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## Direct observations of the ACC transport across the Kerguelen Plateau

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[1] Major pathways and transport of the Antarctic Circumpolar Current (ACC) crossing the Kerguelen Plateau were directly observed during the 2009 Track cruise. The net eastward transport to the south of the Heard/McDonald Islands is estimated as 56 Sv ( $1 \text{ Sv} = 10^6 \text{ m}^3 \text{ s}^{-1}$ ), 43 Sv of which is tightly channelled into the Fawn Trough that appears as a predominant cross-plateau gateway of circumpolar flow associated with the Southern ACC Front (SACCF). There are also two secondary passages, with one (6 Sv) being attached to the nearshore slope just south of the Heard/McDonald Islands and the other (7 Sv) passing through the northern Princess Elizabeth Trough. With an additional 2 Sv inferred just south of the Kerguelen Islands, the transport across the entire plateau amounts to 58 Sv, accounting for  $\sim 40\%$  of the total ACC transport transiting through the region, 147–152 Sv, quantities consistent with other independent estimates in the Indian sector of the Southern Ocean. **Citation:** Park, Y.-H., F. Vivier, F. Roquet, and E. Kestenare (2009), Direct observations of the ACC transport across the Kerguelen Plateau, *Geophys. Res. Lett.*, 36, L18603, doi:10.1029/2009GL039617.

### 1. Introduction

[2] The Kerguelen Plateau is the largest ( $\sim 16^\circ$  in latitude) near-meridional submarine plateau in the Southern Ocean and constitutes a major topographic barrier for the eastward flowing ACC, diverting about two thirds of its total transport to the north of the plateau, with the remaining transport having to pass through the vast area between the Kerguelen Islands and Antarctica [Park *et al.*, 1993]. The Kerguelen-Amsterdam passage has been relatively well documented by the Suzil cruise [Park *et al.*, 1993] as well as by several historical hydrographic sections, yielding a bottom-referenced geostrophic transport of 95–100 Sv to the north of the Kerguelen Islands. By contrast, no systematic high-quality observations have been made to the south, especially across the Fawn Trough, a deep passage ( $< 2760 \text{ m}$ ) separating the Kerguelen Plateau into the northern and southern plateaux. Our knowledge of major flow branches and associated transports to the south of the Kerguelen Islands remains therefore largely indirect and debated, with previous transport estimates ranging from 30 to 100 Sv [Park *et al.*, 1991; Sparrow *et al.*, 1996; McCartney and Donohue, 2007, hereinafter referred to as MD07].

[3] In February–March 2009 we undertook full-depth hydrographic and direct current measurements in the Fawn Trough area during the Track (Transport across the Kerguelen Plateau) cruise on board the R/V Marion Dufresne II. This cruise, which occupied in particular a near-meridional section across the Fawn Trough and repeated the western boundary segment of the WOCE (World Ocean Circulation Experiment) I8S section at  $58^\circ \text{S}$ , has permitted us to estimate the ACC transport across the plateau and resolve the current structure south of the Kerguelen Islands. For a proper interpretation of observations, the frontal pattern of the study area is reviewed in the next section, followed by the analysis of Track data in Section 3 and conclusions in Section 4.

### 2. Circumpolar Fronts Across the Kerguelen Plateau

[4] Based on analyses of historical station data available up to 1990, Orsi *et al.* [1995] (hereinafter referred to as OWN) provided a comprehensive map of the ACC fronts. However, more recent studies utilizing high-quality synoptic hydrography collected in the past decade show a substantial difference in frontal locations compared with OWN. For example, OWN do not show any front passing through the Fawn Trough, while evidence of a concentrated strong flow there has been continuously accumulating [Park and Gambéroni, 1995; Sparrow *et al.*, 1996; MD07; Park *et al.*, 2008b; Roquet *et al.*, 2009]. The Southern Boundary of the ACC (SB) of OWN does not extend northward along the eastern flank of the Kerguelen Plateau but stays south of  $62^\circ \text{S}$  in the Australian-Antarctic Basin. This is in conflict with altimetric and direct observational evidence of a cyclonic subpolar gyre extending northward as far as  $57^\circ \text{S}$  to the east of the Kerguelen Plateau [Park and Gambéroni, 1995; MD07; Aoki *et al.*, 2008].

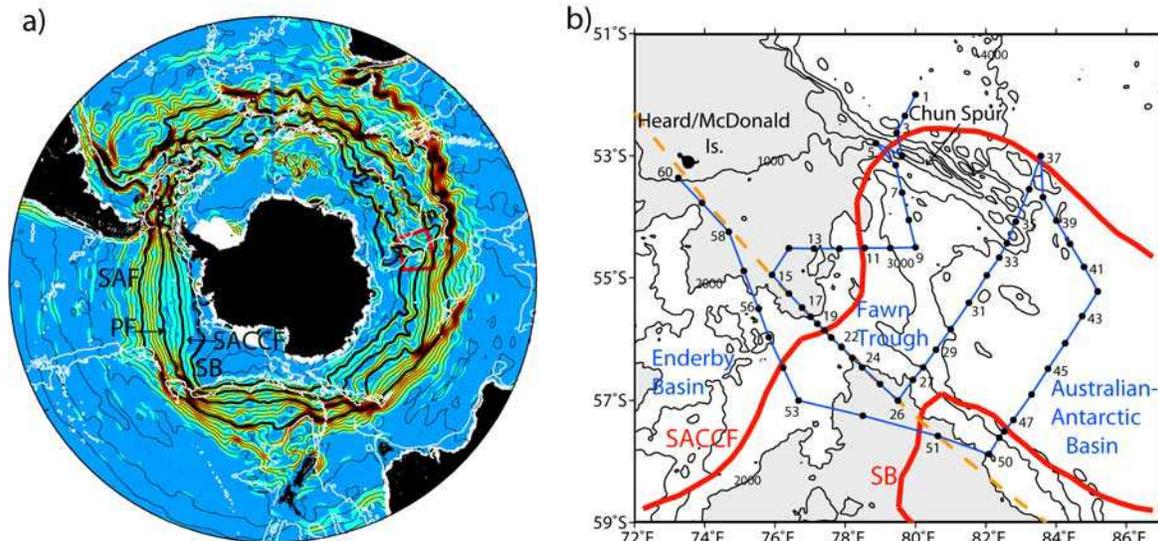
[5] Figure 1a shows the refined circumpolar fronts estimated from the altimetry-derived mean dynamic topography of Rio and Hernandez [2004], which is qualitatively consistent with those derived from float and subsurface buoy observations [Gille, 2003; Niiler *et al.*, 2003]. Streamlines corresponding to four circumpolar fronts were determined as those associated with strong flow closely overlapping with previously well-defined frontal locations by OWN and others in the areas far upstream from the Kerguelen Plateau. The SB, which in our approach corresponds to the southernmost circumpolar streamline passing through the Drake Passage, differs near the Kerguelen Plateau by up to  $6^\circ$  in latitude from that defined by OWN using the property criterion of  $\theta_{\text{max}} = 1.5^\circ \text{C}$ . However, it lies close to their initial (but not finally adopted) definition using the  $0.35 \text{ dyn m}$  dynamic height contour or the southernmost extent of the Upper Circumpolar Deep Water using oxygen data (OWN, Figures 3 and 6).

[6] Our SACCF passes right through the Fawn Trough, corresponding thus to the so-called Fawn Trough Current

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**Figure 1.** (a) Surface streamlines in the Southern Ocean estimated from the mean dynamic height of *Rio and Hernandez* [2004]. Bold streamlines stand for four circumpolar fronts discussed in the text and colour shading represents the relative strength of surface geostrophic currents. The 3000 m isobath (white) and the study area (red) are also indicated. (b) Track cruise map showing the grid of 60 CTDO stations, with two southernmost circumpolar fronts being superimposed. A dotted line is the Jason altimeter ground track #94. Isobaths are every 1000 m and bottom depths <2000 m are shaded.

[MD07; *Park et al.*, 2008b; *Roquet et al.*, 2009], although *Sparrow et al.* [1996] interpret the latter current as the surface expression of the Polar Front (PF). It also differs greatly from OWN who used the property criterion of  $\theta_{\max} = 1.8^{\circ}\text{C}$ , which runs rather closer to our SB. Such a difference in frontal locations among authors is related to the fact that the property value of a given front may not be constant all along its circumpolar path [*Park et al.*, 1993; *Belkin and Gordon*, 1996], implying that a criterion using a constant property value can locally differ significantly from other phenomenological or streamline criteria, especially near the Kerguelen Plateau, as already remarked by OWN.

[7] The refined SB and SACCF are superimposed on the Track cruise map (Figure 1b), which shows a total of 60 conductivity-temperature-depth-oxygen (CTDO) stations. The SB is shown to extend northward up to  $57^{\circ}\text{S}$  over the eastern part of the southern plateau, cutting the southern cruise track. A western section purposely follows the Jason altimeter ground track #94, crossing precisely the Fawn Trough at its narrowest point, almost orthogonally to the SACCF. Encompassing both the SB and SACCF, this section is therefore ideally situated to capture the ACC transport across the plateau, while the Deep Western Boundary Current (DWBC) originating from Antarctic coasts (MD07) can be detected by the south(east)ern section that is the repeat WOCE I8S section segment. A lowered acoustic Doppler current profiler (LADCP) recorded currents throughout the whole water column, in addition to measurements of surface-layer currents by a 75 kHz shipborne ADCP (SADCP).

### 3. Results

#### 3.1. Temperature and Velocity Fields in the Surface and Bottom Layers

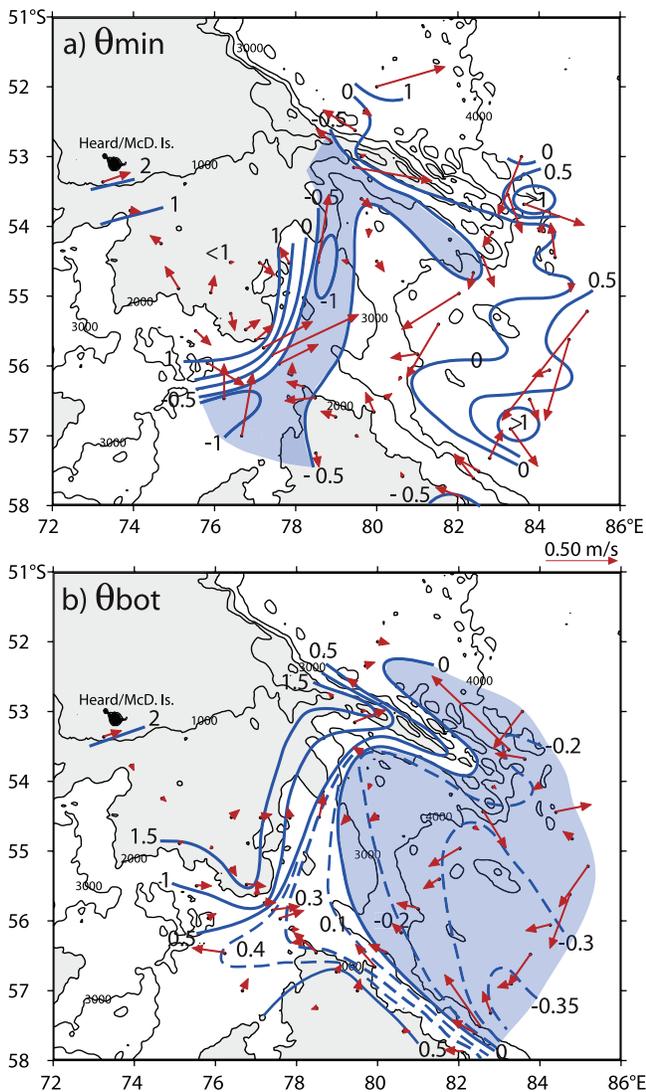
[8] The large-scale surface circulation pattern of the study area is depicted in Figure 2a, which maps the

temperature of the subsurface temperature minimum (or Winter Water) (observed at depths ranging from 60 to 290 m) together with the superimposed LADCP-derived surface layer-mean (0–300 m) velocity vectors. The eastward flow from the Enderby Basin is strongly channelled through the Fawn Trough before bending north towards the Chun Spur's northwestern junction, in good agreement with *Roquet et al.* [2009]. Most remarkable is the presence of a narrow band of very cold water ( $<-0.5^{\circ}\text{C}$ ) along the SACCF, which advects northward through the Fawn Trough the coldest Winter Water originating from the southeastern Enderby Basin [*Roquet et al.*, 2009], confirming the origin of the subsurface cold water tongue observed along the eastern flank of the northern Kerguelen Plateau [*Park et al.*, 2008b].

[9] Bottom temperatures and associated velocity vectors (Figure 2b) reveal a cyclonic circulation pattern within the semi-enclosed basin between the Kerguelen Plateau and Chun Spur. The DWBC is also seen entering the area near  $57^{\circ}30'\text{S}$ ,  $82^{\circ}30'\text{E}$  as a concentrated northwestward flow attached to the steep escarpment of the southern Kerguelen Plateau. The AABW, as defined by temperatures  $<0^{\circ}\text{C}$ , does not cross the Kerguelen Plateau through the Fawn Trough ( $\theta_{\text{bot}} > 0.26^{\circ}\text{C}$ ) but comes solely from the south alongside the northwestward flowing DWBC ( $\theta_{\text{bot}} > -0.36^{\circ}\text{C}$ ). The AABW fills the deep basin at depths  $>3000\text{ m}$  and reaches as far north as  $53^{\circ}30'\text{S}$  before turning back to the south along the western flank of the Chun Spur. Part of the AABW rounds the spur to flow northwestward along its eastern flank, consistent with the deep-layer transport schematic of MD07.

#### 3.2. Transport Estimates of the ACC and DWBC

[10] Vertical profiles of cross-track LADCP velocities and corresponding transport across the western (Sts. 60–58, 15–26, 51–50) and southern (Sts. 50–42) sections are shown in Figure 3. In the western section (Figure 3a) most



**Figure 2.** Temperature distribution at (a) the subsurface temperature minimum depth and (b) the bottom. Superimposed are the LADCP velocities averaged in the 0–300 m layer for Figure 2a and in the 100 m-thick layer above the bottom for Figure 2b. Areas with temperatures  $< -0.5^\circ\text{C}$  and  $< 0^\circ\text{C}$  are shaded in light blue respectively in Figures 2a and 2b.

of the eastward flow is tightly concentrated in the Fawn Trough, with the strongest surface flow of  $0.6\text{ m s}^{-1}$  being found at the deepest site (St. 20, 2760 m). Here, we also observe the strongest vertical shear with a velocity decreasing to  $0.3\text{ m s}^{-1}$  at 1000 m, below which the velocity is nearly constant reaching  $>0.2\text{ m s}^{-1}$  at 2000 m, indicating that both the baroclinic and barotropic components of current are equally important. A secondary eastward flow branch with a depth-averaged velocity on the order of  $0.2\text{ m s}^{-1}$  is observed on the nearshore slope just south of the Heard/McDonald Islands (Sts. 59–60). The net transport across this 750 km-long western section amounts to 50 Sv northeastward, 43 Sv of which are concentrated at the SACCF passing through the Fawn Trough, mostly within

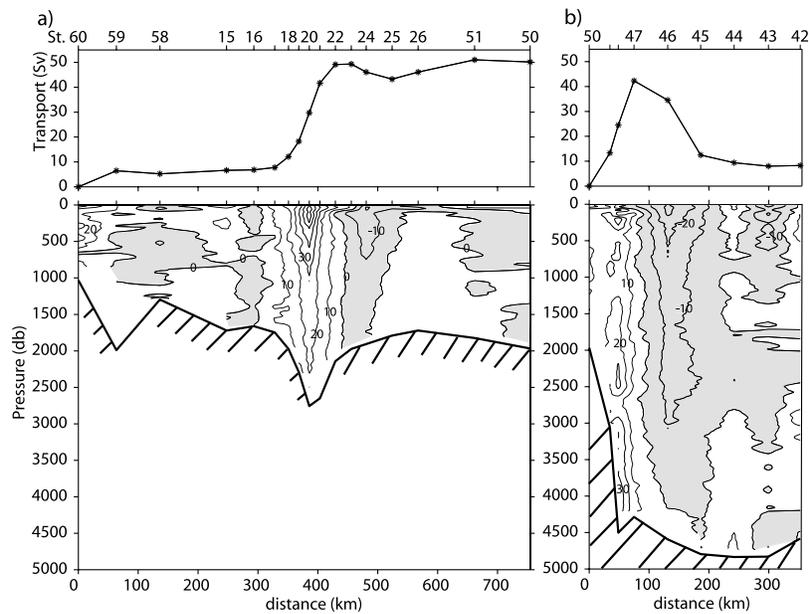
a distance of 100 km between Sts. 17 and 22, and 6 Sv immediately south of the Heard/McDonald Islands.

[11] In the southern section (Figure 3b) the northwestward flowing DWBC is highly barotropic and mostly confined within a narrow ( $\sim 75\text{ km}$ ) continental slope (Sts. 50–47). It is also characterized by a bottom-intensified flow, with the highest velocity  $>0.3\text{ m s}^{-1}$  being found at the bottom at St. 48. With inclusion of a net transport of 1 Sv between Sts. 23 and 50 together with 42 Sv at Sts. 50–47, the total northward transport of the DWBC amounts to 43 Sv, a value somewhat smaller than 48 Sv estimated by MD07 from the 1994/5 WOCE I8S data. Regarding the origin of the DWBC, MD07 remarked that deep and bottom waters with temperatures  $>0.1^\circ\text{C}$  come from the Weddell-Enderby Basin via the northern Princess Elizabeth Trough, while those with temperatures  $<0.1^\circ\text{C}$  represent the northward turning branch from the westward flowing Antarctic Slope Current. In our data the bottom boundary between these two sources (or  $0.1^\circ\text{C}$  bottom isotherm) runs midway between Sts. 50 ( $0.39^\circ\text{C}$ ) and 49 ( $-0.22^\circ\text{C}$ ) (see Figure 2b), which enables us to attribute  $\sim 7\text{ Sv}$  (half transport between Sts. 50 and 49 plus 1 Sv between Sts. 23 and 50) to the contribution from the southernmost ACC branch passing through the northern Princess Elizabeth Trough. This leaves most of the DWBC transport, 36 Sv, being attributable to the contribution from the northward turning of the Antarctic Slope Current along the western limb of the cyclonic subpolar gyre. Further offshore, the DWBC is largely compensated by a poleward transport of 34 Sv that is mostly confined within a width of 100 km centered at St. 46. Aoki *et al.* [2008] described a similar flow pattern, although their transport values are much greater than ours.

[12] Finally, the reliability of our LADCP velocities has been checked in comparison with independent data from the SADC to obtain a small mean difference of  $-0.20 \pm 3.6\text{ cm s}^{-1}$  between LADCP and on-station SADC cross-track velocities averaged over the 24–264 m depth for the western and southern sections. Uncorrected barotropic tidal currents of amplitudes of  $3\text{--}5\text{ cm s}^{-1}$  [MD07; Park *et al.*, 2008b] may yield a tidal cycle-averaged rms error on the order of  $3\text{ cm s}^{-1}$ , which should by far dominate the depth-averaged LADCP instrument error of  $1.0\text{ cm s}^{-1}$  [Hacker *et al.*, 1996], and may thus be considered as a representative barotropic velocity error of our LADCP data. By multiplying this velocity error by a sectional surface for those areas with significant cross-track velocities, we roughly estimate a transport error of 6–7 Sv for the Fawn Trough and DWBC areas where the transport estimate is 42–43 Sv, suggesting a relative error of  $\sim 15\%$  in our transport estimation.

#### 4. Conclusions

[13] The Track cruise has provided us with high-quality hydrographic and direct current measurement data in the Fawn Trough area, with its western and southern sections having been adequately located to capture the quasi-totality of the ACC transport crossing the entire Kerguelen Plateau. The main results are synthesized in Figure 4 and Table 1 summarises our transport estimates in comparison with previous work.

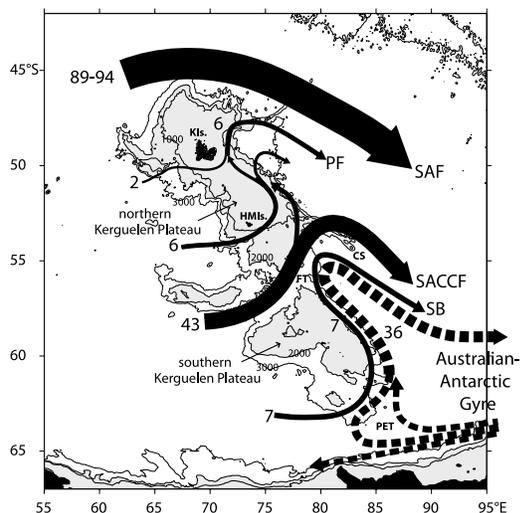


**Figure 3.** Vertical profiles of cross-track LADCP velocities (in  $\text{cm s}^{-1}$ ) and cumulative top-to-bottom transport (in Sv) in the (a) western and (b) southern sections discussed in the text. Positive (negative: shaded) velocities stand for the NE (SW) component in Figure 3a and the NW (SE) component in Figure 3b.

[14] The net eastward transport to the south of the Heard/McDonald Islands amounts to 56 Sv, which is composed of 43 Sv associated with the SACCF passing through the Fawn Trough, 6 Sv attached to the nearshore slope just south of the Heard/McDonald Islands, and 7 Sv at the western end of the DWBC flowing northwestward along the eastern flank of the southern Kerguelen Plateau. The latter 7 Sv, which

being a minor component of the DWBC carrying 43 Sv, is most likely to be originated from the eastward flow branch associated with the SB through the northern Princess Elizabeth Trough, while its major component (36 Sv) comes from the northward turning of the Antarctic Slope Current along the western limb of the cyclonic subpolar gyre.

[15] The PF just south of the Kerguelen Islands was not directly observed during the cruise, but we infer  $\sim 2$  Sv eastward over the steep nearshore slope with depths  $< 600$  m, assuming a depth-averaged velocity of  $0.2 \text{ m s}^{-1}$  and a current width of 30 km, as estimated from *Park et al.* [2008a]. We suggest therefore 58 Sv as the total eastward transport across the entire Kerguelen Plateau. According to *Park et al.* [1993], the ACC main branch associated with the Subantarctic Front (SAF) north of the plateau should carry 89–94 Sv out of the total 95–100 Sv estimated to the north of the Kerguelen Islands because  $\sim 6$  Sv is attributed to the northward flowing PF just east of the islands, where all streamlines over the shallow plateau south of the islands strongly converge [*Park et al.*, 2008a]. These transports estimated to both the north and south of the PF sum up to 147–152 Sv as the total ACC transport at the Kerguelen longitude, consistent with independent estimates of  $147 \pm 10$  Sv at  $140^\circ \text{E}$  [*Rintoul and Sokolov*, 2001] and 153 Sv south of South Africa [*Gladyshev et al.*, 2008]. Note that these ACC transport estimates in the Indian sector of the Southern Ocean are also consistent with the Drake Passage transport of  $137 \pm 8$  Sv [*Cunningham et al.*, 2003] augmented by 10–15 Sv of the Indonesian Throughflow.



**Figure 4.** Schematic of major pathways and transports (in Sv) of the ACC system (bold continuous lines) and DWBC of the Australian-Antarctic Gyre in the Kerguelen Plateau area based on the synthesis of our major findings and previous work discussed in the text. Topographic features are KIs, Kerguelen Islands; HMIs, Heard/McDonald Islands; FT, Fawn Trough; CS, Chun Spur; PET, Princess Elizabeth Trough.

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**Table 1.** Transports (in Sv) of the ACC System and DWBC in the Kerguelen Plateau Area

	This Study	Park et al. [1991, 1993]	MD07	Sparrow et al. [1996]	Aoki et al. [2008]
SAF N of Kerguelen Is.	89–94	95–100 <sup>a</sup>	143		
PF S of Kerguelen Is.	2				
S of Heard/McD. Is.	6				
SACCF-Fawn Trough	43	30	38	65	
SB-P. Elizabeth Trough	7		21	35	
DWBC at 58°S	43		48		69

<sup>a</sup>6 Sv at the PF just east of the Kerguelen Is. is included.

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