

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

Loïc Jullion, Alberto C. Naveira Garabato, Sheldon Bacon, Michael P. Meredith, Peter J. Brown, Sinhue Torres-Valdés, Kevin Speer, Paul H. Holland, Jun Dong, Dorothée Bakker, et al.

# ▶ 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  $\,$ 

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

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

Loïc Jullion<sup>1,2</sup>, Alberto C. Naveira Garabato<sup>1</sup>, Sheldon Bacon<sup>3</sup>, Michael P. Meredith<sup>4,5</sup>, Pete J. Brown<sup>4,6</sup>, Sinhue Torres-Valdés<sup>3</sup>, Kevin G. Speer<sup>2</sup>, Paul R. Holland<sup>4</sup>, Jun Dong<sup>2</sup>, Dorothée Bakker<sup>6</sup>, Mario Hoppema<sup>7</sup>, Brice Loose<sup>8</sup>, Hugh J. Venables<sup>4</sup>, William J. Jenkins<sup>9</sup>, Marie-José Messias<sup>10</sup> and Eberhard Fahrbach<sup>7\*</sup>

<sup>1</sup>University of Southampton, National

X - 2 JULLION ET AL.: THE WEDDELL GYRE IN THE GOC 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  $42 \pm 8$  Sv (1 Sv =  $10^6$  m<sup>3</sup> s<sup>-1</sup>) across the central Weddell Sea

Oceanography Centre, Southampton, U.K.

<sup>2</sup>Geophysical Fluid Dynamics Institute,

Florida State University, Tallahassee, U.S.A.

<sup>3</sup>National Oceanography Centre,

Southampton, U.K.

<sup>4</sup>British Antarctic Survey, Cambridge,

U.K.

<sup>5</sup>Scottish Association for Marine Science,

Oban, U.K.

<sup>6</sup>University of East Anglia, Norwich, U.K.

<sup>7</sup>Alfred-Wegener-Institut, Bremerhaven,

Germany

<sup>8</sup>University of Rhode Island,

Narragansett, U.S.A.

<sup>9</sup>Woods Hole Oceanographic Institution,

Woods Hole, U.S.A.

<sup>10</sup>University of Exeter, Exeter, U.K.

and to intensify to  $54\pm15$  Sv further offshore. This circulation injects  $36\pm$ 7 13 TW of heat from the Antarctic Circumpolar Current to the gyre, and ex-8 ports 51  $\pm$  23 mSv of freshwater, including 13  $\pm$  1 mSv as sea ice to the 9 mid-latitude Southern Ocean. The gyre's overturning circulation has an asym-10 metric double-cell structure, in which  $13 \pm 4$  Sv of Circumpolar Deep Wa-11 ter (CDW) and relatively light Antarctic Bottom Water (AABW) are trans-12 formed into upper-ocean water masses by mid-gyre upwelling (at a rate of 13  $2 \pm 2$  Sv) and into denser AABW by downwelling focussed at the western 14 boundary (8  $\pm$  2 Sv). The gyre circulation exhibits a substantial through-15 flow component, by which CDW and AABW enter the gyre from the Indian 16 sector, undergo ventilation and densification within the gyre, and are exported 17 to the South Atlantic across the gyre's northern rim. The relatively mod-18 est net production of AABW in the Weddell Gyre  $(6\pm 2 \text{ Sv})$  suggests that 19 the gyre's prominence in the closure of the lower limb of global oceanic over-20 turning stems largely from the recycling and equatorward export of Indian-21 sourced AABW. 22

#### 1. Introduction

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

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

X - 5

30°E [Orsi and Whitworth, 1993; Gouretski and Danilov, 1993; Park et al., 2001] and 44 is gradually cooled and freshened by mixing with ambient waters as it flows westward 45 near Antarctica. Further downstream, CDW interacts with dense, relatively saline wa-46 ters cascading off the broad continental shelves of the southwestern and western Weddell 47 Sea, resulting in the production of AABW [Gill, 1973; Foster and Carmack, 1976]. The 48 regional variety of AABW is made up of two water masses: Weddell Sea Bottom Wa-49 ter (WSBW), produced primarily near the Filchner-Ronne ice shelves, is the coldest and 50 densest AABW in the Weddell Gyre ( $\theta < -0.7^{\circ}$ C,  $\gamma^n > 28.40$  kg m<sup>-3</sup>, see Orsi et al. 51 [1999]). The warmer and lighter Weddell Sea Deep Water (WSDW;  $0 > \theta > -0.7$ °C, 52  $28.27 < \gamma^n < 28.40 \text{ kg m}^{-3}$ ) may be formed directly by mixing between shelf waters 53 and CDW, or indirectly by entrainment of CDW into WSBW as the shelf water plume 54 cascades down the continental slope. A distinct variety of WSDW is formed near the 55 Larsen ice shelves (LIS) in the western Weddell Sea that is lighter and fresher than deep 56 water formed further south [Fahrbach et al., 1995; Gordon et al., 2001; Huhn et al., 2008; 57 Gordon et al., 2010]. The reader may refer to Nicholls et al. [2009] for a detailed review 58 of AABW in the Weddell Sea. 59 The newly formed AABW is conveyed northeastward by the Weddell Gyre and exported 60

to the mid-latitude Southern Ocean and beyond through openings in the topographic barriers bounding the gyre to the north, most conspicuously along the South Sandwich Trench near 25°W [Orsi et al., 1999]. In spite of the presumed high-ranking status of the Weddell Gyre in AABW formation, present estimates of AABW production in the gyre are unsatisfactorily wide-ranging (Table 1). These differences represent a combination of inconsistencies between different estimation techniques, AABW definitions or regional flow regimes; and temporal variability [*Naveira Garabato et al.*, 2002a]. This large uncertainty in the quantification of water mass transformation and ventilation in the Weddell Gyre has historically posed a significant obstacle to determining its standing in the closure of the GOC.

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

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

X - 6

<sup>90</sup> circulation and thermodynamical budgets, and the latter describes the vertical circulation.
 <sup>91</sup> Section 6 discusses the implications of our results for the present paradigm of the Weddell
 <sup>92</sup> Gyre circulation. Our main findings are synthesized in section 7.

# 2. Data

#### 2.1. Hydrographic data

Four hydrographic transects spanning 5 years (2005 - 2010) were analysed in this study 93 Table 2). The configuration of the inverse model box, which incorporates two complete 94 coast-to-coast sections, allows us to differentiate between the water mass transformations 95 and overturning circulation occurring in association with shelf-slope processes in the vicin-96 ity of the continental shelves and ice shelves of the southwestern Weddell Sea, and the con-97 tributions to transformations and overturning by gyre interior processes. CTD profiles of 98 temperature and salinity were measured during the cruises, as well as velocity with vesselmounted and lowered acoustic Doppler current profilers. All four hydrographic cruise data 100 sets were subjected to secondary quality control testing by performing crossover analyses 101 with CARINA [Key et al., 2010] and GLODAP [Key et al., 2004] regional data products 102 (following [Hoppema et al., 2009]) to analyse for systematic biases inherent in individual 103 cruise measurements. In this work, crossover analyses were performed for salinity only; 104 as occurred during GLODAP, CARINA and PACIFICA [Key et al., 2004, 2010; Tanhua 105 et al., 2010 temperature was not analysed as it is considered by far the most accurately 106 measured parameter and it is assumed that its random and systematic errors are negligi-107 ble. All four salinity data sets used in the Weddell region inversion were found to be of 108 high quality, with derived data offsets being below the adjustment threshold of 0.005. 109

DRAFT

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

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

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

DRAFT

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

#### 2.2. Sea Ice

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

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

#### 2.3. Southern Ocean State Estimate (SOSE)

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

#### X - 10 JULLION ET AL.: THE WEDDELL GYRE IN THE GOC

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

#### 3. A box inverse model of the Weddell Gyre

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

## 3.1. Hydrographic setting

Figure 2 shows the vertical distribution of potential temperature and salinity along the rim of the main box. In the northeastern corner, the ACC is visible in potential temperature and salinity maxima near stations 85 - 97 and extends nearly all the way to the continental slope, as evidenced by the southward-shoaling isopycnals along the I6S section. Near the continental slope, the ASF (stations 111-125) is marked by a southward deepening of isopycnals and a thick layer of cold and fresh WW.

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

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

$$\sum_{j=1}^{m} \left[\sum_{i=1}^{n} [\delta_{i} L_{i} D_{ij} (V_{ij} + b_{i}) \rho_{ij} C_{ij}] + \nu_{j} (C) - [A \overline{\rho C \omega_{c}^{*}}^{\gamma}]_{\gamma_{j}}^{\gamma_{j+1}} + F_{j}^{A-S} (C) + F_{j}^{SI} (C)] = 0, \quad (1)$$

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

X - 12

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

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

$$E\mathbf{x} + \mathbf{n} = \mathbf{y},\tag{2}$$

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

DRAFT

#### 3.3. The standard solution

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

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

# 4. Horizontal circulation, heat and freshwater budgets of the Weddell Gyre4.1. Horizontal circulation

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

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

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

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

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

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

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

#### 4.2. Heat budget

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

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

The southward transport of heat is diminished by the loss of  $10 \pm 1$  TW of oceanic heat 313 (equivalent to  $2 \pm 0$  W m<sup>-2</sup>) within the main box, consistent with the aforementioned net 314 sea ice production in that area. However, the bulk of the heat entering the gyre across the 315 ANDREX / I6S section (specifically,  $26 \pm 13$  TW) penetrates into the gyre's southwestern 316 corner across the SR4 section, with contributions of  $23 \pm 13$  TW and  $3 \pm 1$  TW from 317 the ocean circulation and sea ice, respectively. This implies that a considerably more 318 intense rate of heat loss  $(14\pm6 \text{ W m}^{-2})$  occurs south of the SR4 transect than in the gyre 319 interior. Unlike in the ANDREX / I6S section, the bulk of the heat transport across the 320 SR4 transect is effected by the ASF along the continental slope, suggesting that relatively 321 warm CDW is entrained into the ASF via the recirculation in the central Weddell Sea. 322

#### 4.3. Freshwater budget

X - 18

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

DRAFT

 $_{332}$  mSv in liquid and sea ice forms, respectively). An additional  $28 \pm 4$  mSv is supplied by addition of meteoric water within the main box.

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

#### 5. The vertical circulation of the Weddell Gyre

#### 5.1. Overturning circulation

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

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

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

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

#### 5.2. Water mass transformation

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

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

DRAFT

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 loss  $(1.3 \times 10^{-9} \text{ m}^2 \text{ s}^{-3})$ , with the salinity increase due to sea ice production playing a secondary role  $(0.3 \times 10^{-9} \text{ m}^2 \text{ s}^{-3})$ .

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

## 6. Discussion

X - 22

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

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

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

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

The gyre exports  $51 \pm 23$  mSv of freshwater toward the mid-latitude Southern Ocean, 444 mainly across the South Scotia Ridge (Figure 7). The  $22 \pm 13$  mSv supplied by the inner 445 gyre across the SR4 section is supplemented by  $27 \pm 4$  mSv of meteoric water input to the 446 main box. Our diagnosed sea ice-mediated freshwater export from the inner gyre  $(315\pm32)$ 447  $\rm km^3 \ yr^{-1}$ ) is lower than the prior estimate based on the literature, but not significantly 448 so within uncertainties. For example, the modelling studies of *Petty et al.* [2013] and 449 Haid and Timmermann [2013] find respective freshwater exports in sea ice form from the 450 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. 451 [2011] estimate  $390 \pm 130$  km<sup>3</sup> yr<sup>-1</sup> from satellite images. One possible explanation for our 452 comparatively weak sea ice export is that, as our sections are summer-biased, the ocean 453 contains more meltwater than at other times of year, and therefore requires a relatively 454 low flow of sea ice to balance the addition of meteoric water south of the SR4 transect. A 455 second plausible explanation relates to the lack of winter sea ice thickness measurements 456 in the ASPeCt data base, which may lead to an underestimation of the annual-mean sea 457 ice thickness. 458

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

X - 24

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

Our results suggest that the CDW upwelling across the permanent pychocline of the 471 Weddell Gyre interior is exported both toward the north, into the ACC (at a rate of 472  $5 \pm 1$  Sv, and toward the western and southwestern edge of the Weddell Sea  $(2 \pm 1$  Sv), 473 where it is implicated in the strong near-boundary downwelling. Observational evidence of 474 downwelling and AABW formation at rates comparable to ours  $(6 \pm 2 \text{ Sv})$  along the slope 475 region of the western and southwestern Weddell Gyre is abundant, and there are some 476 indications in the literature of mid-gyre upwelling in line with our diagnostics too (e.g., 477 estimated upwelling rates of  $5.4 \times 10^{-7}$  m s<sup>-1</sup> [Gordon et al., 1984] and  $1.4 \times 10^{-6}$  m s<sup>-1</sup> 478 Gordon and Huber, 1990], and an upwelling transport of 1.9 Sv [Hoppema et al., 1999]). 479 However, the connection between up- and downwelling in the gyre and their integration 480 into a double-celled overturning circulation seem to have gone largely unnoticed to date. 481 A further important feature of the water mass transformation in the Weddell Gyre 482 is underpinned by factor (2) above. Specifically, the import of waters from the Indian 483 sector across the gyre's eastern edge injects ACC-sourced CDW and an Indian-sourced 484 variety of AABW (within the WSDW density class) to the gyre at respective rates of 485  $14 \pm 2$  and  $9 \pm 2$  Sv. The former water mass supplies the upwelling limb and contributes 486

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

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

X - 26

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

## 7. Synthesis

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

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

We conclude that, if efforts to monitor and understand the Weddell Gyre's contribution to global-scale overturning and deep-ocean ventilation are to provide a balanced view of the gyre's climatic evolution and its drivers, they cannot focus solely on the sites of intense densification and AABW export, as they have largely done to date, but must also capture mid-gyre upwelling processes and the inflows from the Indian sector across the gyre's eastern rim. In the latter case, there are recent indications that decadal-scale changes in the Indian-sourced inflows are beginning to perturb significantly the circulation of the gyre [*Couldrey et al.*, 2013].

## 538 Acknowledgments.

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

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

#### References

Archambeau, A., C. Pierre, A. Poisson, and B. Schauer (1998), Distributions of oxygen
and carbon stable isotopes and CFC-12 in the water masses of the Southern Ocean at
30°E from South Africa to Antarctica: results of the CIVA1 cruise, J. of Mar. Sys., 17,
25–38.

DRAFT

April 28, 2014, 3:07pm

DRAFT

- Bacon, S., and L. Jullion (2009), RRS James Cook: Antarctic Deep Water Rates of 553 EXport (ANDREX), Tech. Rep. 08, National Oceanography Centre. 554
- Beckmann, A., H. Hellmer, and R. Timmermann (1999), A numerical model of the Weddell 555
- Sea: Large-scale circulation and water mass distribution, J. Geophys. Res., 104 (C10), 556 23,375-23,391. 557
- Carmack, E., and T. Foster (1975), Flow of water out of the Weddell Sea, *Deep-Sea Res.*, 558 22(11), 711-724.559
- Cavalieri, D., C. Parkinson, P. Gloersen, and H. J. Zwally (1996), Sea ice concentrations 560 from nimbus-7 SMMR and DMSP SSM/I-SSMIS passive microwave data, Tech. rep., 561 National Snow and Ice Data Center, Boulder, Colorado, USA.
- Couldrey, M., L. Jullion, A. C. Naveira Garabato, C. Rye, L. Herráiz-Borreguero, 563 P. J. Brown, M. P. Meredith, and K. G. Speer (2013), Remotely induced warming 564 of Antarctic Bottom Water in the eastern Weddell Gyre, Geophys. Res. Letters, 40, 565 1-6, doi:10.1002/grl.50526. 566
- Drucker, R., S. Martin, and R. Kwok (2011), Sea ice production and export from coastal 567 polynyas in the Weddell and Ross Seas, Geophys. Res. Letters, 38(17), L17,502. 568
- Fahrbach, E. (2005), Expedition FS Polarstern ANT-XXII/3, Tech. rep., Alfred Wegener 569 Institut für polar und Meeresforschung in der Helmholtz-Gemeinschaft. 570
- Fahrbach, E., M. Knoche, and G. Rohardt (1991), An estimate of water mass transfor-571 mation in the southern Weddell Sea, Marine Chemistry, 25-44(1-4), 515-538. 572
- Fahrbach, E., G. Rohardt, M. Schröder, and V. Strass (1994), Transport and structure of 573
- the Weddell Gyre, Annales Geophysicae, 12(9), 840–855. 574

562

- X 30 JULLION ET AL.: THE WEDDELL GYRE IN THE GOC
- <sup>575</sup> Fahrbach, E., G. Rohardt, N. Scheele, M. Schröder, V. Strass, and A. Wisotzki (1995),
- Formation and discharge of deep and bottom water in the northwestern Weddell Sea,
  J. Mar. Res., 53(4), 515–538.
- <sup>578</sup> Fahrbach, E., S. Harms, G. Rohardt, M. Schroder, and R. Woodgate (2001), Flow of <sup>579</sup> bottom water in the northwestern Weddell Sea, *J. Geophys. Res.*, *106*, 2761–2778.
- <sup>580</sup> Fahrbach, E., M. Hoppema, G. Rohardt, O. Boebel, O. Klatt, and A. Wisotzki (2011),
- Warming of deep and abyssal water masses along the Greenwich Meridian on decadal
- time scales the Weddell Gyre as a heat buffer, Deep-Sea Research II, 58(25-26), 2509-2509-2509
- <sup>583</sup> 2523, doi:10.1016/j.dsr2.2011.06.007.
- <sup>584</sup> Foldvik, A., T. Gammelsrød, S. Østerhus, E. Fahrbach, G. Rohardt, M. Schröder, K. W.
- <sup>585</sup> Nicholls, L. Padman, and R. Woodgate (2004), Ice shelf water overflow and bottom <sup>586</sup> water formation in the southern Weddell Sea, *J. Geophys. Res.*, *109*, C02,015.
- Foster, T., and E. Carmack (1976), Frontal zone mixing and Antarctic Bottom Water formation in the southern Weddell Sea, *Deep-Sea Research*, 23(4), 301–317.
- <sup>589</sup> Fowler, C. (2003), Sea ice concentrations from nimbus-7 SMMR and DMSP SSM/I-SSMIS
- <sup>590</sup> passive microwave data personal communication with Mark Tschudi, Tech. rep., Na-
- <sup>591</sup> tional Snow and Ice Data Center, Boulder, Colorado, USA.
- Ganachaud, A. (2003), Error budget of inverse box models: The North Atlantic, J. of Atmospheric and Oceanic Technology, 20(11), 1641–1655.
- Gill, A. (1973), Circulation and bottom water production in the Weddell Sea, *Deep-Sea Research*, 20(2), 111–140.
- <sup>596</sup> Gordon, A. L. (1998), Western Weddell Sea Thermohaline Stratification, Ocean, Ice, <sup>597</sup> and Atmosphere: Interactions at the Antarctic Continental Margin, Antarctic Research

- <sup>598</sup> Series, 75, 215–240.
- Gordon, A. L., and B. A. Huber (1990), Southern Ocean winter mixed layer, J. Geophys. Res., 95(C), 11,655.
- Gordon, A. L., C. Chen, and W. G. Metcalf (1984), Winter mixed layer entrainment of Weddell Deep Water, J. Geophys. Res., 89(1), 637–640.
- Gordon, A. L., M. Visbeck, and B. Huber (2001), Export of Weddell Sea Deep and Bottom
  Water, J. Geophys. Res., 106 (C5), 9005–9017.
- Gordon, A. L., B. Huber, D. Mckee, and M. Visbeck (2010), A seasonal cycle in the
- export of bottom water from the Weddell Sea, *Nature Geoscience*, 3(8), 551–556, doi:
- 10.1038/ngeo916.
- Gouretski, V. V. and A. I. Danilov (1993), Weddell Gyre: structure of the eastern boundary, *Deep Sea Research*, 40(3), 561–582.
- <sup>610</sup> Haid, V., and R. Timmermann (2013), Simulated heat flux and sea ice production at <sup>611</sup> coastal polynyas in the southwestern Weddell Sea, J. Geophys. Res., 118(5), 2640–2652.
- Harms, S., E. Fahrbach, and V. Strass (2001), Sea ice transports in the Weddell Sea, J. *Geophys. Res.*, 106, 9057–9073.
- Heywood, K. J., A. C. Naveira Garabato, D. P. Stevens, and R. Muench (2004), On the
  fate of the Antarctic Slope Front and the origin of the Weddell Front, *J. Geophys. Res.*,
  109(C6), C06,021.
- <sup>617</sup> Hoppema, M., E. Fahrbach, M. H. Stoll, and H. J. de Baar (1999), Annual uptake of <sup>618</sup> atmospheric CO<sub>2</sub> by the Weddell Sea derived from a surface layer balance, including <sup>619</sup> estimations of entrainment and new production, *J. Mar. Res.*, 19(4), 219–233.

- Hoppema, M., O. Klatt, W. Roether, E. Fahrbach, K. Bulsiewicz, C. Rodehacke, and
- G. Rohardt (2001), Prominent renewal of Weddell Sea Deep Water from a remote source, J. Mar. Res., 59(2), 257–279.
- Hoppema M., A. Velo, S. V. Heuven and T. Tanhua (2009), Consistency of cruise data of
- the CARINA database in the Atlantic sector of the Southern Ocean, Earth Syst. Sci.
- 625 Data, 1, 63–75.doi:10.3334/CDIAC/otg.CARINA.SO.V1.0
- <sup>626</sup> Huhn, O., H. H. Hellmer, M. Rhein, C. Rodehacke, W. Roether, M. Schodlok, and
- M. Schroder (2008), Evidence of deep-and bottom-water formation in the western Weddell Sea, *Deep-Sea Research II*, 55(8-9), 1098–1116.
- Jackett, D., and T. McDougall (1997), A neutral density variable for the world's oceans, J. Phys. Oceanogr., 27(2), 237–263.
- Jacobs, S. S. (2004), Bottom water production and its links with the thermohaline circulation, *Antarctic Science*, 16(4), 427–437.
- Kerr, R., K. J. Heywood, M. M. Mata, and C. A. E. Garcia (2012), On the outflow
  of dense water from the Weddell and Ross Seas in OCCAM model, *Ocean Sci.*, 8(3),
  369–388, doi:10.5194/os-8-369-2012.
- Key R, Kozyr A, Sabine C, Lee K, Wanninkhof R, Bullister J, R. A. Feely, F. J. Millero,
  C. Mordy, and T. H. Peng (2004), A global ocean carbon climatology: Results from
  Global Data Analysis Project (GLODAP), *Global Biogeochem. Cycles*, 18, 1–23, doi:
  10.1029/2004GB002247.
- Key, R.M., T. Tanhua, A. Olsen, M. Hoppema, S. Jutterström, C. Schirnick, S. van
  Heuven, A. Kozyr, X. Lin, A. Velo, D. W. R. Wallace and L. Mintrop (2010), The
- <sup>642</sup> CARINA data synthesis project: Introduction and overview., *Earth Syst. Sci. Data*, 8,

X - 32

X - 33

643 105–122.

- <sup>644</sup> Klatt, O., E. Fahrbach, M. Hoppema, and G. Rohardt (2005), The transport of the <sup>645</sup> Weddell Gyre across the Prime Meridian, *Deep-Sea Research II*, 52(3-4), 513–528.
- Lenaerts, J., and M. R. van den Broeke (2012), A new, high-resolution surface mass
- balance map of Antarctica (1979–2010) based on regional atmospheric climate modeling,
- <sup>648</sup> Geophys. Res. Letters, 39, L04,501, doi:10.1029/2011GL050713.
- Lumpkin, R., and K. Speer (2007), Global Ocean Meridional Overturning, J. Phys.
   Oceanogr., 37(10), 2550–2562.
- Marinov, I., A. Gnanadesikan, J. R. Toggweiler, and J. L. Sarmiento (2006), The Southern

 $_{652}$  Ocean biogeochemical divide, *Nature*, 441(7096), 964–967.

- Mazloff, M. R., P. Heimbach, and C. Wunsch (2010), An eddy-permitting Southern Ocean
  state estimate, J. of Phys. Oceanogr., 40(5), 880–899, doi:10.1175/2009JPO4236.1.
- McIntosh, P. C., and S. R. Rintoul (1997), Do box inverse models work?, J. Phys.
   Oceanogr., 27, 291–308.
- Mensch, M., R. Bayer, J. Bullister, P. Schlosser, and R. Weiss (1996), The distribution
   of tritium and CFCs in the Weddell Sea during the mid-1980s, *Prog. Oceanogr.*, 38(4),
   377–415.
- Meredith, M. (2010), Cruise report, RRS James Clark Ross, jr235/236/239, Tech. rep.,
   British Antarctic Survey.
- Meredith, M., R. Locarnini, K. V. Scoy, A. Watson, K. Heywood, and B. King (2000),
  On the sources of Weddell Gyre Antarctic Bottom Water, J. Geophys. Res., 105 (C1),
  1093–1104.

- Meredith, M. P., A. Watson, and K. V. Scoy (2001), Chlorofluorocarbon-derived formation
  rates of the deep and bottom waters of the Weddell Sea, J. Geophys. Res., 106 (C2),
  2899–2919.
- <sup>668</sup> Naveira Garabato, A. C., E. McDonagh, D. P. Stevens, K. J. Heywood, and R. J. Sanders
- (2002a), On the export of Antarctic Bottom Water from the Weddell Sea, *Deep-Sea Research II*, 49, 4715–4742.
- Naveira Garabato, A. C., K. J. Heywood, and D. P. Stevens (2002b), Modification and
  pathways of Southern Ocean deep waters in the Scotia Sea, *Deep-Sea Research I*, 49(4),
  681–705.
- <sup>674</sup> Naveira Garabato, A. C., A. Williams, and S. Bacon (2013), The three-dimensional over-
- turning circulation of the Southern Ocean during the WOCE era, *Prog. Oceanogr.*, 120,
  41–78 doi:10.1016/j.pocean.2013.07.018
- <sup>677</sup> Nicholls, K. W., S. Østerhus, K. Makinson, T. Gammelsrød, and E. Fahrbach (2009),
- <sup>678</sup> Ice-ocean processes over the continental shelf of the southern Weddell Sea, Antarctica:
- <sup>679</sup> A review, *Rev. Geophys.*, 47(3), 2007RG000,250.
- Ohshima, K. I., Y. Fukamachi, G. D. Williams, S. Nihashi, F. Roquet, Y. Kitade,
- T. Tamura, D. Hirano, L. Herraiz-Borreguero, I. Field, M. Hindell, S. Aoki, M. Wakat suchi (2013), Antarctic Bottom Water production by intense sea-ice formation in the
- $G_{663}$  Cape Darnley polynya, *Nature Geoscience*, 6(3), 235–240.
- <sup>684</sup> Orsi, A., and T. Whitworth (1993), On the circulation and stratification of the Weddell <sup>685</sup> Gyre., *Deep-Sea Research I*, 40, 169–203.
- <sup>686</sup> Orsi, A. H., G. C. Johnson, and J. L. Bullister (1999), Circulation, mixing, and production <sup>687</sup> of Antarctic Bottom Water, *Prog. Oceanogr.*, 43(1), 55–109.

- <sup>688</sup> Orsi, A. H., W. S. Jr, and J. Bullister (2002), On the total input of Antarctic Waters <sup>689</sup> to the deep ocean: A preliminary estimate from chlorofluorocarbon measurements, J. <sup>690</sup> Geophys. Res., 107(C8), 3122.
- <sup>691</sup> Park, Y.-H., E. Charriaud, P. Craneguy, and A. Kartavtseff (2001), Fronts, transport,
  <sup>692</sup> and Weddell Gyre at 30°E between Africa and Antarctica, J. Geophys. Res., 106 (C2),
  <sup>693</sup> 2857–2879.
- Petty, A. A., P. R. Holland, and D. L. Feltham (2013), Sea ice and the ocean mixed layer
  over the Antarctic shelf seas, *The Cryosphere*, 7(4), 4321–4377.
- Rignot, E., J. L. Bamber, M. R. van den Broeke, C. Davis, Y. Li, W. J. V. D. Berg, and
- E. V. Meijgaard (2008), Recent Antarctic ice mass loss from radar interferometry and regional climate modelling, *Nature Geoscience*, 1(2), 106–110, doi:10.1038/ngeo102.
- <sup>699</sup> Rintoul, S., and A. C. Naveira Garabato (2013), Dynamics of the Southern Ocean circu-<sup>700</sup> lation, in *Ocean Circulation and Climate: A* 21<sup>st</sup> *Century Perspective*, edited by J. G.
- <sup>701</sup> G. Siedler, S. Griffies and J. Church, pp. 471–492, Academic Press.
- Schodlok, M., H. H. Hellmer, and A. Beckmann (2002), On the transport, variability and origin of dense water masses crossing the South Scotia ridge, *Deep-Sea Research II*, 49(21), 4807–4825.
- Schröder, M., and E. Fahrbach (1999), On the structure and the transport of the eastern
  Weddell Gyre, *Deep-Sea Research II*, 46, 501–527.
- <sup>707</sup> Sloyan, B. M., and S. R. Rintoul (2000), Estimates of area-averaged diapycnal fluxes from
   <sup>708</sup> basin-scale budgets, *J. Phys. Oceanogr.*, *30*, 2320–2349.
- <sup>709</sup> Sloyan, B. M., and S. R. Rintoul (2001), The Southern Ocean limb of the global deep
  <sup>710</sup> overturning circulation, J. Phys. Oceanogr., 31, 143–173.

- X 36 JULLION ET AL.: THE WEDDELL GYRE IN THE GOC
- <sup>711</sup> Speer, K. G., and T. Dittmar (2008), Cruise report, RV Revelle, 33rr20080204, *Tech. rep.*,
  <sup>712</sup> Florida State University.
- <sup>713</sup> Speer, K. G., S. R. Rintoul, and B. M. Sloyan (2000), The diabatic Deacon cell, J. of <sup>714</sup> Phys. Oceanogr., 30(12), 3212-3222.
- <sup>715</sup> Sverdrup, H. (1947), Wind-driven currents in a baroclinic ocean; with application to
  <sup>716</sup> the equatorial currents of the eastern Pacific, *Proc. Natl. Acad. Sci.*, 33(11), 318–326,
  <sup>717</sup> doi:10.1073/pnas.33.11.318.
- <sup>718</sup> Suzuki, T., M. Ishii, M. Aoyama, J. R. Christian, K. Enyo, T. Kawano, R. M. Key,
- <sup>719</sup> N. Kosugi, A. Kozyr, L. A. Miller, A. Murata, T. Nakano, T. Ono, T. Saino, K. Sasaki,
- D. Sasano, Y. Takatani, M. Wakita and C. Sabine (2013), PACIFICA Data Synthe-
- sis Project, ORNL/CDIAC-159, NDP-092. Carbon Dioxide Information Analysis Cen-
- *ter*, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee.
- Talley, L.D. (2010), Closure of the global overturning circulation through the Indian,
- Pacific, and Southern Oceans: Schematics and transports., Oceanography, 26(1), 80–
  97.
- Tanhua T, S. van Heuven, R. M. Key, A. Velo, A. Olsen, C. Schirnick (2010), Quality
- control procedures and methods of the CARINA database., Earth Syst. Sci. Data, 2(1),
- <sup>728</sup> 35–49. doi:10.5194/essd-2-35-2010
- Thompson, A. F., and K. J. Heywood (2008), Frontal structure and transport in the
  northwestern Weddell Sea, *Deep-Sea Research I*, 55(10), 1229–1251.
- Thompson, A. F., K. J. Heywood, S. E. Thorpe, A. H. H. Renner, and A. Trasviña
  (2009), Surface Circulation at the Tip of the Antarctic Peninsula from Drifters, J. *Phys. Oceanogr.*, 39(1), 3–26.

#### DRAFT

- Tsubouchi, T., S. Bacon, A. C. Naveira Garabato, Y. Aksenov, S.W. Laxon, E. Fahrbach,
- A. Beszczynska-Möller, E. Hansen, C.M. Lee and R.B. Ingvaldsen, (2012), The Arctic
- Ocean in summer: A quasi-synoptic inverse estimate of boundary fluxes and water mass transformation, J. Geophys. Res., 117(C1), C01,024.
- <sup>738</sup> Wang, Q., S. Danilov, and J. Schröter (2009), Bottom water formation in the southern
- Weddell sea and the influence of submarine ridges: Idealized numerical simulations, Oc.Dyn., 28(1-3), 50-59, doi:10.1016/j.ocemod.2008.08.003.
- <sup>741</sup> Whitworth, T., W. D. Nowlin, A. H. Orsi, R. A. Locarnini, and S. G. Smith (1994),
- Weddell Sea Shelf Water in the Bransfield Strait and Weddell-Scotia Confluence, DeepSea Research I, 41, 629–636.
- Worby, A. P., C. Geiger, M. J. Paget, M. van Woert, S. F. Ackley, and T. DeLiberty
  (2008), Thickness distribution of Antarctic sea ice, J. Geophys. Res., 113, C05S92,
  doi:10.1029/2007JC004254.
- <sup>747</sup> Wunsch, C. (1996), The Ocean inverse circulation inverse problem, *Cambridge University* <sup>748</sup> Press, 442 pp.
- <sup>749</sup> Yaremchuk, M., D. Nechaev, J. Schroter, and E. Fahrbach (1998), A dynamically con-
- <sup>750</sup> sistent analysis of circulation and transports in the southwestern Weddell Sea, Annales
- $_{751}$  Geophysicae, 16(8), 1024-1038.



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.

0 200 400

600 800 1000

2000

3000

SOP



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 9ofhAllE Island for SR4) full-depthApping&rafisport (in SP), 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.

X - 43



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.

DRAFT



Figure 10. Volumetric  $\theta$ -S diagram along the SR4 section only (left) and along the rim of the model box (right). For each  $\theta$ -S bin, the net volume transport is computed. Negative values (in blue) indicate a consumption of a  $\theta$ -S class, and positive values (in red) denote a production of a  $\theta$ -S class. Dashed lines show water mass boundaries as defined in Table 3. The mean volume-transport-weighted  $\theta$ -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 separeted 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 D R A F T mobile sea ice (second term in brackets) components. The hatched region represents the AABW formation processes in the SW box.

	-	Production rate (Sv)		
Source	Method	WSDW	WSBW	AABW
This study	Inverse model	$2\pm 2$	$4\pm 2$	$6\pm 2$
Kerr et al. [2012]	Numerical model			$10.6\pm3.1$
Wang et al. [2009]	Numerical model		2.2	
Huhn et al. [2008]	CFC and noble gas in-		$5.0 \pm 1.2$	
	ventory			
Lumpkin and Speer [2007]	Inverse Model			$5.6\pm3.0$
Klatt et al. [2005]	Geostrophic transport		3	
Foldvik et al. [2004]	DBC transport		$4.3 \pm 1.4$	
Naveira Garabato et al.	Inverse Model	$5.8 \pm 3.0$	$3.9 \pm 0.8$	$9.7 \pm 3.7$
[2002a]				
Orsi et al. [2002]	CFC inventory	4.9		
$Schodlok \ et \ al. \ [2002]$	Numerical model	$6.4 \pm 0.6$		
Sloyan and Rintoul [2001]	Inverse Model			$11 \pm 1$
Harms et al. [2001]	Freshwater budget		2.6	
Fahrbach et al. [2001]	DBC transport		$1.3 \pm 0.4$	
Meredith et al. [2001]	CFC inventory			$3.7\pm1.6$
Orsi et al. [1999]	CFC inventory			4.9
Gordon [1998]	DBC transport		5 - 4	
Mensch et al. [1996]	CFC inventory		11	
Fahrbach et al. [1995]	DBC transport		1.4	
Fahrbach et al. [1994]	DBC transport	2.6	1.2	
Fahrbach et al. [1991]	Geostrophic transport		3 - 4	
Foster and Carmack [1976]	DBC transport		3.6	
Carmack and Foster [1975]	DBC transport		2 - 5	
$Gill \ [\overline{1973}]$	Shelf Water budget		6 - 9	

 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.

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

**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  $\theta$  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).

$\gamma_n$ limits	Layer no.	Error	$\overline{\theta} \pm std(\theta)$	$\overline{S} \pm std(S)$	Water mass
$(kg m^{-3})$	v	(Sv)	(°C)		
Sea surface					
07 70	1	4	$-0.40 \pm 0.72$	$33.947 \pm 0.167$	SW
27.70					
21.10	2	4	$-0.69 \pm 0.89$	$34.385 \pm 0.068$	WW
28.00	_	-	0.000 - 0.000	01.0000.000	
28.00					
22.10	3	3	$-0.18 \pm 0.89$	$34.568 \pm 0.069$	
28.10	4	2	$0.90 \pm 0.91$	$24$ eee $\pm 0.020$	CDW
28.20	4	3	$0.38 \pm 0.31$	$54.000 \pm 0.030$	CDW
20.20	5	2	$0.17 \pm 0.21$	$34.673 \pm 0.020$	
28.27	-				
28.27					
	6	2	$-0.09 \pm 0.07$	$34.668 \pm 0.006$	
28.31	7	0	0.22 1.0.00	$24.661 \pm 0.006$	
28.35	1	Z	$-0.35 \pm 0.08$	$54.001\pm0.000$	WSDW
20.00	8	2	$-0.48 \pm 0.08$	$34.656 \pm 0.004$	WSD W
28.37	_				
	9	2	$-0.59 \pm 0.08$	$34.653 {\pm} 0.004$	
28.40					
28.40	10	1		24 648 1 0 005	WODW
See floor	10	1	$-0.73 \pm 0.06$	$34.048 \pm 0.005$	WSBW
Full-depth	11	1	$-0.14 \pm 0.33$	$34.603 \pm 0.090$	

 Table 4.
 Extra conservation constraints applied to the model.

	11		
	ANDREX/I6S	SR4	ACC
	(1-123)	(124-175)	(82-111)
Full depth vol. trans.	$0 \pm 1$ Sv	$0 \pm 1$ Sv	$0\pm 5$ Sv
Full depth S anom trans.	$0 \pm 1$ Sv	$0 \pm 1$ Sv	$0\pm 5$ 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	Heat	met. water	Sea ice	heat	met. water
	$\mathrm{mSv}$	TW	$\mathrm{mSv}$	mSv	TW	$\mathrm{mSv}$
A priori	$18 \pm 9$	0	$21 \pm 11$	$16\pm 8$	0	$49 \pm 25$
A posteriori	$10 \pm 1$	$26 \pm 18$	$22 \pm 3$	$4\pm1$	$10 \pm 1$	$28 \pm 4$

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

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