indistinguishable from zero within one posterior standard
228 deviation (Figure 3) and perturbations to the initial estimates of the unknowns are within
229 one a priori standard deviation (Figure 4a). Flux (heat and freshwater) calculations re-
230 quire a closed mass budget, so (small) residuals to the standard solution are eliminated by
231 a second model run with solely two constraints: full-depth volume and salinity conserva-
232 tion applied to horizontal reference velocities only (Layer 11 in Figure 3). The root mean
233 square adjustment to the initial barotropic velocities is 0.045 m s^{-1} (Figure 4b), with the
234 largest perturbations being produced on the Antarctic continental shelf at the I6S section
235 (0.34 m s^{-1}). In contrast, barotropic velocity corrections in the Weddell - Enderby basin
236 (station pairs 65-80) are small ($< 0.01 \text{ cm s}^{-1}$).

237 Adjustments to other variables are generally modest. Thus, the diapycnal velocities in
238 the standard solution have a rms value $4.9 \times 10^{-7} \text{ m s}^{-1}$, a magnitude characteristic of
239 open ocean environments away from boundaries. The initial sea ice volume transports
240 across the SR4 and ANDREX / I6S sections are reduced by 41% and 7%, respectively
241 (Table 5). The net addition of volume due to precipitation and glacial runoff is increased
242 by 4% south of SR4 and decreased by 42% within the main box, respectively (Table 5).
243 Finally, the root-mean-square (rms) corrections applied to the eddy fluxes of volume,
244 potential temperature and salinity are 20% 50 % and 10%, respectively.

4. Horizontal circulation, heat and freshwater budgets of the Weddell Gyre

4.1. Horizontal circulation

245 The circulation of the southwestern Weddell Sea is associated with northward volume
246 exports of 12 ± 3 mSv of liquid water and of 10 ± 1 mSv (315 ± 32 km³ yr⁻¹) of sea ice
247 across the SR4 section, balanced by a net meteoric (precipitation plus glacial runoff minus
248 evaporation) freshwater input to the ocean in the SW box of 22 ± 3 mSv, equivalent to a
249 mean net precipitation rate of 389 ± 53 mm yr⁻¹ over the ocean (Table 5). This volume
250 transport is enhanced by a further meteoric input of 28 ± 4 mSv (equivalent to a mean
251 net precipitation rate of 230 ± 25 mm yr⁻¹) within the main box, and 4 ± 1 mSv (126 ± 32
252 km³ yr⁻¹) of sea ice are produced in that region. This leads to a net northward volume
253 export out of the Weddell Gyre of 51 ± 190 mSv, of which 36 ± 190 mSv occur in liquid
254 form and 15 ± 2 mSv (473 ± 63 km³ yr⁻¹) as sea ice.

255 The geostrophic velocity field and barotropic velocities (Figure 4b,c) reproduce the main
256 known features of the large-scale circulation of the Weddell Gyre. An inner gyre transport
257 of 42 ± 8 Sv ($1 \text{ Sv} = 10^6 \text{ m}^3 \text{ s}^{-1}$) is diagnosed across the SR4 section, and an outer gyre
258 transport of 54 ± 15 Sv is found across the ANDREX / I6S section (station pairs 1-72,
259 Figure 4d). In this section (stations 82 - 111), the SACCF and Southern Boundary of
260 the ACC convey 68 ± 18 Sv into and out of the northeastern corner of the model domain.
261 While this is a large transport, comparable to that of the Weddell Gyre, it leads to a small
262 net transport (2 ± 5 Sv) into the main box, as dictated by the additional ACC transport
263 constraint (Table 4).

264 A substantial fraction (85%) of the Weddell Gyre transport is focussed around the ASF,
265 and in the area where the ASF disintegrates over the South Scotia Ridge. At the gyre's

266 eastern edge, in the I6S section, the ASF transports 24 ± 4 Sv westward into the gyre,
267 primarily in the most voluminous water masses (CDW and WSDW, see Figure 4e; see
268 also Table 6). Further downstream, the ASF transport entering the SW box has increased
269 to 38 ± 8 Sv, as a result of recirculation in the gyre. A similar ASF transport (37 ± 9
270 Sv) is found at the northern end of the SR4 transect, off Joinville Island. The breakdown
271 of the ASF over the South Scotia Ridge is evident in the ANDREX section, where the
272 frontal signature is associated with a weak transport of 8 ± 2 Sv at station pair 5, just
273 east of Elephant Island (Figure 4d). This is in line with previous findings by *Heywood*
274 *et al.* [2004] and *Thompson et al.* [2009] on the basis of hydrographic and surface drifter
275 measurements.

276 The remainder of the flow associated with the ASF entering the northwestern Weddell
277 Sea contributes both to net northward transports of 15 ± 7 Sv over the South Scotia Ridge
278 (on the western flanks of the Hesperides, Orkney, Bruce and Discovery passages) and of
279 25 ± 6 Sv further east in association with the Weddell Front (Figure 4c, Table 7). The
280 presence of an interior recirculation of some 20 Sv in the centre of the Weddell - Enderby
281 Basin (between 10°W and 20°E) is indicated by the reversal of the transport between
282 station pairs 75 and 82. The existence of a recirculation cell north of Maud Rise had been
283 suggested by *Beckmann et al.* [1999] and *Fahrbach et al.* [2011], and explains the increase
284 in the ASF transport between the I6S and SR4 sections. The eddy contribution to the
285 volume budget is small (-0.4 ± 0.2 Sv) compared with the mean transport suggesting a
286 relatively modest eddy advection (Figure. 5a).

287 Due to the largely equivalent barotropic nature of the flow, the circulation of deep and
288 bottom waters in the Weddell Gyre reflects strongly the full-depth transport. CDW and

289 WSDW circulate cyclonically around the gyre. A total of 14 ± 2 Sv of CDW and 9 ± 2 Sv
290 of WSDW flow westward into the gyre across the I6S section, with 19 ± 4 Sv and 14 ± 3
291 Sv respectively entering the SW box across the southern end of the SR4 transect (Table
292 6). As the gyre circulates back across the northern edge of that section, the transport
293 of WSBW has increased from 0 to 4 ± 2 Sv, with little modification in the transport of
294 CDW and WSDW. Approximately 75% (3 ± 1 Sv) of the WSBW outflow from the SW
295 box occurs in a thin bottom layer over the continental slope of the northern Antarctic
296 Peninsula (Figure 2, Table 6) and the remaining 25% in the abyssal Weddell Sea. The
297 bulk of the WSDW export from the gyre toward the mid-latitude Southern Ocean (a total
298 of 17 ± 4 Sv) occurs between station pairs 1 and 69, with 6 ± 2 Sv of newly ventilated
299 WSDW flowing over the South Scotia Ridge and 11 ± 4 Sv being exported to the east of
300 the Scotia Sea. The WSBW is generally too dense to overflow the ridge system bounding
301 the Weddell Gyre to the north, and largely recirculates cyclonically between station pairs
302 63 and 82. Only 2 ± 1 Sv of WSBW are found to flow northward out of the model domain,
303 in station pairs 92 - 93, toward the Indian Ocean mid latitudes.

4.2. Heat budget

304 The net flux of heat entering the Weddell Gyre across the ANDREX / I6S section is
305 36 ± 13 TW (Figure 6). The bulk of this value is contributed by the ocean circulation,
306 which accounts for 31 ± 13 TW. Of this, 5 ± 1 TW is by eddy-induced transports (Figure
307 5b), indicating that transient eddies play a significant role in the heat budget of the gyre.
308 The majority of the heat entering the gyre does so in association with the mean and
309 eddy-induced southward (northward) transport of relatively warm (cold) CDW (WSDW
310 and WSBW), with surface waters contributing a modest northward heat flow. A further

311 notable factor in the heat budget of the gyre is the export of sea ice out of the Weddell
312 Sea, which contributes 5 ± 1 TW (southward).

313 The southward transport of heat is diminished by the loss of 10 ± 1 TW of oceanic heat
314 (equivalent to 2 ± 0 W m⁻²) within the main box, consistent with the aforementioned net
315 sea ice production in that area. However, the bulk of the heat entering the gyre across the
316 ANDREX / I6S section (specifically, 26 ± 13 TW) penetrates into the gyre's southwestern
317 corner across the SR4 section, with contributions of 23 ± 13 TW and 3 ± 1 TW from
318 the ocean circulation and sea ice, respectively. This implies that a considerably more
319 intense rate of heat loss (14 ± 6 W m⁻²) occurs south of the SR4 transect than in the gyre
320 interior. Unlike in the ANDREX / I6S section, the bulk of the heat transport across the
321 SR4 transect is effected by the ASF along the continental slope, suggesting that relatively
322 warm CDW is entrained into the ASF via the recirculation in the central Weddell Sea.

4.3. Freshwater budget

323 The freshwater budget of the Weddell Gyre is assessed by calculating freshwater trans-
324 ports across the boundaries of the model domain as in *Tsubouchi et al.* [2012]. The gyre
325 is found to export 51 ± 23 mSv of freshwater to the mid-latitude Southern Ocean across
326 the ANDREX / I6S section, of which 38 ± 23 mSv are exported in liquid form (34 ± 4 mSv
327 by the mean circulation and 4 ± 1 mSv by eddy-induced fluxes) and 13 ± 1 mSv in sea
328 ice (note that the sea ice-mediated freshwater transport is not equal to the sea ice volume
329 transport due to the presence of salt in sea ice). This net freshwater export is supplied
330 by a matching meteoric input to the ocean within the gyre. In the SW box, 22 ± 3 mSv
331 of meteoric water is added and exported northward across SR4 (13 ± 13 mSv and 9 ± 3

332 mSv in liquid and sea ice forms, respectively). An additional 28 ± 4 mSv is supplied by
333 addition of meteoric water within the main box.

334 A general feature of the freshwater budget of the Weddell Gyre is that freshwater
335 transports are dominated by the circulation of the surface layers (SW and WW), where
336 most of the sea ice production and melt and meteoric inputs of precipitation and glacial
337 freshwater take place (Figure 7). A prevalence of precipitation over glacial sources in
338 determining the meteoric freshwater input is suggested by a comparison of state-of-the-
339 art estimates of precipitation and ice mass loss in the Weddell Sea, which indicate values
340 on the order of 50 mSv [*Lenaerts and van den Broeke, 2012*] and 10 mSv [*Rignot et al.,*
341 2008], respectively. The inversion reduces the volume of precipitation within the model
342 domain to 28 ± 4 mSv (cf. 49 ± 25 mSv a priori, Table 5). While the posterior meteoric
343 input in the box is within prior uncertainties, the model suggests lower precipitation than
344 that found in atmospheric reanalyses. Note, however, that the extent to which icebergs
345 or precipitation falling on sea ice may be exported from the gyre before melting is not
346 considered here. A final point of note is that the eddy-induced transport of freshwater
347 across the gyre boundary is modest in comparison with the eddy heat flux (Figure 5c),
348 most likely because eddy exchanges occur primarily at the gyre's northeastern edge, away
349 from the main areas of sea ice production, precipitation and glacial runoff.

5. The vertical circulation of the Weddell Gyre

5.1. Overturning circulation

350 The diapycnal overturning circulation of the Weddell Gyre is found to consist of a double
351 cell, the upper and lower branches of which are localised in distinct regions (Figure 8).
352 A total of 13 ± 4 Sv of CDW and the classes of WSDW lighter than $\gamma^n = 28.35 \text{ kg m}^{-3}$

353 flow into the gyre across the ANDREX / I6S section, and are returned equatorward as
354 denser WSDW and WSBW (8 ± 2 Sv) and as upper-ocean waters lighter than $\gamma^n = 28.00$
355 kg m^{-3} (5 ± 2 Sv).

356 The upper limb, the upwelling of CDW into the WW layer (2 ± 2 Sv, equivalent to an
357 upwelling rate of $6.3 \pm 4.5 \times 10^{-7} \text{ m s}^{-1}$) occurs in the gyre interior (Figure 9), whereas
358 the bulk of the downwelling leading to AABW formation (6 ± 2 Sv) takes place near the
359 gyre's southwestern edge, south of the SR4 section (Figure 8, left panel). Within the
360 gyre interior, upwelling is accompanied by a transformation of CDW into the lightest
361 WSDW class (2 ± 1 Sv, equivalent to a downwelling rate of $6.5 \pm 4.5 \times 10^{-7} \text{ m s}^{-1}$). As
362 a consequence, the CDW and light WSDW inflow to the gyre is diminished to 6 ± 2 Sv
363 across the SR4 transect, although this is partially compensated by the reversal of the
364 near-surface flow in the SW box underpinning a poleward transport of 2 ± 1 Sv of those
365 waters across that section. This results in a single-celled overturning circulation of 8 ± 2
366 Sv across the SR4 transect.

367 Note that half of the 4 ± 1 Sv of WSBW entering the model domain across the SR4
368 section (2 ± 1 Sv) upwells diapycnally into WSDW at a rate of $7.3 \pm 6.6 \times 10^{-7} \text{ m s}^{-1}$ before
369 leaving the Weddell Gyre (Figure 9), likely because of entrainment as WSBW cascades
370 down the continental slope of the Antarctic Peninsula. In contrast, the lighter classes of
371 WSDW experience diapycnal downwelling at a rate of $5.6 \pm 4.8 \times 10^{-7} \text{ m s}^{-1}$ within the
372 gyre interior (Figure 9), consistent with densification of WSDW by diapycnal mixing with
373 WSBW.

5.2. Water mass transformation

374 A more complete perspective of the water mass transformations implicit in the overturn-
 375 ing circulation of the Weddell Gyre may be obtained by examining the θ - S volumetric
 376 transport diagrams in Figure 10. The volume transports across the model boundaries (i.e.
 377 the ANDREX / I6S and SR4 transects, which bound the gyre interior) and across the
 378 inner gyre boundary of the model domain (i.e. the SR4 section, which bounds the SW
 379 box) are mapped to θ - S space, using bins of $\delta\theta = 0.02$ and $\delta S = 0.01$. For each θ - S
 380 bin, the volume transport that occurs within that thermohaline class across the pertinent
 381 section(s) is integrated. Thus, positive (negative) values in the diagrams indicate that
 382 there is an excess of water with those thermohaline properties flowing out of (into) the
 383 control volume in each diagram. The choice of control volumes allows us to distinguish
 384 between the water mass transformations occurring in the gyre interior and those near the
 385 gyre's southwestern boundary.

386 The left panel in Figure 10 reveals that a consumption of the warmest and saltiest
 387 CDW and the WSDW warmer than approximately -0.5°C takes place in the SW box.
 388 This is balanced primarily by a production of colder WSDW and WSBW, associated with
 389 the diapycnal downwelling characterised above, and of a relatively cool and fresh variety
 390 of CDW, which is likely a result of the ventilation of CDW by shelf waters cascading
 391 down the continental slope of the southwestern and western Weddell Sea. Following these
 392 thermohaline changes, a net densification (by 0.028 kg m^{-3}) of the waters circulating
 393 around the SW box occurs, visible in the translation to higher density of the transport-
 394 weighted mean θ - S of the flow (inflow: $\theta = -0.222^\circ\text{C}$, $S = 34.543$, $\gamma^n = 27.942 \text{ kg m}^{-3}$;
 395 outflow: $\theta = -0.489^\circ\text{C}$, $S = 34.553$, $\gamma^n = 27.970 \text{ kg m}^{-3}$). This densification is equivalent

396 to a rate of oceanic buoyancy loss of $1.6 \times 10^{-9} \text{ m}^2 \text{ s}^{-3}$, which is supplied by oceanic heat
 397 loss ($1.3 \times 10^{-9} \text{ m}^2 \text{ s}^{-3}$), with the salinity increase due to sea ice production playing a
 398 secondary role ($0.3 \times 10^{-9} \text{ m}^2 \text{ s}^{-3}$).

399 A very different set of water mass transformations take place in the gyre interior (Figure
 400 10, right panel). There is a net consumption of WSBW, indicative of diapycnal upwelling,
 401 and of several classes of CDW (most clearly, those in the range $0.1 < \theta < 0.7^\circ\text{C}$). This
 402 is balanced by a production of the denser classes of WSDW (linked to the upwelling of
 403 WSBW and downwelling of dense CDW into WSDW), a cool and fresh variety of CDW
 404 with potential temperature near 0°C , and several types of pycnocline and surface waters
 405 lighter than $\gamma^n = 28.0 \text{ kg m}^3$. The cool and fresh variety of CDW appears primarily in the
 406 vicinity of the ASF over the South Scotia Ridge (Figure 2), suggesting that it is formed
 407 through ventilation of CDW by relatively light shelf waters in the northern Antarctic
 408 Peninsula [Whitworth *et al.*, 1994]. While it is not possible to ascertain the processes
 409 which underpin the production of pycnocline and surface waters, diapycnal upwelling
 410 across the base of the winter mixed layer in the gyre interior (see section 5a) is likely to
 411 play a major role. Overall, the oceanic buoyancy loss in the region is modest (3.5×10^{-10}
 412 $\text{m}^2 \text{ s}^{-3}$), as oceanic cooling and sea ice production are counteracted by a net meteoric
 413 input. The waters circulating around the gyre interior experience a cooling of 0.01°C and
 414 a freshening of 0.018, leading to a small densification of 0.007 kg m^{-3} (inflow: $\theta = 0.192^\circ\text{C}$,
 415 $S = 34.545$, $\gamma^n = 27.860 \text{ kg m}^{-3}$; outflow: $\theta = 0.182^\circ\text{C}$, $S = 34.527$, $\gamma^n = 27.867 \text{ kg m}^{-3}$).

6. Discussion

416 The diagnosed circulation of the Weddell Gyre reproduces well-known qualitative fea-
 417 tures of the regional flow, and adds significant new quantitative information. The gyre is

418 estimated to transport *ca.* 40 - 50 Sv cyclonically around the Weddell - Enderby Basin
419 and to exhibit modest recirculation near the Prime Meridian, in line with the findings of
420 studies based on direct velocity measurements and general circulation models [*Fahrbach*
421 *et al.*, 1994; *Beckmann et al.*, 1999; *Klatt et al.*, 2005; *Schröder and Fahrbach*, 1999].
422 Along the gyre's southern and western flanks, more than 80% of the gyre transport is
423 concentrated near the continental boundary, at the ASF, as previously noted by *Klatt*
424 *et al.* [2005]. This frontal jet disintegrates as the gyre flows over the complex topography
425 around the northern tip of the Antarctic Peninsula and the South Scotia Ridge, resulting
426 in a broadening of the gyre's northern limb over an extensive region spanning the ridge
427 and the northern edge of the Weddell - Enderby Basin [*Heywood et al.*, 2004]. An im-
428 portant, little appreciated feature of the Weddell Gyre evident in our diagnostics is that
429 it hosts a substantial throughflow component. This entails a net import of 13 ± 4 Sv
430 across the gyre's eastern edge from the Indian sector of the subpolar Southern Ocean, in
431 association with the ASF, and a net export of the same value across the gyre's northern
432 edge, following the ASF's disintegration.

433 The heat budget of the Weddell Gyre qualitatively agrees with previous estimates based
434 on different methods and data sets [*Fahrbach et al.*, 1994; *Klatt et al.*, 2005]. The ACC is
435 found to inject heat to the gyre at a rate of 36 ± 13 TW, primarily along the gyre's northern
436 and eastern edges and in part via eddy exchanges (14%, cf. *Schröder and Fahrbach* [1999])
437 and mobile sea ice export (14%). The heat transport across the eastern rim of the gyre
438 (9 ± 13 TW) is weaker than the net southward heat flux across the SR4 section (26 ± 3
439 TW), because most of the heat enters the gyre through its northern rim (cf. *Klatt et al.*
440 [2005]). Our diagnosed heat flux across the SR4 transect is significantly lower than that

441 of *Fahrbach et al.* [1994], who estimated it as 35 TW from CTD and current meter data
442 but agrees well with *Yaremchuk et al.* [1998] who found 28 PW based on an inverse model
443 of an earlier occupation of the SR4 section.

444 The gyre exports 51 ± 23 mSv of freshwater toward the mid-latitude Southern Ocean,
445 mainly across the South Scotia Ridge (Figure 7). The 22 ± 13 mSv supplied by the inner
446 gyre across the SR4 section is supplemented by 27 ± 4 mSv of meteoric water input to the
447 main box. Our diagnosed sea ice-mediated freshwater export from the inner gyre (315 ± 32
448 $\text{km}^3 \text{ yr}^{-1}$) is lower than the prior estimate based on the literature, but not significantly
449 so within uncertainties. For example, the modelling studies of *Petty et al.* [2013] and
450 *Haid and Timmermann* [2013] find respective freshwater exports in sea ice form from the
451 southwestern Weddell Sea of $690 \pm 243 \text{ km}^3 \text{ yr}^{-1}$ and $993 \text{ km}^3 \text{ yr}^{-1}$, and *Drucker et al.*
452 [2011] estimate $390 \pm 130 \text{ km}^3 \text{ yr}^{-1}$ from satellite images. One possible explanation for our
453 comparatively weak sea ice export is that, as our sections are summer-biased, the ocean
454 contains more meltwater than at other times of year, and therefore requires a relatively
455 low flow of sea ice to balance the addition of meteoric water south of the SR4 transect. A
456 second plausible explanation relates to the lack of winter sea ice thickness measurements
457 in the ASPeCt data base, which may lead to an underestimation of the annual-mean sea
458 ice thickness.

459 In the preceding characterisation of the Weddell Gyre, two factors are key in determining
460 the nature of the overturning circulation and water mass transformations in the gyre: (1)
461 the concentration of oceanic heat loss in the SW box region, and (2) the existence of a
462 significant throughflow component to the gyre. The overturning circulation of the gyre has
463 an asymmetric double-cell structure, with diapycnal upwelling of 2 ± 2 Sv of CDW across

464 the winter mixed layer base in the gyre interior, and comparatively stronger downwelling
465 of 8 ± 2 Sv across the intermediate classes of WSDW ($\gamma^n = 28.35 \text{ kg m}^{-3}$) near the
466 western / southwestern boundary. While the occurrence of a double-celled overturning
467 with upwelling in the gyre interior is expected from the structure of the wind-forced
468 Ekman vertical motion in a cyclonic gyre [*Sverdrup*, 1947], the strong bias toward and
469 localisation of downwelling arises from factor (1) above, which leads to intense buoyancy
470 loss (through cooling) in the SW box.

471 Our results suggest that the CDW upwelling across the permanent pycnocline of the
472 Weddell Gyre interior is exported both toward the north, into the ACC (at a rate of
473 5 ± 1 Sv, and toward the western and southwestern edge of the Weddell Sea (2 ± 1 Sv),
474 where it is implicated in the strong near-boundary downwelling. Observational evidence of
475 downwelling and AABW formation at rates comparable to ours (6 ± 2 Sv) along the slope
476 region of the western and southwestern Weddell Gyre is abundant, and there are some
477 indications in the literature of mid-gyre upwelling in line with our diagnostics too (e.g.,
478 estimated upwelling rates of $5.4 \times 10^{-7} \text{ m s}^{-1}$ [*Gordon et al.*, 1984] and $1.4 \times 10^{-6} \text{ m s}^{-1}$
479 [*Gordon and Huber*, 1990], and an upwelling transport of 1.9 Sv [*Hoppema et al.*, 1999]).
480 However, the connection between up- and downwelling in the gyre and their integration
481 into a double-celled overturning circulation seem to have gone largely unnoticed to date.

482 A further important feature of the water mass transformation in the Weddell Gyre
483 is underpinned by factor (2) above. Specifically, the import of waters from the Indian
484 sector across the gyre's eastern edge injects ACC-sourced CDW and an Indian-sourced
485 variety of AABW (within the WSDW density class) to the gyre at respective rates of
486 14 ± 2 and 9 ± 2 Sv. The former water mass supplies the upwelling limb and contributes

487 significantly to the downwelling limb of the overturning circulation of the gyre [*Nicholls*
488 *et al.*, 2009]. Additionally, it sustains the export across the gyre’s northern edge of 10 ± 4
489 Sv of a distinctively cooler and fresher CDW (Table 7) type produced by mixing with
490 shelf waters cascading downslope around the continental boundaries of the gyre. This
491 CDW type plays a major role in the ventilation of the deep layers of the ACC in the
492 South Atlantic [*Whitworth et al.*, 1994; *Naveira Garabato et al.*, 2002a].

493 Most remarkably, the import of AABW from the Indian sector makes up as much
494 as $\sim 30\%$ of the 8 ± 2 Sv of AABW exported from the Weddell Gyre. The Indian-
495 sourced AABW enters the gyre primarily in the $28.27 < \gamma^n < 28.35$ kg m⁻³ density
496 class (model layers 6 and 7, Figure. 8), and is found to feed the net production of 6 ± 2
497 Sv of denser WSDW ($28.35 < \gamma^n < 28.40$ kg m⁻³, model layers 8 and 9) and WSBW
498 within the gyre. Thus, while the gyre plays a prominent role in the export of AABW
499 to the mid-latitude Southern Ocean, contributing close to half of the net circumpolar
500 export [*Naveira Garabato et al.*, 2013], our results suggest that its standing in net AABW
501 formation (defined as the downward diapycnal volume transport across the $\gamma^n = 28.27$
502 kg m⁻³ surface) is more modest than previously thought. However, the intense oceanic
503 buoyancy loss occurring in the SW box results in the ventilation and densification of all
504 the interior water masses entering the gyre’s eastern edge (not solely CDW), effectively
505 leading to the recycling of the Indian-sourced AABW into a cooler, fresher and denser
506 Weddell variety of AABW. Some of this AABW (WSBW) must then upwell diapycnally
507 within the gyre to be exported to the mid latitudes as WSDW. The occurrence of a
508 significant influx of Indian-sourced AABW to the Weddell Gyre has been reported in
509 several transient tracer-based investigations [*Archambeau et al.*, 1998; *Meredith et al.*,

510 2000; *Hoppema et al.*, 2001] and in a numerical modelling study [*Schodlok et al.*, 2002],
511 and its formation traced to the Prydz Bay / Cape Darnley polynya region (see *Couldrey*
512 *et al.* [2013] and *Ohshima et al.* [2013]).

7. Synthesis

513 The circulation of the Weddell Gyre diagnosed in this study is characterised schemati-
514 cally in Figure 11. CDW and light WSDW enter the gyre across its eastern boundary. In
515 the gyre interior, the inflowing water is consumed by upwelling, forming the upper-cell of
516 the Weddell overturning. The remaining CDW and light WSDW, as well as upper-ocean
517 waters produced by mid-gyre upwelling, enter the southwestern Weddell Sea, where they
518 are ventilated and transformed into denser WSDW and WSBW, forming the lower cell of
519 the Weddell overturning.

520 Our findings suggest several significant revisions to present views of the role of the
521 Weddell Gyre in closing the lower limb of the GOC. Of paramount importance amongst
522 these are the asymmetric, double-celled structure of the overturning in the gyre, linked to
523 wind-driven mid-gyre upwelling and intense oceanic buoyancy loss near the gyre's western
524 and southwestern boundary; and the existence of a significant throughflow component to
525 the gyre, via which CDW and AABW are imported from the Indian sector, ventilated
526 and densified in the inner Weddell Sea, and exported to the mid-latitude Southern Ocean
527 across the gyre's northern edge. This implies that the prominence of the Weddell Gyre in
528 exporting AABW to and ventilating the deep layers of the mid-latitude Southern Ocean
529 stems in part from the influx of remotely formed water masses from the Indian sector.

530 We conclude that, if efforts to monitor and understand the Weddell Gyre's contribution
531 to global-scale overturning and deep-ocean ventilation are to provide a balanced view of

532 the gyre’s climatic evolution and its drivers, they cannot focus solely on the sites of intense
533 densification and AABW export, as they have largely done to date, but must also capture
534 mid-gyre upwelling processes and the inflows from the Indian sector across the gyre’s
535 eastern rim. In the latter case, there are recent indications that decadal-scale changes
536 in the Indian-sourced inflows are beginning to perturb significantly the circulation of the
537 gyre [*Couldrey et al.*, 2013].

538 **Acknowledgments.**

539 The ANDREX project was supported by the National Environmental Research Council
540 (NE/E01366X/1). We thank Dr. Matthew Mazloff (Scripps Institution of Oceanogra-
541 phy) for providing the SOSE output, and Dr. Takamasa Tsubouchi for many insightful
542 discussions on inverse modeling. It is a great pleasure to acknowledge the outstanding
543 contribution of the Masters, officers and crew of RRS James Clark Ross, RRS James Cook,
544 RV Roger Revelle and PFS Polarstern, as well as the many scientists who participated to
545 the data collection and processing. We thank two anonymous reviewers whose comments
546 greatly improved the clarity of the manuscript.

547 This work is dedicated to the memory of Eberhard Fahrbach, a great polar scientist
548 and mentor whose legacy in polar oceanography will carry on for the years to come.

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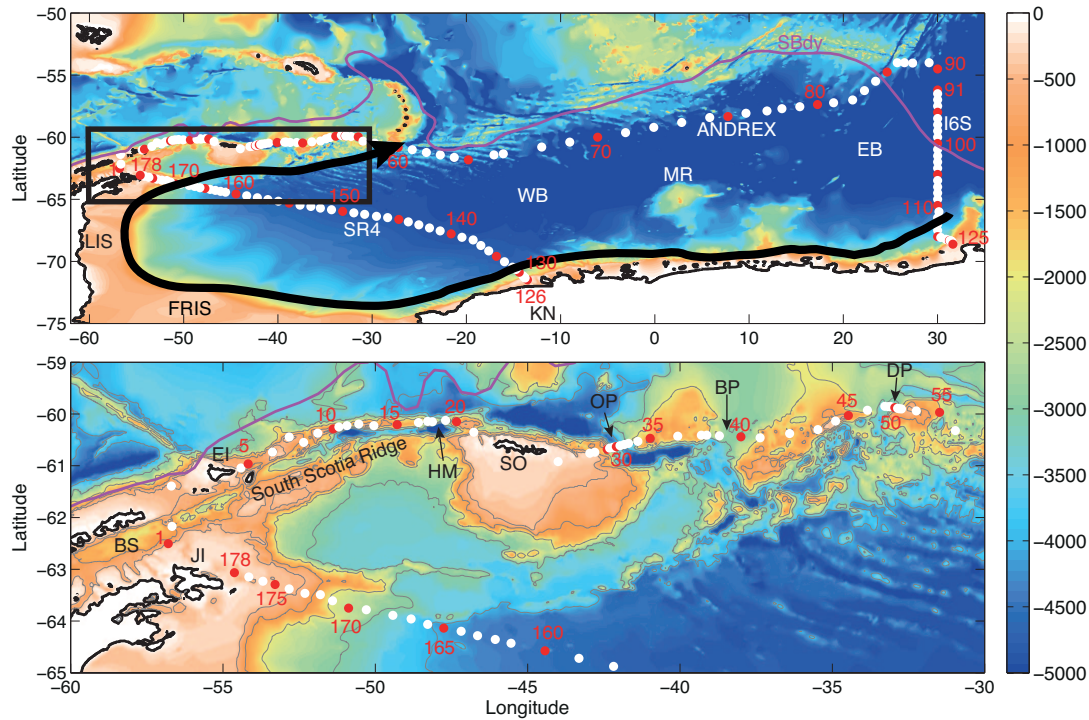


Figure 1. Top panel: Map and bathymetry (from GEBCO) of the Weddell Gyre region showing the 3 sections used in this study (ANDREX, I6S, SR4). For each section, the first and last stations as well as every fifth stations are shown in red. The Southern Boundary of the ACC in magenta; the Weddell Gyre is indicated schematically by the black arrow. From left to right, LIS: Larsen Ice Shelves; FRIS: Filchner-Ronne Ice Shelves; KN: Kapp Norvegia; WB: Weddell Basin, MR: Maud Rise, EB: Enderby Basin. Bottom panel: detailed map of the South Scotia Ridge (black rectangle in top panel). From left to right, BS: Bransfield Strait; JI: Joinville Island; EI: Elephant Island; HM: Hesperides Mouth; SO: South Orkney Islands; OP: Orkney Passage; BP: Bruce Passage; DP: Discovery Passage.

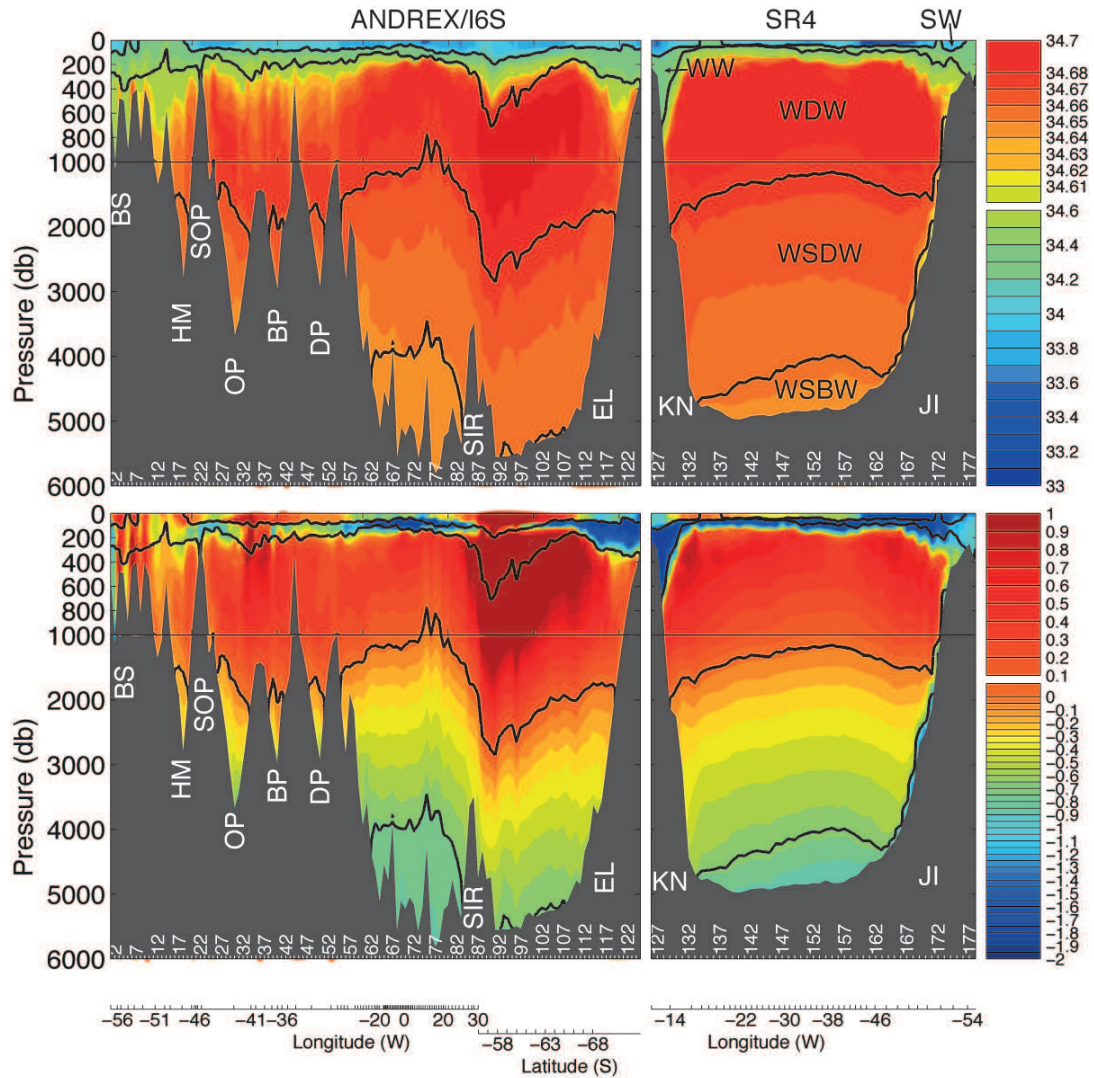


Figure 2. Salinity (top) and potential temperature (bottom) along the rim of the model box going clockwise from the Antarctic Peninsula (station 1) along the ANDREX/I6S section and SR4 section back to Joinville Island (station 175). Water mass neutral density boundaries (Table 3) are shown as black contours. Water masses and stations are labelled in black and white, respectively. The main bathymetric features are labelled in white. From left to right, BS: Bransfield Strait, HM: Hesperides Mouth, SOP: South Orkney Plateau, OP: Orkney Passage, BP: Bruce Passage, DP: Discovery Passage, SIR: South Indian Ridge, EL: Enderby Land. Water masses as defined in Table 3: WW: Winter Water; CDW: Circumpolar Deep Water; WSDW: Weddell Sea Deep Water; WSBW: Weddell Sea Bottom Water.

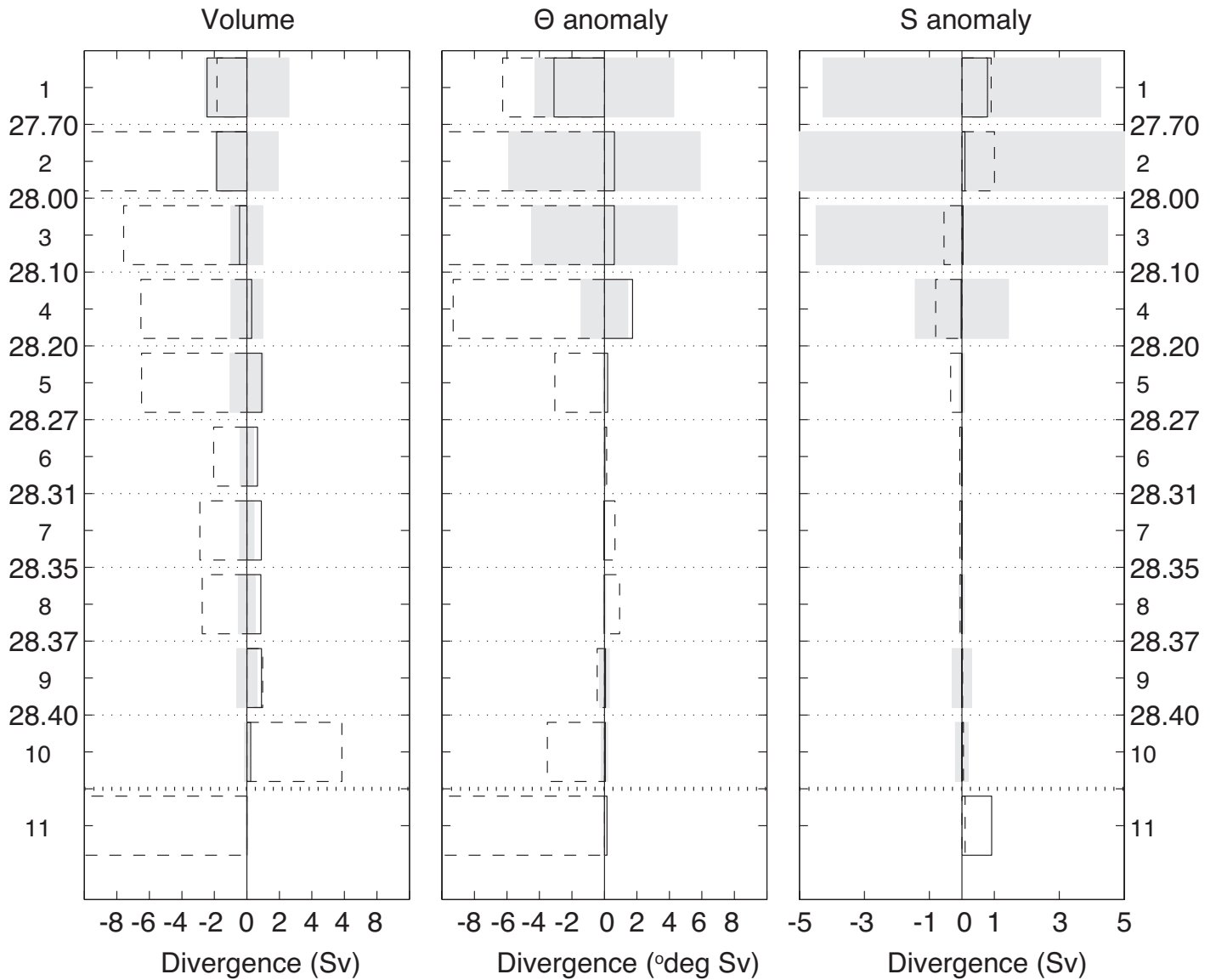


Figure 3. Transport divergence for the box. a) volume, b) potential temperature anomaly, c) salinity anomaly (right) before (black dashed lines) and after (black lines) inversion. The neutral density limits of the layers are shown as black dotted lines. Grey bars are posterior uncertainties calculated using the Gauss-Markov formalism. Positive is into the box, negative is out of the box.

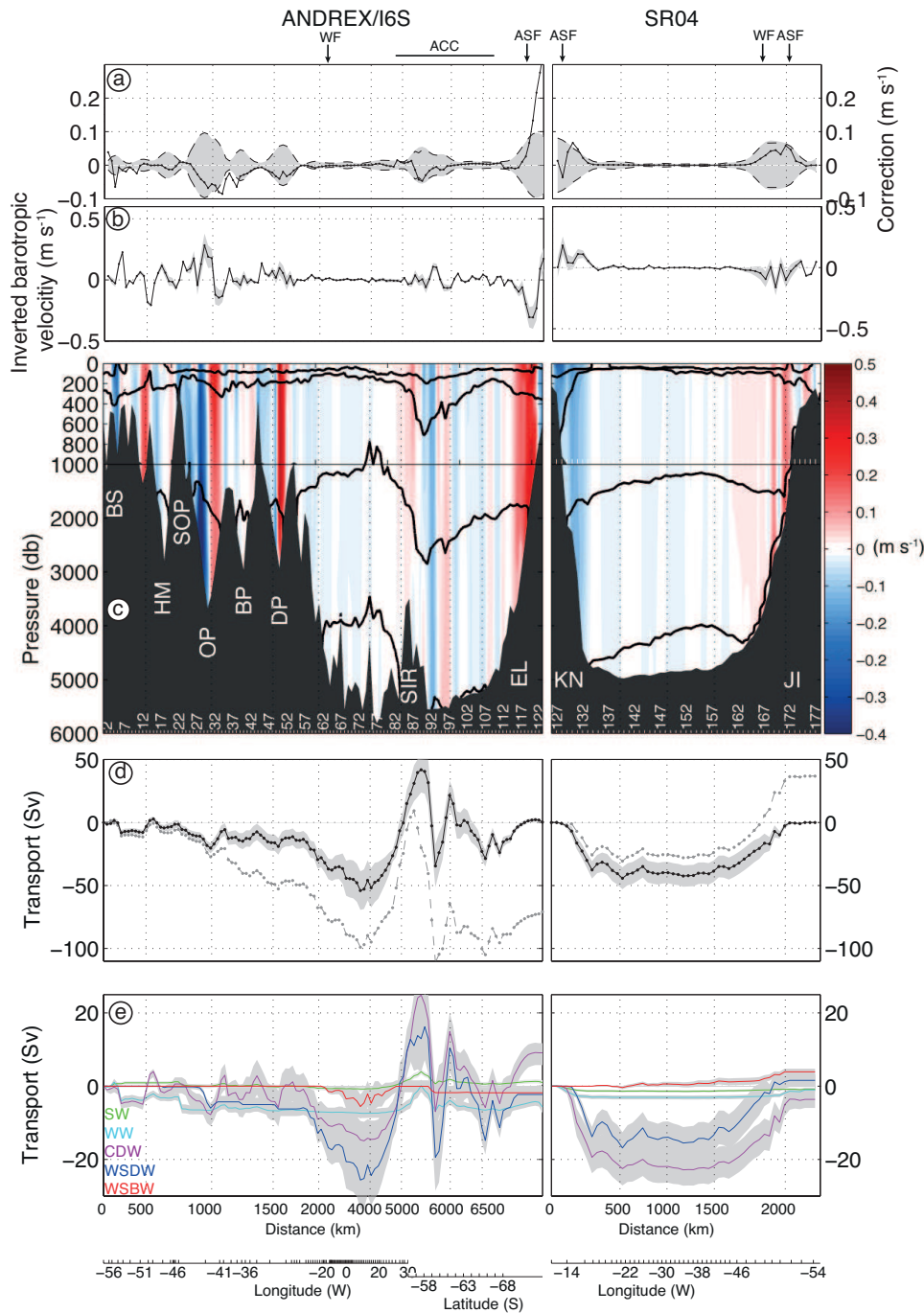


Figure 4. a) Corrections applied by the inverse model to the barotropic velocities; the shaded envelope is the prior uncertainty, and the dashed line the posterior uncertainty. b) Inverted barotropic velocities (initial + correction); the grey envelope indicates the prior uncertainty. c) Geostrophic velocity, with positive (negative) values indicating flow into (out of) the model box. Black contours represent the water mass boundaries. d) Accumulated (clockwise from the Antarctic Peninsula to the Enderby Land for ANDREX/I6S and from Kapp Norvegia until Joinville Island for SR4) full-depth volume transport (in Sv), with the same sign convention as in (c): prior (dashed black line) and posterior (black line). e) Accumulated volume transport (in

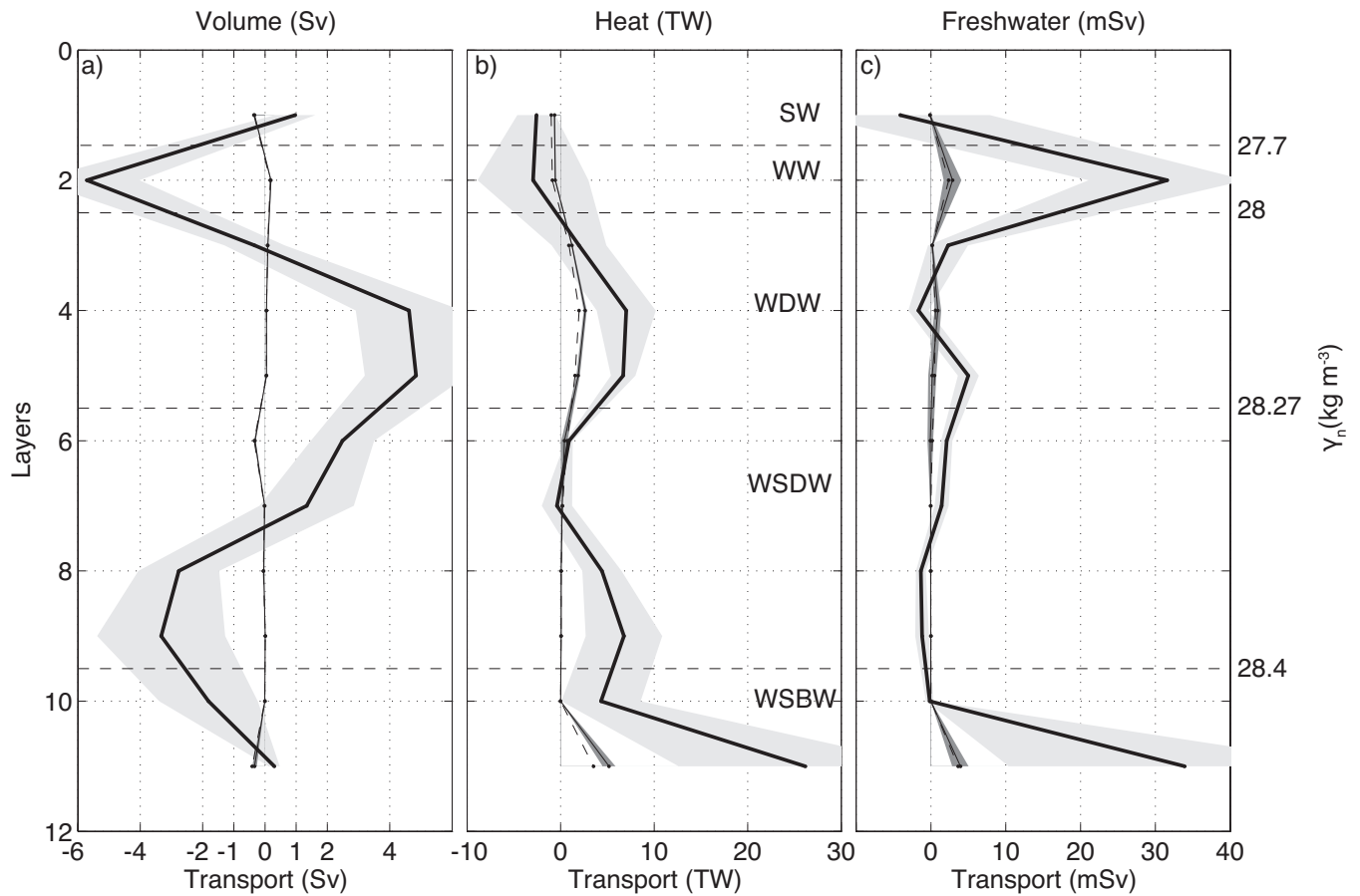


Figure 5. Net a) Volume, b) heat and c) freshwater mean (thick black line) *vs.* eddy (thin black line) transports across the ANDREX/I6S section. Positive transports are directed into the box (southward). Grey envelopes represent one standard deviation uncertainties.

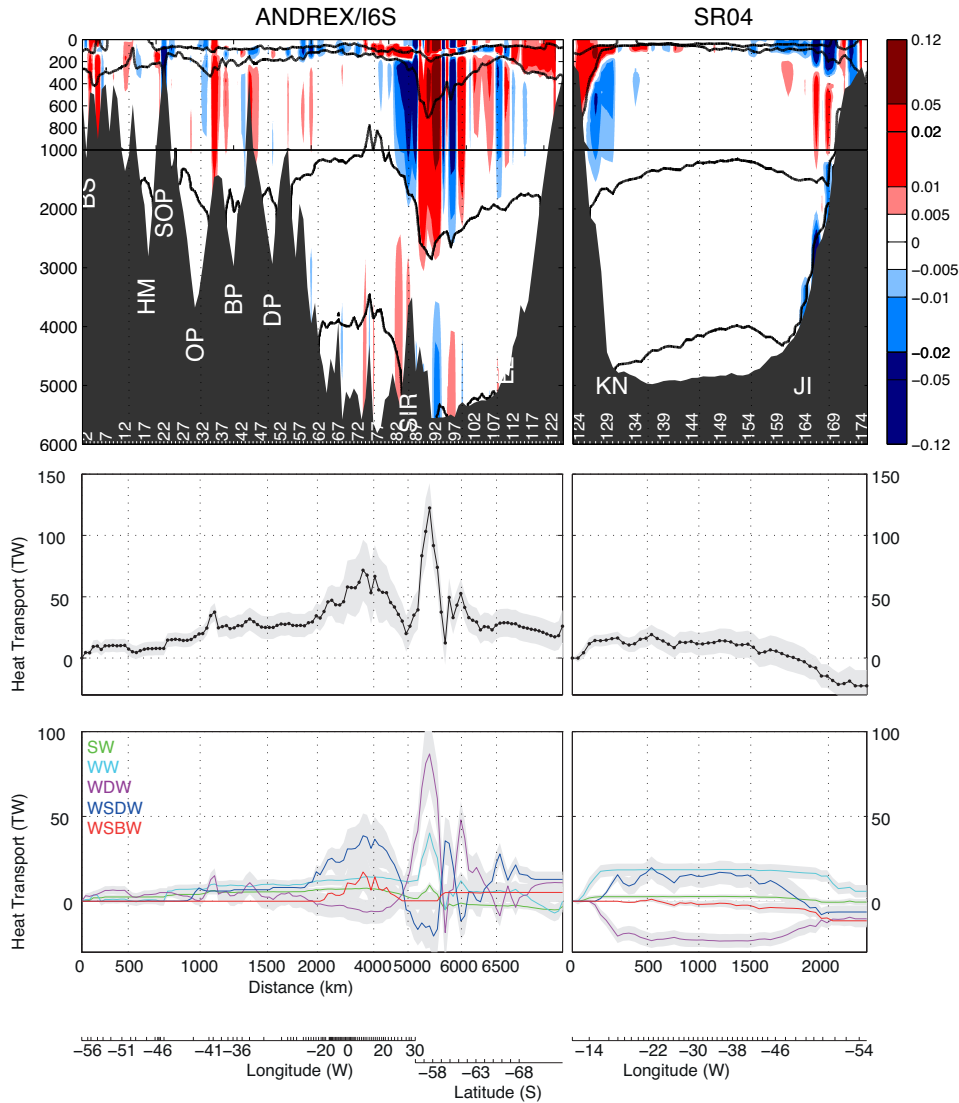


Figure 6. Top: Heat flux along the rim of the model box (in TW). Black contours indicate water mass boundaries. Middle: Accumulated full-depth heat transport (in TW). Bottom: Accumulated heat transport (in TW) of individual water masses, as labelled.

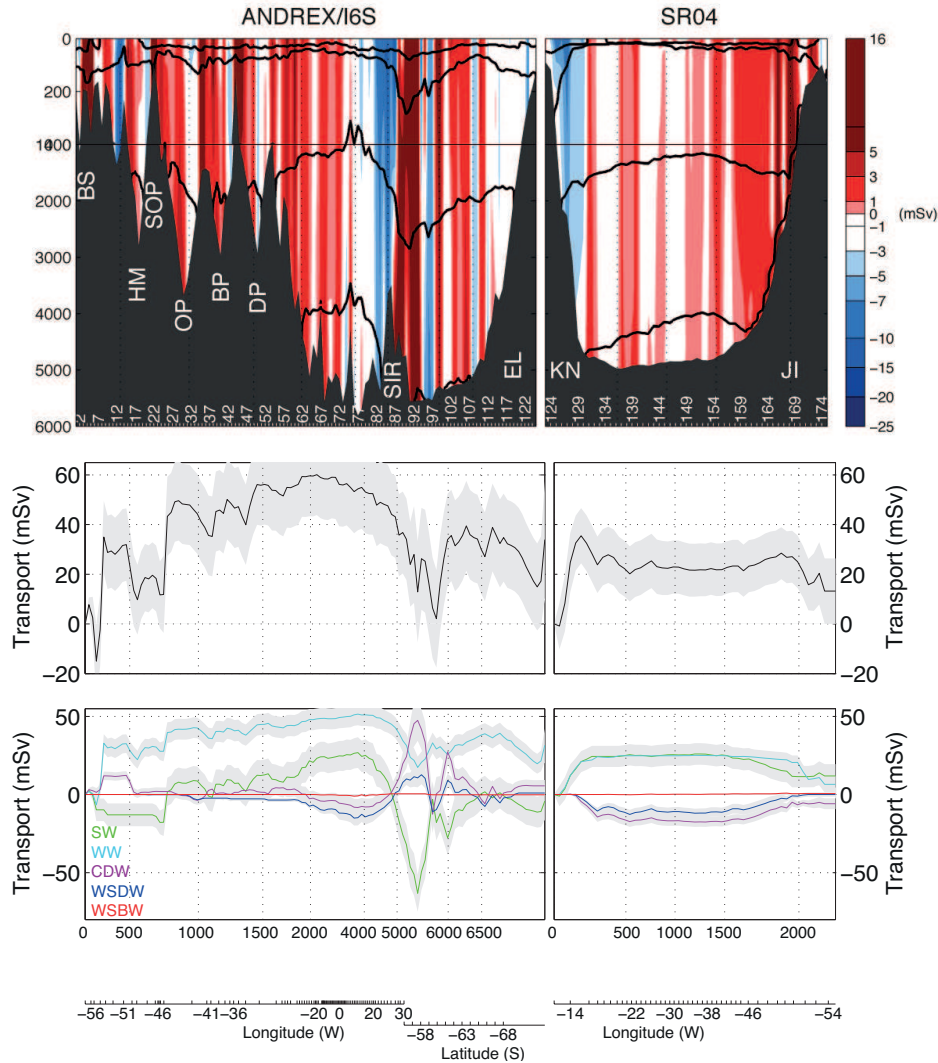


Figure 7. Top: Freshwater flux along the rim of the model box (in mSv). Black contours indicate water mass boundaries. Middle: Accumulated full-depth freshwater transport (in mSv). Bottom: Accumulated freshwater transport (in mSv) of individual water masses, as labelled.

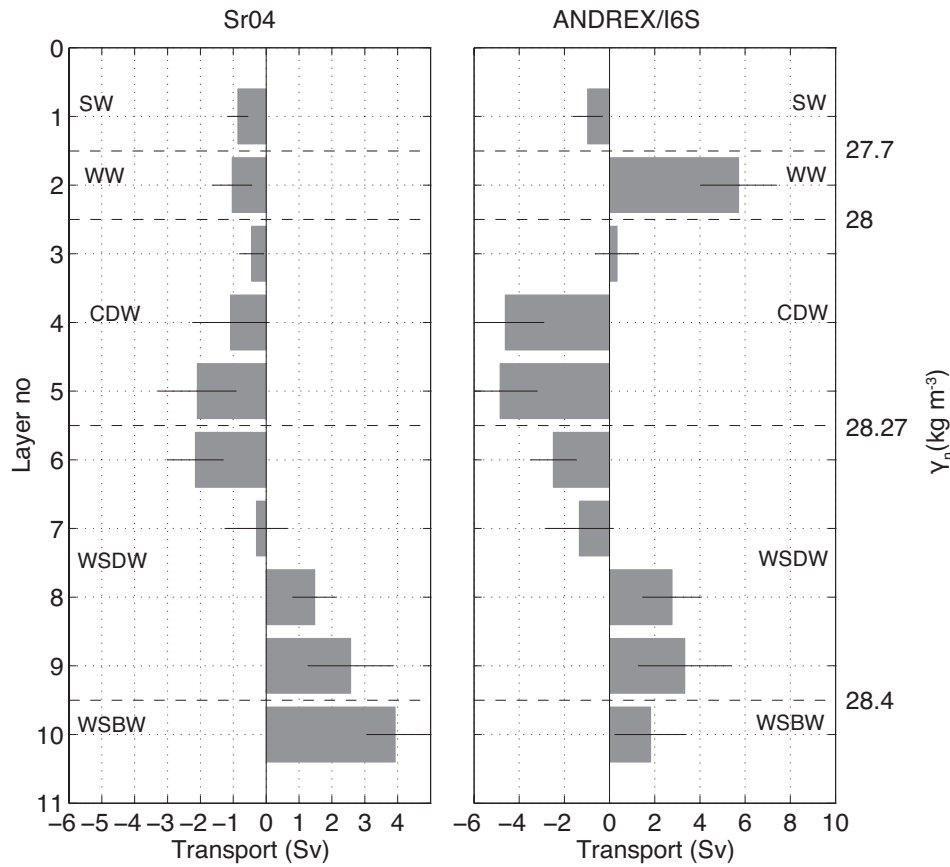


Figure 8. Overturning circulation (defined the volume transport divergence for each coast-to-coast section) across the SR4 (left) and ANDREX/I6S (right) transects. Positive values are directed northward. Horizontal dashed lines indicate water mass boundaries as defined in Table 3.

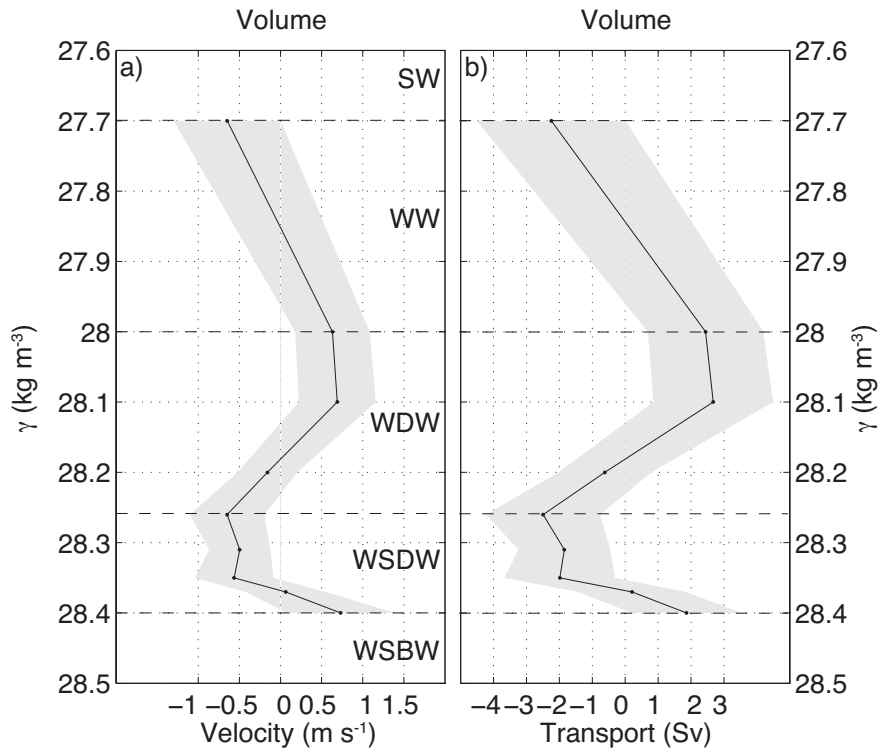


Figure 9. a) Diapycnal velocities for volume across the model layer interfaces. b) Corresponding diapycnal transports of volume. In all panels, positive values are directed toward lighter layers. Grey envelopes represent one standard deviation uncertainties. Horizontal dashed lines indicate water mass boundaries as defined in Table 3.

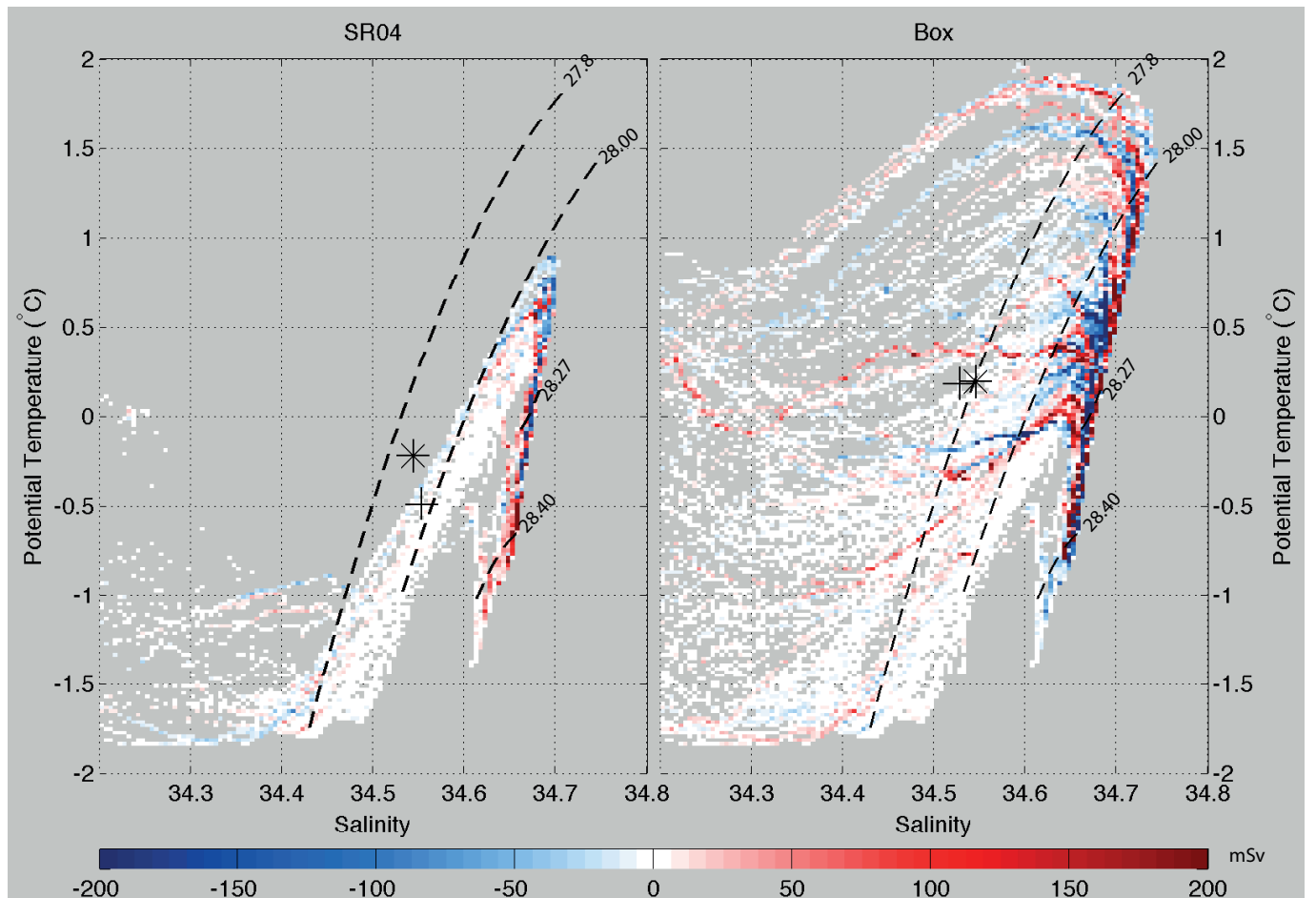


Figure 10. Volumetric θ -S diagram along the SR4 section only (left) and along the rim of the model box (right). For each θ -S bin, the net volume transport is computed. Negative values (in blue) indicate a consumption of a θ -S class, and positive values (in red) denote a production of a θ -S class. Dashed lines show water mass boundaries as defined in Table 3. The mean volume-transport-weighted θ -S of the inflow and outflow are respectively marked as black asterisks and crosses.

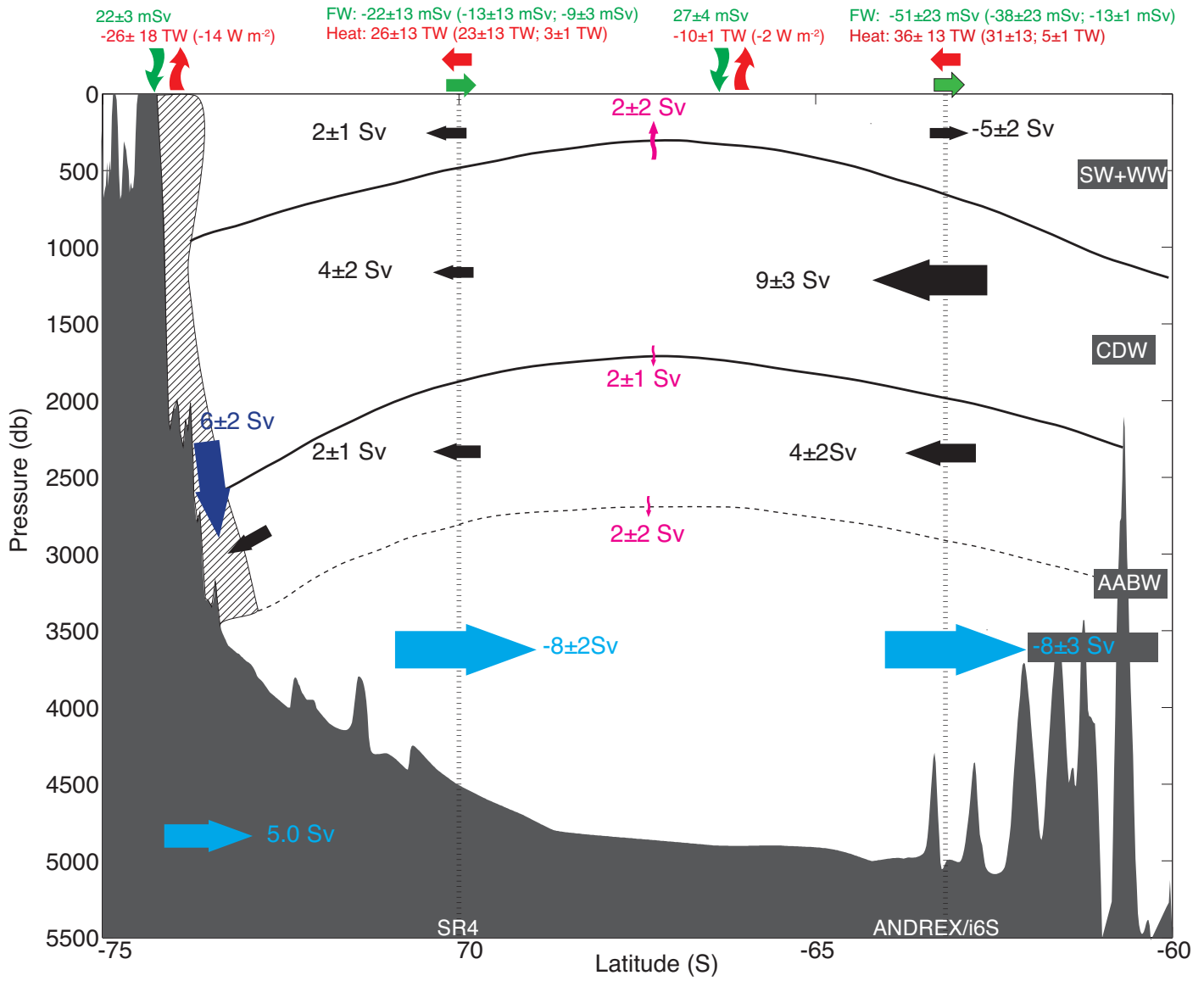


Figure 11. Schematic of the overturning circulation, heat and freshwater budgets of the Weddell Gyre. The main water masses are represented and separated by the horizontal solid black contours. The ANDREX/I6S and SR4 sections are indicated as dotted vertical lines. Westward- / southward- flowing layers, shown as black arrows, are separated from the northward-flowing layers, represented by the blue arrows, by the horizontal dashed contour. The diapycnal fluxes are shown in magenta and the transformation of deep and surface water in bottom water in dark blue. Air-sea and full-depth fluxes of heat and freshwater are indicated as red and green arrows at the surface, respectively. The fluxes are partitioned into oceanic (first term in brackets) and mobile sea ice (second term in brackets) components. The hatched region represents the AABW

Table 1. Summary of the historical estimates of Antarctic Bottom Water, Weddell Sea Bottom Water and Weddell Sea Deep Water production in the Weddell Sea.

Source	Method	Production rate (Sv)		
		WSDW	WSBW	AABW
This study	Inverse model	2 ± 2	4 ± 2	6 ± 2
<i>Kerr et al.</i> [2012]	Numerical model			10.6 ± 3.1
<i>Wang et al.</i> [2009]	Numerical model		2.2	
<i>Huhn et al.</i> [2008]	CFC and noble gas inventory		5.0 ± 1.2	
<i>Lumpkin and Speer</i> [2007]	Inverse Model			5.6 ± 3.0
<i>Klatt et al.</i> [2005]	Geostrophic transport		3	
<i>Foldvik et al.</i> [2004]	DBC transport		4.3 ± 1.4	
<i>Naveira Garabato et al.</i> [2002a]	Inverse Model	5.8 ± 3.0	3.9 ± 0.8	9.7 ± 3.7
<i>Orsi et al.</i> [2002]	CFC inventory	4.9		
<i>Schodlok et al.</i> [2002]	Numerical model	6.4 ± 0.6		
<i>Sloyan and Rintoul</i> [2001]	Inverse Model			11 ± 1
<i>Harms et al.</i> [2001]	Freshwater budget		2.6	
<i>Fahrbach et al.</i> [2001]	DBC transport		1.3 ± 0.4	
<i>Meredith et al.</i> [2001]	CFC inventory			3.7 ± 1.6
<i>Orsi et al.</i> [1999]	CFC inventory			4.9
<i>Gordon</i> [1998]	DBC transport		5 - 4	
<i>Mensch et al.</i> [1996]	CFC inventory		11	
<i>Fahrbach et al.</i> [1995]	DBC transport		1.4	
<i>Fahrbach et al.</i> [1994]	DBC transport	2.6	1.2	
<i>Fahrbach et al.</i> [1991]	Geostrophic transport		3 - 4	
<i>Foster and Carmack</i> [1976]	DBC transport		3.6	
<i>Carmack and Foster</i> [1975]	DBC transport		2 - 5	
<i>Gill</i> [1973]	Shelf Water budget		6 - 9	

Table 2. Summary of the cruise data sets entering the inverse model. The station numbers for each section in the box is indicated.

Year	Month	Vessel	Cruise no.	Section name	Box station no	Reference
2005	01-02	PFS Polarstern	ANT XXII/3	SR4	126 - 178	<i>Fahrbach</i> [2005]
2008	02-03	RV Roger Revelle	33RR20080204	I6S	91 - 125	<i>Speer and Dittmar</i> [2008]
2009	01	RRS James Cook	JC30	ANDREX	67 - 90	<i>Bacon and Jullion</i> [2009]
2010	03-04	RRS James Clark Ross	JR239	ANDREX	1 - 66	<i>Meredith</i> [2010]

Table 3. Model layer definitions and characteristics: *A priori* errors in the volume conservation for model layers following the recommendations of *Ganachaud* [2003]. The mean and standard deviation of the θ and S of each layer are quoted, and water mass equivalences indicated (SW: Surface Water; WW: Winter Water; CDW: Circumpolar Deep Water; WSDW: Weddell Sea Deep Water; WSBW: Weddell Sea Bottom Water).

γ_n limits (kg m^{-3})	Layer no.	Error (Sv)	$\theta \pm \text{std}(\theta)$ ($^{\circ}\text{C}$)	$S \pm \text{std}(S)$	Water mass
Sea surface 27.70	1	4	-0.40 ± 0.72	33.947 ± 0.167	SW
27.70 28.00	2	4	-0.69 ± 0.89	34.385 ± 0.068	WW
28.00 28.10	3	3	-0.18 ± 0.89	34.568 ± 0.069	CDW
28.10 28.20	4	3	0.38 ± 0.31	34.666 ± 0.030	
28.20 28.27	5	2	0.17 ± 0.21	34.673 ± 0.020	
28.27 28.31	6	2	-0.09 ± 0.07	34.668 ± 0.006	WSDW
28.31 28.35	7	2	-0.33 ± 0.08	34.661 ± 0.006	
28.35 28.37	8	2	-0.48 ± 0.08	34.656 ± 0.004	
28.37 28.40	9	2	-0.59 ± 0.08	34.653 ± 0.004	
28.40 Sea floor	10	1	-0.73 ± 0.06	34.648 ± 0.005	WSBW
Full-depth	11	1	-0.14 ± 0.33	34.603 ± 0.090	

Table 4. Extra conservation constraints applied to the model.

	ANDREX/I6S (1-123)	SR4 (124-175)	ACC (82-111)
Full depth vol. trans.	0 ± 1 Sv	0 ± 1 Sv	0 ± 5 Sv
Full depth S anom trans.	0 ± 1 Sv	0 ± 1 Sv	0 ± 5 Sv

Table 5. *A priori* and *a posteriori* values for the sea ice, air-sea-ice heat and meteoric water fluxes

	SR4			ANDREX/I6S		
	Sea-ice mSv	Heat TW	met. water mSv	Sea ice mSv	heat TW	met. water mSv
<i>A priori</i>	18 ± 9	0	21 ± 11	16 ± 8	0	49 ± 25
<i>A posteriori</i>	10 ± 1	26 ± 18	22 ± 3	4 ± 1	10 ± 1	28 ± 4

Table 6. Water mass and full-depth volume transports (in Sv) diagnosed by the inverse model within the Antarctic Slope Front across the I6S section (left), near Kapp Norvegia across the SR4 transect (middle), and near Joinville Island (right) diagnosed by the inverse model. The station pairs over which the transport of these fronts is integrated are given in brackets.

Water mass	I6S (112-123)	SR4 Kapp Norvegia (124-131)	SR4 Joinville Island (159-175)
SW	0 ± 0	-1 ± 0	0 ± 0
WW	1 ± 1	-3 ± 1	2 ± 0
CDW	14 ± 2	-19 ± 4	17 ± 4
WSDW	9 ± 2	-14 ± 3	14 ± 4
WSBW	0 ± 0	-0 ± 0	3 ± 1
Full-depth	24 ± 4	-38 ± 8	37 ± 9

Table 7. Water mass and full-depth volume transports (in Sv) through the deep passages of the South Scotia Ridge, and net transports over the ridge and within the Weddell Front. The station pairs over which the transport of these fronts is integrated are given in brackets.

Water mass	Hesperides M. (16-18)	Orkney P. (24-33)	Bruce P. (38-41)	Discovery P. (47-51)	SSR + WF (1-64)
SW	0 ± 0	0 ± 0	-0 ± 0	0 ± 0	-1 ± 0
WW	-1 ± 0	1 ± 0	-0 ± 0	0 ± 0	-7 ± 1
CDW	-3 ± 2	2 ± 3	0 ± 4	4 ± 1	-12 ± 5
WSDW	0 ± 1	-4 ± 1	-1 ± 1	-1 ± 0	-17 ± 4
WSBW	0 ± 0	0 ± 0	0 ± 0	0 ± 0	-2 ± 1
Full-depth	-4 ± 3	-1 ± 4	-1 ± 5	3 ± 2	-40 ± 9