Observations of the Fawn Trough Current over the Kerguelen Plateau from instrumented elephant seals

Fabien Roquet⁎, Young-Hyang Park⁎a, Christophe Guinetb, Frédéric Bailleulb, Jean-Benoît Charrassina

⁎ USM 402/LOCEAN, Département Milieux et Peuplements Aquatiques, Muséum National d’Histoire Naturelle, 43 rue Cuvier, 75231 Paris Cedex 5, France

a Centre d’Études Biologiques de Chizé, Centre National de la Recherche Scientifique, 79360 Villiers en Bois, France

A R T I C L E   I N F O

Article history:
Received 29 September 2006
Received in revised form 29 May 2008
Accepted 14 November 2008
Available online 20 February 2009

Keywords:
Fawn Trough Current
Ocean circulation
Oceanic fronts
Southern Ocean
Bio-logging
Elephant seals

A B S T R A C T

Due to its great meridional extent and relatively shallow depths, the Kerguelen Plateau constitutes a major barrier to the eastward flowing Antarctic Circumpolar Current in the Indian sector of the Southern Ocean. While most of the Antarctic Circumpolar Current transport is deflected north of the Kerguelen Islands, the remainder (~50 Sv; 1 Sv = 10⁶ m³ s⁻¹) must pass south of the islands, most probably through the Fawn and Princess Elizabeth troughs. However, the paucity of finely resolved quasi-synoptic hydrographic data in this remote and infrequently sampled area has limited the progress in our knowledge of the regional circulation. Since 2004, a new approach using elephant seals from the Kerguelen Islands as autonomous oceanographic profilers has provided new information on the hydrography over the Kerguelen Plateau, covering the entire Antarctic Zone between the Polar Front and Antarctica, with a mean along-track resolution of about 25 km. These newly resolved bio-logged data revealed details of a strong northeastward current found across the Fawn Trough (sill depth: 2600 m; 56°S, 78°E). This so-called Fawn Trough Current transports cold Antarctic waters found south of the Elan Bank, between the Ice Limit (58°S) and the Antarctic Divergence (64°S) in the eastern Enderby Basin, toward the Australian–Antarctic Basin. Our analysis also demonstrates that the Deep Western Boundary Current, which carries cold Antarctic water along the eastern flank of the southern Kerguelen Plateau collides with Fawn Trough Current at the outlet of the Fawn Trough sill. In other words, the Fawn Trough constitutes a veritable bottleneck, channelling the quasi-totality of the Antarctic Circumpolar flow found south of the Polar Front. Thanks to the unprecedented fine resolution of seal-borne data, a branch of flow centered at the Winter Water isotherm of 1 °C is also revealed along the northern escarpment of the Elan Bank, and then along the southern edge of Heard Island. Further analysis of different supplementary data reveals a complex circulation pattern in the entire Enderby Basin, with several distinctive branches of flow being strongly controlled by prominent topographic features such as the Southwest Indian Ridge, Conrad Rise, Elan Bank, and Kerguelen Plateau. This newly emergent frontal structure refines considerably previous large-scale circulation schematics of the area.

© 2009 Elsevier B.V. All rights reserved.

1. Introduction

The strong effect of bottom topography on the circulation is a conspicuous feature of the Southern Ocean dynamics, which is related to the weak stratification of this high-latitude ocean (e.g. Olbers et al., 2004). Located in the Indian sector of the Southern Ocean, the Kerguelen Plateau is a shallow submarine plateau of great meridional extent (~16° between 46°S and 62°S) surrounded by deep basins (Fig. 1). This plateau forms a natural barrier to the Antarctic Circumpolar Current (ACC), forcing the core of the ACC to pass along its northern escarpment (e.g. Park et al., 1993). Two deep passages allow a substantial inter-basin exchange of Antarctic water masses in between the ACC core and Antarctica, namely the Fawn and Princess Elizabeth troughs. The Fawn Trough (sill depth: 2600 m; 56°S, 78°E) splits the plateau into two parts, hereafter designated as the northern Kerguelen Plateau (46°S–56°S), and the southern Kerguelen Plateau (57°S–62°S). The 2000 m isobath helps to distinguish the two parts (Fig. 1). The Princess Elizabeth Trough (sill depth: 3600 m; 64°S, 84°E) stands between the Kerguelen Plateau and Antarctica. We note that the northern Kerguelen Plateau, which includes the Kerguelen Islands (49°S, 70°E) and the Heard Islands (53°S, 74°E), is much shallower than the southern Kerguelen Plateau.

The presence of the Kerguelen Plateau in the Southern Ocean raises two major dynamic issues. The first one concerns the associated frontal structure, i.e., how the ACC negotiates the prominent bottom topography of the plateau. The existence of intense deep-reaching thermohaline fronts structuring the ACC has long been recognized. Climatological studies have demonstrated the circumpolar nature of the major ACC-related fronts, namely the Subantarctic Front, Polar Front, and Southern ACC Front (Orsi et al., 1995). These fronts interact strongly with the Kerguelen Plateau, which constrains their pathways,
transport, and hydrographic characteristics (Park et al., 1991, 1993; Orsi et al., 1995; Belkin and Gordon, 1996; Sparrow et al., 1996; Park et al., 1998a). Moreover, the meridional extent of the Antarctic Zone between the Polar Front and the Southern Boundary of the ACC (Orsi et al., 1995) is largest in this sector of the Southern Ocean (>15° in latitude compared to several degrees in other sectors), covering the entire Kerguelen Plateau (Fig. 2). As these circumpolar fronts are generally thought to constitute the major streams of the ACC, this figure could give a misleading impression that no significant amount of ACC flow crosses the Kerguelen Plateau, which is in contradiction

Fig. 1. Trajectories of the 8 instrumented elephant seals from Kerguelen Islands in March 2004 (bold lines). The shaded bathymetry is shown at 1, 2, 3 and 4 km contours. Major topographic features are indicated: the Del Cano Rise (DCR), Crozet Plateau (CP), Conrad Rise (CR), Elan Bank (EB), northern Kerguelen Plateau (NKP), southern Kerguelen Plateau (SKP), Fawn Trough (FT), and Princess Elizabeth Trough (PET).

Fig. 2. Circumpolar distribution of the Subtropical Front (STF), Subantarctic Front (SAF), Polar Front (PF), Southern ACC Front (SACCF), and Southern Boundary of the ACC (SB) adapted from Orsi et al. (1995).
with several previous works (Park et al., 1991; Park and Gambéroni, 1995; Sparrow et al., 1996; Park et al., 1998a; Sultan et al., 2007; Park et al., 2008a) showing evidence of a strong flow through the Fawnpassage. The second issue concerns the role of the Kerguelen Plateau in the meridional circulation. Indeed, as a prominent topographic barrier to the ACC, the Kerguelen Plateau supports the formation of concentrated meridional flows such as the Deep Western Boundary Current (DWBC) evidenced along the eastern escarpment of the southern Kerguelen Plateau (Speer and Forbes, 1994; Dononhue et al., 1999; McCartney and Dononhue, 2007; Aoki et al., 2008). These authors showed that this DWBC carries equatorward the Antarctic Bottom Water coming from the Antarctic coast of the Australian–Antarctic Basin. A similar DWBC, although likely weaker, has recently been identified along the eastern escarpment of the northern Kerguelen Plateau, carrying northward cold Antarctic waters of Enderby Basin (Speer and Forbes, 1994; Donohue et al., 1999; McCartney and Dononhue, 2007; Aoki et al., 2008). These authors described the hydrography and circulation over the Kerguelen Plateau. Particular attention was paid to the Fawnpassage area and associated frontal structure and currents, because this area is most efficiently covered by animal-borne CTD sections with a nominal along-section resolution of 25 km. These finely resolved data cut near perpendicularly across different fronts associated with concentrated flow, enabling the better definition of the circulation of the area.

2. Data

2.1. Elephant seal dataset

Since 2004, a number of southern elephant seals have been equipped with a Satellite Relayed Data Logger (SRDL, Fig. 3) which integrates a miniaturized CTD unit manufactured by Valeport Ltd, UK. The CTD unit is composed of a platinum temperature sensor (time lag: 0.7 s), an inductive conductivity sensor, and a pressure sensor. Assembled by the Sea Mammal Research Unit (SMRU, University of St Andrews, Scotland), SRDLs are capable of collecting, compressing and storing oceanographic and behavioural data before transmitting a data summary via the Argos satellite system in near real-time (Fedak, 2004). Locations are provided by Argos satellite triangulation during transmissions.

In March 2004, 8 instrumented elephant seals moved rapidly toward the Antarctic shelf after leaving the Kerguelen colony at the end of their moult period. The remarkable fan-shaped distribution of these quasi-simultaneous trajectories (Fig. 1) provided us with a unique opportunity to construct a synoptic view of the March 2004 conditions over the entire Kerguelen Plateau. Relevant statistics on the 8 animal-borne SRDLs are summarized in Table 1. Most elephant seals travelled from the Kerguelen Islands to the Antarctic continent (~2000 km) at a mean speed of 100 km/day, transmitting 3 to 4 profiles/day. SRDL #6 had no salinity data because it was an older

<table>
<thead>
<tr>
<th>Number of temperature profiles</th>
<th>Number of salinity profiles</th>
<th>Starting date</th>
<th>Duration (days)</th>
<th>Maximum depth (m)</th>
<th>Mean depth (m)</th>
<th>Mean number of profiles/100 km</th>
<th>Mean number of profiles/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>82</td>
<td>71</td>
<td>2 Mar</td>
<td>23</td>
<td>880</td>
<td>587</td>
<td>4.0</td>
</tr>
<tr>
<td>#2</td>
<td>64</td>
<td>59</td>
<td>20 Feb</td>
<td>19</td>
<td>840</td>
<td>446</td>
<td>3.3</td>
</tr>
<tr>
<td>#3</td>
<td>79</td>
<td>70</td>
<td>8 Mar</td>
<td>24</td>
<td>910</td>
<td>552</td>
<td>4.3</td>
</tr>
<tr>
<td>#4</td>
<td>67</td>
<td>56</td>
<td>7 Mar</td>
<td>20</td>
<td>1090</td>
<td>618</td>
<td>4.3</td>
</tr>
<tr>
<td>#5</td>
<td>77</td>
<td>70</td>
<td>1 Mar</td>
<td>22</td>
<td>780</td>
<td>491</td>
<td>4.0</td>
</tr>
<tr>
<td>#6</td>
<td>130</td>
<td>0</td>
<td>4 Mar</td>
<td>35</td>
<td>830</td>
<td>541</td>
<td>6.1</td>
</tr>
<tr>
<td>#7</td>
<td>77</td>
<td>68</td>
<td>3 Mar</td>
<td>24</td>
<td>1400</td>
<td>757</td>
<td>3.6</td>
</tr>
<tr>
<td>#8</td>
<td>77</td>
<td>0</td>
<td>28 Feb</td>
<td>22</td>
<td>930</td>
<td>556</td>
<td>3.5</td>
</tr>
<tr>
<td>Mean</td>
<td>82</td>
<td>66</td>
<td>4 Mar</td>
<td>22 ± 2</td>
<td>950 ± 200</td>
<td>574 ± 93</td>
<td>4.1 ± 0.9</td>
</tr>
</tbody>
</table>

Table 1
Statistics on the 8 elephant seal sections used in the present study.
generation without the conductivity sensor. SRDL #8 had a conductivity sensor failure, so no salinity data are reported here. Seals dived up to 1400 m (SRDL #7) but most frequently to a depth of 300 to 600 m. This dataset provided unprecedented finely-resolved hydrographic sections (every 25 km along the trajectories, on average), enabling us to map the detailed frontal structure and currents in the region, especially those associated with the Fawn Trough.

Due to several important transmission constraints such as the limited time spent at the surface by animals, the allocated Argos bandwidth was not sufficient to transmit the whole logged dataset. Only 3 to 4 compressed profiles could be transmitted daily, although elephant seals perform more than 60 dives/day. A data compression method termed “broken stick” was applied on logged profiles, which consisted of selecting the 12 most important inflection points in the temperature and conductivity profiles. This method effectively ensured the acquisition of 12 data points/temperature profile, while the resolution of salinity profiles was variable (7 to 12 data points/profile). A detailed description of the micro-controller programming, including the compression algorithm, can be found in Lydersen et al. (2002).

To assess the quality of the miniaturized CTD data, calibrations/validations were performed both in the laboratory and at sea, which will be reported elsewhere (Roquet et al., in preparation). Only the at-sea tests are summarized below. Before the deployment on elephant seals in March 2004, SRDLs were attached to a standard pre-calibrated CTD (SBE 911plus) on board the R/V Marion Dufresne, and the ensemble was lowered to a depth of 1500 m at two different sites in the Kerguelen area. Based on these tests, a data correction procedure was established, which consisted of a linear pressure correction and a quadratic temperature correction. This correction was applied afterwards to the transmitted animal-borne pressure and temperature data. After the correction, the final data error was estimated at 2 dbar for pressure and 0.03 °C for temperature. Pressure-dependent offsets were also detected in the conductivity measurements but they could not be directly corrected from at-sea tests because the offset profiles were quite different at the two test sites, in contrast to the very consistent offset profiles for temperature.

To reduce the salinity biases induced by the conductivity offsets, an a posteriori correction procedure was applied on salinity data based on comparisons with historical hydrographic data, which is now described. First, the salinity profiles were calculated with corrected pressures, temperatures, and raw conductivities. These salinity profiles along each SRDL section were then compared with the World Ocean Atlas 2005 (WOA05, Antonov et al., 2006) climatology. For this, we interpolated linearly the WOA05 profiles at every data point along each SRDL section. We limited our comparisons to the deep layer where climatological salinities are greater than 34.6 psu (corresponding to the Circumpolar Deep Water layer) because the seasonal and interannual variability of salinity is expected to be weakest there, as compared to the near surface layer. The ensemble mean of salinity differences between the two datasets (SRDL and WOA05) were considered as the systematic bias of SRDL. Finally, the correction of the latter bias was applied to the raw salinity profiles. This correction procedure was repeated separately for each SRDL. The corrected salinities in the above-mentioned deep layer show an ensemble-mean standard deviation of 0.025 psu relative to the climatology, which we attribute primarily to measurement errors. We recognize that our simple method of salinity correction may not be ideal and one might wonder why we do not use the stable potential temperature–salinity (T–S) relationships of deep waters to compare SRDLs and historical profiles, as for example in Böhme and Send (2005) for Argo float salinities. Unfortunately, this latter method was found to be inadequate in our study area because deep water temperature is almost homogeneous there and the associated T–S curves are nearly horizontal, rendering the T–S relationships highly ill-defined.

2.2. Other supplementary datasets

We used the Combined Mean Dynamic Topography (CMDT) of Rio and Hernandez (2004) (available at www.jason.oceanobs.com) as a reference to describe the circulation in the Enderby Basin and over the Kerguelen Plateau and validate seal-derived results (see Sections 5 and 6). Briefly, this dynamic topography was obtained as follows. A first guess was estimated in combining a geoid model with the altimetric mean sea surface and the Levitus climatology. This first guess was then improved by synthesizing all available in situ data (hydrographic and drifter) using an inverse method. The CMDT has a spatial resolution of 0.5° latitude ×1° longitude, which may be considered as the best currently available solution because of its optimal synthesis of all available information.

In order to characterize different fronts within the whole Enderby Basin, we also used an updated hydrographic database made available by the French oceanographic data centre SISMER/IFREMER (Systèmes d’Informations Scientifiques pour la Mer/Institut Français de Recherche pour l’Exploitation de la Mer, Brest, see www.ifremer.fr/sismer/). This database includes quality-controlled temperature profiles from historical bottles and CTD data, supplemented with recent Argo and expandable bathythermograph (XBT) profiles.

Since mid-2002, the Advanced Microwave Scanning Radiometer for the Earth Observing System (AMSR-E) provides sea surface temperature (SST) data with twice-daily temporal resolution on a 0.25° ×0.25° grid. This satellite sensor has the most valuable ability to provide SST measurements regardless of the cloud cover, which is critical in the Southern Ocean (Dong et al., 2006). Five years (June 2002–June 2007) of weekly SST data from version-4 AMSR-E ocean products (available at http://www.ssmi.com) are used in this study.

3. Hydrographic background

Before presenting and interpreting our results, we briefly review the present knowledge on fronts and water masses of the study area, namely the Antarctic Zone between the Polar Front and the Southern Boundary of the ACC (hereafter referred to as the Southern Boundary for brevity).

3.1. Water masses definitions in the Antarctic Zone

The Antarctic Surface Water in the austral summer is characterized by a subsurface temperature minimum (T-min) layer or Winter Water (WW) that is the remnant of the previous winter mixed layer capped by seasonal warming and freshening within the surface mixed layer (SML) (Toole, 1981; Park et al., 1998a,b). Once formed at the end of the 380 F. Roquet et al. / Journal of Marine Systems 78 (2009) 377–393
Austral winter, the WW is continuously altered by vertical mixing processes across the boundaries with the UCDW below and the SML above. Therefore, it is difficult to determine precisely the previous winter mixed layer conditions from summer sections, and the WW depth defined here somewhat underestimates its real depth. As argued by Park et al. (1998a), the previous winter conditions are best conserved at the T-min core. However, in some cases such as close to the Antarctic Divergence where the WW is shallowest and upwelling is most intense, the WW properties can depart significantly from the previous winter conditions, especially for temperature (Lutjeharms, 1985; Park et al., 1998a). Advection can also significantly distort the WW property distribution (Toole, 1981).

To characterize the UCDW, we used the T-max layer. Due to the limited depth range of elephant seal profiles, the T-max layer is found mostly in the southern half of our study area.

### 3.2. Circumpolar fronts in the Antarctic Zone

Pollard et al. (2002) remarked that the real circumpolar features in the ACC are not the frontal jets associated with large transports, but rather the latitudinal changes in structure induced by the changing contributions of temperature and salinity to the stratification. In particular, the Antarctic Zone is characterized by a salinity control of stratification permitting the existence of the deep T-max in UCDW found between the Polar Front and the Southern Boundary. We want to make clear that Antarctic fronts, which are basically defined as sharp horizontal changes in temperature and/or salinity properties, are not necessarily associated with concentrated currents. Indeed, temperature and salinity changes across a front are sometimes compensated in density, without yielding associated strong geostrophic currents. Therefore, although fronts and currents are often observed together, they are not necessarily always so.

The Polar Front is generally characterized by the northernmost position of the subsurface T-min colder than 2 °C (Rotnikov, 1963; Park et al., 1991, 1993; Orsi et al., 1995; Belkin and Gordon, 1996; Park and Gambéroni, 1997; Park et al., 1998a, 2001; Pollard and Read, 2001; Pollard et al., 2002). However, there appear important latitudinal discrepancies among different front locations proposed in the literature in our study area, particularly over the Kerguelen Plateau (Fig. 4). Indeed, several authors placed it to the north of the Kerguelen Islands, crossing the shallowest plateau (depth ~200 m) (Orsi et al., 1995; Sparrow et al., 1996) or running along the northern flank of the Kerguelen Plateau (Belkin and Gordon, 1996). In Park et al. (1998a), the Polar Front passes immediately south of the islands and bends northward to their east, hugging the inner part of the continental slope between the 200 m and 500 m isobaths. The southernmost location is proposed by Moore et al. (1999) who used maxima in satellite SST gradients to localize the Polar Front. The clearest surface manifestation of the Polar Front around the Kerguelen Islands may be the chlorophyll-poor tongue developed consistently in the Austral summer along the inner continental slope just south and east of the islands, cutting the chlorophyll-rich area over the northern Kerguelen Plateau into two parts (Park et al., 2002; Charrassin et al., 2004; Park et al., 2008a), consistent with the Polar Front location proposed by Park et al. (1998a). Recently, Park et al. (2008b) confirmed the existence of a strong northward current along the inner continental slope east of the Kerguelen Islands (depth-mean velocities up to 25 cm s⁻¹) from a systematic analysis of fishing gear drifts between setting and recovery positions of demersal longlines deployed in recent years. They also found a weaker current along the northern flank of the Kerguelen Plateau. However, this current appears as a secondary branch and may correspond to the Polar Front of Belkin and Gordon (1996), which they defined as the northernmost position of the subsurface T-min of 2.5 °C in the Kerguelen Plateau area (A. V. Romanov, personal communication, 2008). In the following, we will implicitly refer to the main branch characterized by the classical definition of the 2 °C T-min when referring to the Polar Front. Further supporting evidence for the Polar Front’s location will be provided from the altimetry-derived mean dynamic topography of Rio and Hernandez (2004) as well from a WW temperature climatology and satellite SST data (see Sections 5 and 6).

The Southern Boundary is defined as the southern terminus of UCDW, characterized by a sharp gradient in the T-max layer around the 1.5 °C isotherm (Orsi et al., 1995; Sokolov and Rintoul, 2002). It is
found around 65°S in the eastern Enderby Basin, and shifts north during its crossing of the Princess Elizabeth Trough to reach 62°–63°S in the western Australian–Antarctic Basin (Orsi et al., 1995; Heywood et al., 1999) (Fig. 4). In our study area, it is frequently found close to the Antarctic Divergence (Park et al., 1998a; Heil and Allison, 1999). Heil and Allison (1999) defined the Antarctic Divergence as the transition zone from eastward sea ice drift in the north to westward drift close to Antarctica, while Park et al. (1998a) characterized it by the summit of an asymmetric dome-like structure of property isolines in meridional hydrographic sections. Both definitions are implicitly related to the poleward change in mean surface winds from westerly to easterly, which should correspond to a surface divergence of the Ekman transport and thus to a compensating upwelling of deep waters. For this reason, the Antarctic Divergence can also be identified at the shallowest WW location where the upwelling is expected to be strongest. We emphasize that both the Antarctic Divergence and Southern Boundary may not be considered as “genuine” fronts in the sense that they are not necessarily associated with frontal jets, but rather as boundaries separating two distinct current regimes. For example, the Southern Boundary in the western Enderby Basin west of 50°E may correspond to the boundary between the Weddell Gyre and the ACC (Park et al., 2001).

The Southern ACC Front is generally identified by the 1.8 °C isotherm in the T-max (Orsi et al., 1995). It is found in close proximity to the Southern Boundary across the Princess Elizabeth Trough (80°–85°E), or the Antarctic Divergence in the eastern Enderby Basin between 65°E and 80°E (Fig. 4). In the western side of the Enderby Basin, the Southern ACC Front reveals a remarkable southward shift on crossing the SouthWest Indian Ridge, and it continues to bend south across the breadth of the basin, albeit gradually, from 56°S at 30°E just downstream of the ridge to its southernmost position of 64°S at 80°E in the Princess Elizabeth Trough. Then, the front bends steeply to the north along the eastern flank of the southern Kerguelen Plateau, forming the shallow part of the DWBC (Speer and Forbes, 1994; McCartney and Donohue, 2007; Aoki et al., 2008).

3.3. Other regional fronts in the Enderby Basin

Using the hydrographic climatology HASO (Olbers et al., 1992) and the FRAM model (Webb et al., 1991), Sparrow et al. (1996) showed the existence of a strong current in the Fawn Trough. They noted that this current was associated with an enhanced lateral gradient of the subsurface T-min which developed across the 0 °C isotherm. This was confirmed by Holliday and Read (1998) who analysed three XBT and thermosalinograph sections at the entrance to the Fawn Trough. These latter authors further noted that the current is also associated with the enhanced gradient of surface properties as well as that of the T-max across the 2 °C isotherm. Sparrow et al. (1996) proposed that the current crossing the Fawn Trough would be a southern branch of the Polar Front bifurcating from the northern flank of the Conrad Rise (40°E, 50°S), which they called the surface expression of the Polar Front (Fig. 4).

In a contrasting schematic, the northernmost boundary of seasonal sea ice, namely the Antarctic Ice Boundary by Klyasov (1993) or the Ice Limit by Park et al. (1998a), would constitute the main stream passing through the Fawn Trough (Fig. 4). After a sharp southward shift from 55°S to 58°S across the SouthWest Indian Ridge, the Ice Limit runs almost zonally across the breadth of the Enderby Basin, between 58°S and 59°S, until the entrance to the Fawn Trough at 72°E. It then bends northward to cross the Fawn Trough sill before curling back to the south along the western boundary of the Antarctic–Australian Basin. In analysing the upper-layer thermohaline structure in the Antarctic Zone between 20° and 120°E from two summer CTD–O₂ sections at 30°E and 62°E together with historical hydrographic data, Park et al. (1998a) proposed that the Ice Limit should be the most preferred passage for the advection of meltwater coming from the Weddell Basin, causing a summertime freshening of the surface layer thus inducing a surface salinity minimum south of the Ice Limit. Belkin and colleagues (unpublished document and personal communication cited in Holliday and Read, 1998) remarked from an analysis of historical hydrographic sections that the Ice Limit (quoted by them as the Antarctic Ice Boundary) is generally associated with a sharp meridional step across the 0 °C isotherm of the T-min layer. It is also associated with the T-max 2 °C isotherm in some areas of the Enderby Basin.

Based on reference work on the regional hydrography, McCartney and Donohue (2007) suggested designating the current in the Fawn Trough area as the Fawn Trough Current, without intending anything more than a regional name. Here we adopt this nomenclature in order to avoid any unnecessary debate with the pre-existing confusing terminology of fronts, and also to emphasize the uniqueness of the local topographically-induced concentration of a great majority of upstream fronts from the Enderby Basin, as will be seen below.

4. Analysis of elephant seal data

4.1. Vertical structure of the Fawn Trough Current

Fig. 5 presents two selected vertical sections of water properties obtained by seals #3 and #5, with the depth of each layer (SML, WW, UCDW) being superimposed. Also shown in the top panels are the surface dynamic heights relative to 500 m. A spatial Gaussian smoothing (0.3° latitude window) was applied to temperature and salinity measurements prior to the calculation of the dynamic heights. These two sections were chosen to illustrate the typical hydrographic situation in the upstream area from the Kerguelen Plateau (sections #1 to #4), compared to that crossing directly the Fawn Trough (sections #5 to #8) where the current–topography interaction is expected to be strongest (see Fig. 1). In both sections, WW properties of the northernmost profiles coincide with the Polar Front definition (7-min 2 °C at 200 m), while close to Antarctica, the Antarctic Divergence is found between 63°S and 65°S. There appears a great difference in property distributions along the two sections, which is most visible in the meridional distribution of dynamic heights, with a gradual southward decrease in section #3 compared to an abrupt drop across the Fawn Trough in section #5. The latter feature may illustrate a concentrated strong flow associated with the Fawn Trough Current.

Such an E–W contrast is also clear in other parameters. In the western section (#3), the deepest WW (270 m) is found over the western flank of the northern Kerguelen Plateau at 52°S. Further south, it shoals progressively until the Antarctic Divergence where a minimum of 70 m is observed. In contrast to the gradual southward shoaling of the WW in the western section, the WW depth in the eastern section (#5) shows a steep jump by 100 m across the Fawn Trough. Also, in section #3 the T-max core characterizing the UCDW shoals progressively from 500 m at 58°S to a minimum of 300 m at the Antarctic Divergence (64°S), following closely the isohaline 34.6 psu. In section #5 the shallowest T-max is not found at the Antarctic Divergence, but is displaced far northward by 6° to the northern flank of the southern Kerguelen Plateau at 58°S. North of this latitude, the T-max layer deepens steeply, as can be seen by the pronounced slope of isohalines and isopycnals. All this information may imply that a broad and relatively weak eastward flow in the eastern Enderby Basin becomes the narrow and swift Fawn Trough Current during its passage through the Fawn Trough.

Several characteristic properties along the 8 SRDL sections are presented in Fig. 6 (see Fig. 1 for seal trajectories), which are from top to bottom the SML and WW depths, the SML and WW temperatures, the temperatures at the T-max (only detected in the middle to southern part of profiles due to limited depths of the
sections), and finally the surface dynamic heights relative to 500 m, when available. Although it begins to be apparent eastward from section #5, the Fawn Trough Current is most strongly concentrated in section #6, as can be seen from large meridional temperature gradients (variations of 1.5 °C in SML, 2 °C in T-min, and 0.6 °C in the T-max) and a steep jump of the WW depth by as much as 150 m.
across the 100 km wide front. The current remains very concentrated in sections #7 and #8. In these three easternmost sections, the Fawn Trough Current core is centered on the 2000 m isobath of the northern Kerguelen Plateau, showing a sharp topographically-steered northeastward deflection.

As stated above, the meridional change in properties and surface dynamic heights is much more gradual in the eastern Enderby Basin (sections #1 to #4) than across the Fawn Trough (sections #5 to #8), indicating a somewhat spatially homogeneous eastward drift in the former area. However, a careful examination of Fig. 6 reveals abrupt changes across the 0 °C and 1 °C isotherms in the WW temperature. Interestingly, these abrupt changes are often associated with locally enhanced meridional gradients of dynamic height (especially in sections #3 to #5, but less so in section #1), indicating local concentrations of geostrophic flow. The WW 0 °C isotherm is found between 58°S and 60°S in the three westernmost sections following roughly the Ice Limit before extending northeastward along the Fawn Trough Current, as clearly seen in sections #5 to #8. The WW 1 °C isotherm is found close to 55°S in the four western sections along the northern flank of the Elan Bank. Further east, the flow associated with this isotherm can be detected in section #5 just south of Heard Island, albeit less clearly compared to the upstream case, implying a gradual eastward weakening of the flow over the plateau. Also, we note that there is a general agreement in latitudinal position between the WW 0 °C and T-max 2 °C isotherms, in particular in sections east of #3. This is in line with previous work of Belkin and colleagues (unpublished document) and Holliday and Read (1998).

4.2. Horizontal property distributions

Horizontal distributions of depth and temperature of both the SML and WW are shown in Fig. 7, providing a quasi-synoptic view for the period of March 2004. These were mapped with an objective analysis using an exponential covariance function, with a decorrelation length scale of 150 km.

The most conspicuous feature common to all these property distributions is a sharp northward bend of property isolines when they approach the Kerguelen Plateau, showing a strong convergence into the Fawn Trough. This is most clear with the WW isobaths of 100 m to 180 m (Fig. 7b), which show a convergence by a factor of four between the upstream area west of 70°E and the Fawn Trough sill at 78°E. Remarkably, most property isolines crossing the Fawn Trough originate from the south of the Elan Bank (57°S), advecting high-latitude cold waters toward the Australian–Antarctic Basin at much lower latitudes. For example, in the area west of 70°E, the WW colder than 0 °C is found solely south of 58°S, but at 80°E it is observed as far north as 54°S, creating a zonal temperature difference of more than 1 °C between the southwestern and southeastern flanks of the

Fig. 6. a: Along-track distribution of SML (x), WW (+) and UCDW (⁎) properties for sections #1 to #4. A smoothed version (gaussian smoothing with a 0.2° latitude window) of these properties is also shown by a solid line for clarity. Hatched vertical bars indicate the location of different fronts mentioned in Fig. 5, with small vertical arrows emphasizing the fronts associated with a sharp latitudinal change in WW temperature across the 1 °C and 0 °C isotherms. Surface dynamic heights relative to 500 m are shown when available. Abbreviations of fronts are same as in Fig. 5. b: Same as Fig. 6a, but for sections #5 to #8.
northern Kerguelen Plateau (Fig. 7d). A similar northward bend and a gradual concentration of isolines through the Fawn Trough are equally observed within the SML properties. In particular, the SML 2 °C isotherm (Fig. 7c) bends sharply to the north to pass through the Fawn Trough and retroflects south downstream from the Fawn Trough sill, roughly in parallel with the Ice Limit (Fig. 4).

A map of surface dynamic heights relative to 500 m of the area west of 80°E is shown in Fig. 8a. Due to the unavailability of salinity data for SRDLs #6 and #8 (Table 1), the dynamic heights along the eastern flank of the southern Kerguelen Plateau are not well resolved and are therefore not shown for clarity. We emphasize that the currents at 500 m may not be zero, thus this figure illustrates only the relative baroclinic flow pattern and the local degree of concentration of streamlines. Consistent with the already discussed property distributions, all streamlines in the eastern Enderby Basin are sharply deflected north on approaching the Kerguelen Plateau. As soon as they “feel” the bottom topography of the Kerguelen Plateau, the streamlines bend anticyclonically. The southern streamlines (0.26–0.38 dyn m), which are found over a large meridional extent (57°–63°S), bend even more sharply to the north with increasing longitude, all passing through the Fawn Trough with a remarkable concentration. Even the 0.26 dyn m streamline found initially at 63°S and running eastward as far as 80°E does not cross over the southern Kerguelen Plateau, but curls back far to the north to pass through the Fawn Trough sill north of 57°S. We also present in Fig. 8b the temperature distribution at the T-max core of the UCDW where isotherms may approximate deep streamlines. It is remarkable that the T-max isotherms 1.9–2.0 °C follow a similar path as that taken by the surface dynamic heights shown in Fig. 8a, with a strong channelling of these deep isotherms into the Fawn Trough.

West of the Princess Elizabeth Trough (82°E), the Antarctic Divergence appears clearly in WW properties as a band of depth minimum (~80 m, Fig. 7b) within a zonally-elongated area between 63°S and 65°S (see also sections #1 to #5 in Fig. 6), which is in good agreement with its climatological location of Park et al. (1998a) (see Fig. 4). This Antarctic Divergence is also associated with a local temperature maximum (~1 °C, Fig. 7d), which seems to be related to an enhanced vertical mixing with the warmer UCDW below due to the WW being very thin there. The Southern ACC Front and the Southern Boundary, defined respectively by the T-max 1.8 °C and 1.5 °C isotherms, are found in the nearly same place as the Antarctic Divergence (see Fig. 6). This proximity among three fronts, which is consistent with previous work shown in Fig. 4, may suggest that the southeastern corner of the Enderby Basin does not constitute a privileged route for the ACC. We will come back to this point later in Section 5. In seal section #6, the Antarctic Divergence is found between 61°S and 62°S, confirming its northward shift on crossing the Princess Elizabeth Trough. In further eastern sections, especially in section #7, the Antarctic Divergence is ill-defined due to multiple maxima and minima in WW depth appearing in these sections (see Fig. 6b). This may be caused by the interference with the meridionally-oriented DWBC that is clearly seen as a narrow band.
of cold UCDW \((T_{\text{max}} \leq 1.8 \, ^\circ C)\) extending along the eastern escarpment of the southern Kerguelen Plateau as far north as the Fawn Trough latitude (Fig. 8b). It is to be noted that the \(T_{\text{max}} \leq 1.8 \, ^\circ C\) characterizing the Southern ACC Front collides with the Fawn Trough Current at this outlet, with the presence of the coldest \(T_{\text{max}}\) as low as 1.4 °C at 54°S in section #7 (see Fig. 6b).

Fig. 7. Horizontal distribution of SML and WW depth (a, b) and temperature (c, d). The 2000 m isobath is superimposed (thick line). Areas shallower than 500 m are shaded grey.

Fig. 8. Horizontal distribution of (a) surface dynamic heights (dyn m) relative to 500 m and (b) temperature at the \(T_{\text{max}}\) of the Upper Circumpolar Deep Water. The \(T_{\text{max}}\) colder than 1.8 °C is dark shaded.
5. Validation of seal-derived fronts against an altimetry-derived dynamic topography

In order to validate fronts identified from seal sections and to pursue their upstream origin, we first refer to the CMDT of Rio and Hernandez (2004) (Fig. 9a). In this altimetry-derived dynamic topography, three distinct bands of relatively strong currents are found south of 50°S in the eastern Enderby Basin. By comparing with climatological front locations suggested in the literature (Fig. 4), it is not difficult to ascertain that the northern band centered at 50°–52°S and extending down to the immediate south of the Kerguelen Islands corresponds to the Polar Front of Park et al. (1998a). The middle band running around 54°–55°S is roughly in the same location as the surface expression of the Polar Front described by Sparrow et al. (1996), but with an important exception that it does not penetrate directly into the Fawn Trough. Instead, it becomes much weakened on approaching the plateau and sharply bends north from the north-eastern side of the Elan Bank to pass immediately south of the Heard Islands. The southern band (58°–59°S) follows closely the Ice Limit of Park et al. (1998a) and constitutes a major contribution to the Fawn Trough Current. There is an indication that the middle band is partially connected with the southern band in the area west of the Elan Bank.
thus contributing indirectly to the Fawn Trough Current. Remarkably, all streamlines forming the Fawn Trough Current pass south of the Elan Bank. The latter current is seen without ambiguity as a band of strong currents following the southwestern flank of the southern Kerguelen Plateau before shifting northward in passing the Fawn Trough sill to run along the southeastern flank of the northern Kerguelen Plateau.

In Fig. 9h, we superimposed on the CMDT streamlines the locations of the different frontal features detected along the eight seal sections (Fig. 6), namely the T-min 2 °C, 1 °C, and 0 °C isotherms, the T-max 2 °C isotherm, and the Antarctic Divergence. The seal-derived frontal locations are in good agreement with the CMDT. Indeed, the three fronts as determined by the T-min isotherms criteria in the seal sections are located in close proximity to the three aforementioned bands of concentrated CMDT streamlines, except that the T-min 0 °C in seal sections #4 and #5 is found about 1° north of the CMDT-derived front at the entrance to the Fawn Trough. Far south of the Elan Bank, the CMDT hints at a weak flow peeling off from the southern band and executing a zonally-elongated anticyclonic loop before its convergence into the Fawn Trough. This feature is in excellent agreement with the seal-derived T-max 2 °C and streamline patterns (Fig. 8). The Antarctic Divergence determined from the seal sections follows two CMDT streamlines running around 64°S in the southeastern Enderby Basin, and is located in close proximity to the Southern ACC Front (determined by the T-max 1.8 °C). We believe that this realistic large-scale circulation has been made possible due to the unprecedented fine resolution of the seal data covering quasi-synoptically the vast area surrounding the whole Kerguelen Plateau. Also it is noteworthy that both datasets are very consistent although the CMDT is a climatological average in contrast with the quasi-synoptic seal data, highlighting the strong permanent bathymetric control which may induce a weak seasonal variability of front positions.

In the eastern Enderby Basin, there does not appear any clear evidence of strong currents associated with the Southern ACC Front south of 60°S where CMDT-derived surface velocities are much weaker than 5 cm s⁻¹, in line with our general feeling that the ACC branch crossing the Princess Elizabeth Trough is only secondary compared to the Fawn Trough Current. The absence of a concentrated DWBC along the eastern flank of the southern Kerguelen Plateau in the CMDT may be in contradiction with recent observations (McCartney and Donohue, 2007; Aoki et al., in preparation). It is likely that the zonal resolution of the CMDT (1° in longitude) should be too coarse to resolve this narrow (<50 km) northward boundary current. Moreover, as only a few surface drifter and hydrographic data are available south of 60°S to constrain the altimeter solution, it is not surprising that the CMDT cannot resolve the narrow and elongated DWBC developed along the eastern flank of the plateau. Noteworthily, our seal data clearly support the existence of this boundary current, revealing a cold variety of UCDW with T-max > 1.8 °C within several segments along sections #6 and #7 (see also Figs. 6b and 8b).

6. Origin of the Fawn Trough Current

6.1. Fronts and their pathways in the Enderby Basin from the WW and UCDW climatology

To investigate further the origin of the Fawn Trough Current, we plotted in Fig. 10 several characteristic WW (T-min) and UCDW (T-max) isotherms superimposed on CMDT streamlines in the far extended area between 20°E and 100°E, covering the entire Enderby Basin and the western Australian–Antarctic Basin. The spatial distribution of these isotherms was calculated using the SISMER/IFREMER hydrographic database (see Section 2.2).

In the CMDT map, we see the concentrated ACC in the area south of South Africa, between 45°S and 52°S at 20°E, which bends sharply south on crossing the Southwest Indian Ridge between 48°S and 54°S. Downstream from this ridge, the initially concentrated ACC splits into several diverging branches. The northernmost branch north of 50°S advances northeastward hugging the southern flank of the Del Cano Rise before penetrating into the Crozet Basin through a deep passage between the rise and the Crozet Plateau (see Fig. 4 for nomenclature), and then reflecting east to pass north of the latter plateau. This is precisely the Subantarctic Front most comprehensively described by Pollard and Read (2001). Further east, this front extends to the north of the Kerguelen Plateau, constituting the main component of the ACC core (Park et al., 1993).

All streamlines running through the Enderby Basin south of the Subantarctic Front are initially found in a very limited area over the
Southwest Indian Ridge between 50°S and 54°S, before diverging across the full width of the basin on approaching the Kerguelen Plateau. In the southern part of the basin, some streamlines run southeastward from 54°S up to 65°S at 60°E, before retreating west close to the Antarctic continent, forming the eastern limb of the Weddell Gyre (Park et al., 2001). Such an uncommon divergence of streamlines in the Enderby Basin is equally well observed with our selected isotherms that are initially confined within a limited latitudinal range of 3° over the Southwest Indian Ridge but dispersed by up to 16° across the Kerguelen Plateau, i.e. a factor of 5 or more in divergence.

Nevertheless, significant currents are confined between 50°S and 60°S, especially along the three bands of relatively strong flow mentioned in Section 5. These bands of current describe a large-scale oscillation on crossing the prominent topographic features such as the Conrad Rise and Kerguelen Plateau, with a general northward (southward) bend upstream (downstream) from a topographic obstacle, consistent with a potential vorticity conservation theory. The near-zonal northern band centered at around 51°S coincides with the T-min 2 °C isotherm, providing an additional indication that it is precisely the Polar Front. Before reaching the Kerguelen Plateau, the flow has first to negotiate the triangular-shaped Conrad Rise (40°–50°E) whose topographic effect is evident by the presence of an extensive area of sluggish flow over shallow depths, which is surrounded by intense flow concentrations north and south of the rise. To the north of the rise, we can distinguish the T-min 2 °C isotherm (Polar Front) from two collocated isotherms of T-min 1 °C and T-max 2.2 °C found about 100–200 km further south. To the south of the rise, a second band of current hugging the southern flank of the rise is associated with the T-min 0 °C and T-max 2 °C isotherms that are in close proximity. The triangular form of the Conrad Rise creates a convergence of currents at the eastern tip of the rise at 48°E.

In the area between the Conrad Rise and the Kerguelen Plateau, the isotherms clearly diverge to form the three distinctive frontal bands discussed in Section 5. When approaching the Elan Bank, the initially collocated T-min 1 °C and T-max 2.2 °C isotherms, which have run so far along the middle band, begin to separate in the area west of the bank, with the former passing north of the bank and then over the Kerguelen Plateau just south of the Heard Islands. The latter isotherm bends south, converging into the southern band associated with the T-min 0 °C isotherm, before entering into the Fawn Trough. At the longitudes of the Elan Bank (65°–75°E), the T-max 2 °C isotherm curls far southward to make a zonally-elongated anticyclonic loop before channelling into the Fawn Trough. This is consistent with the elephant seal data and CMDT. This complex pattern of convergence/divergence of hydrographic frontal markers is remarkably coherent with the pattern of CMDT streamlines, which show evidence of some exchanges between the main branches as well as the detachment of secondary branches peeling off from the main branches.

It is interesting to note that the hydrographic fronts in the WW layer, as defined by the T-min isotherms, are comparatively zonal, while those in the UCDW, defined by the T-max isotherms, shift far southward by several degrees. This veering tendency observed between the two layers is likely to be related to the fact that the surface layer circulation is under direct influence of the coupled atmosphere–ocean–sea ice interactions, while the deep layer circulation is more strongly affected by topographic steering.

The T-max 1.8 °C isotherm characterizing the Southern ACC Front follows the southernmost route in the eastern Enderby Basin, roughly consistent with the frontal location proposed by Orsi et al. (1995). However, the most notable discrepancy between these two frontal locations may be found along the eastern flank of the southern Kerguelen Plateau where a much larger northward meander extending as far north as the Fawn Trough sill latitude can be seen in our climatology. Although the possibility of such a northerly extended meandering front has already been suggested in the literature (Orsi et al., 1995; Aoki et al., 2008), it is the first time to our knowledge that the convergence of this front with waters forming the Fawn Trough Current has been demonstrated without ambiguity both from our elephant seal data (see Section 4) and climatology.

6.2. Large-scale circulation in the Enderby Basin from satellite SST and float trajectories

In order to investigate further the different pathways of upper and deep layer currents, we examined the frontal structure in both layers using the satellite SST data and available mid-depth float trajectories. We show in Fig. 11 a map of Austral winter (August to October mean) SST gradients (colour) superimposed on the corresponding SST field (lines). Both fields were calculated from weekly maps of AMSR-E

![Fig. 11. Winter (August to October) mean SST (lines) and its gradients (colour) obtained from the 5-year-long AMSR-E satellite SST data. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)](image-url)
satellite SST observations, by averaging over the whole period of observations (2002–2007) separately for different seasons. We presented only the winter season because it not only reveals the clearest surface frontal structure but also provides useful information on the surface thermal condition during the WW formation period, which can be related to the previously discussed T-min isotherms (see Figs. 7 and 10). We also note that north of the Ice Limit in the Enderby Basin, the spatial distribution of isotherms is almost identical in winter and summer (not shown), except that in summer SST gradients are somewhat weaker and isotherms are about 2 °C warmer than in winter.

As expected, isotherms are remarkably similar to the CMDT streamlines (Fig. 10), suggesting that they may indicate surface streamlines to a first approximation. SST gradients are relatively low in the Enderby Basin, in great contrast to the northernmost part of the map where the Subantarctic Front runs within the ACC core. Yet, several regions of the basin consistently show relatively high gradients throughout the year, which is clearly related to the topographic steering, namely along the northern and southern flanks of the Conrad Rise, south of the Elan Bank, and across the Fawn Trough along the southern 2000 m isobath of the northern Kerguelen Plateau. In this winter map, the Ice Limit, corresponding to the southernmost position where SST data are available, is clearly seen as a near-zonal band at about 59°S with pronounced SST gradients around the −0.5 °C isotherm, which compares quite well with its climatological location given in Fig. 4. This winter isotherm is well correlated with the southern CMDT band of current seen in Fig. 10, suggesting that they may indicate surface streamlines (Fig. 10), testifying for the origin of this current. There is also a weak banded structure of trajectories, which drifted in a depth range of 700–2000 m, can be used as proxies of deep streamlines carrying the Circumpolar Deep Water originating from the North Atlantic Deep Water (e.g., Park et al., 2001). One float passed north of the Conrad Rise and then north of the Elan Bank before entering into the Fawn Trough. Another float passed also north of the Conrad Rise, but deflected southward along the western flank of the Elan Bank to pass to its south. Two other floats passed south of the Conrad Rise and then south of the Elan Bank, a pathway quite similar to that described by the T-min 0 °C or to a less extent by the T-max 2 °C (Fig. 10). We also note that a float launched in the west of the Elan Bank (green track) rounded the bank, first drifting southward and then passing south of the bank before entering into the Fawn Trough. This south Elan Bank route, which matches well the T-max 2.2 °C isotherm to the east of 60°E (Fig. 10), may represent the most frequent route for deep flows, as the float out of five followed it before entering the Fawn Trough. In this respect, the north Elan Bank route may only constitute a secondary passage of the deep circulation converging into the Fawn Trough.

Although the float data we used here are certainly limited, their trajectories are remarkably consistent with several frontal isotherms shown in Fig. 10, so we are quite confident of the deep circulation pathways they described. It becomes clear now that the quasi-totality of swift deep-reaching streams forming the Fawn Trough Current originate from the limited frontal zone (50°–53°S) developed over the Southwest Indian Ridge. These streams take more or less undulating courses around a rather straight NW–SE oriented mean line connecting the rise (51°S, 29°E) and the Fawn Trough entrance (57°S, 74°E). This is in contrast with the fronts associated with the surface intensified circulation such as the Polar Front and the middle front north of the Elan Bank, which cross the Kerguelen Plateau through much shallower depths, such as just south of the Kerguelen (650 m) and Heard (1000 m) Islands. In these relatively shallow passages, the crossing of the deep-reaching Circumpolar Deep Water is physically inhibited, so the associated transport is also limited. For instance, Park et al. (1993) attributed a small 5 Sv transport to the Polar Front of the Kerguelen area, compared to more than 30 Sv for the Fawn Trough Current (see below).

7. Discussion and conclusions

In this study, we have reported new results on the circulation of the Kerguelen Plateau region obtained by the use of instrumented
elephant seals. In summer 2004, eight Kerguelen elephant seals equipped with miniaturized CTDs headed directly toward Antarctica, resulting in eight finely-resolved cross-current hydrographic sections covering the entire Kerguelen Plateau. The fortuitous fan-shaped distribution of these animal-born sections allowed us to map several quasi-synoptic surface and subsurface water properties in the vast Antarctic Zone around the Kerguelen Plateau, yielding unprecedented detailed information on the northeastwardly flowing Fawn Trough Current. It was also shown that most of the Antarctic waters flowing within the 57°–63°S latitude range in the eastern Enderby Basin (roughly between the Ice Limit south of the Elan Bank and the Antarctic Divergence) are strongly channelled into the Fawn Trough at 56°S to form a jet-like current before their entering into the Australian–Antarctic Basin.

The channelling of Enderby Basin waters in the Fawn Trough is often clearly seen in summer SeaWiFS images of chlorophyll concentrations as a clear-cut plume of chlorophyll-poor waters (Fig. 13). This remarkable feature, which has been highlighted in the Science Focus section of the NASA website as the “Low Zone” (http://disc.sci.gsfc.nasa.gov), is very consistent with our surface geostrophic current field as estimated from the seal data. Also, the two overlaid historical trajectories of Argo floats followed a similar path as the Fawn Trough Current. The presence of the swift Fawn Trough Current likely affects negatively the local primary productivity of the area (Park et al., 2008a).

The existence of a deep-reaching jet-like current channelling most of Antarctic waters coming from the Enderby Basin has important consequences for the dynamics in the western Australian–Antarctic Basin. We have shown that the Fawn Trough Current at its outlet collides with the DWBC flowing northward along the eastern flank of the southern Kerguelen Plateau. Outstanding visual evidence supporting this argument may have been provided by Young (1999) who presented a remarkable track of an iceberg that initially drifted westward along the Antarctic coast of the Australian–Antarctic Basin until the Princess Elizabeth Trough at 78°E where it retroflected eastward and then northward to ride on the DWBC as far north as the Fawn Trough latitude. Such an equatorward evacuation along the western boundary of the basin of coastal icebergs coming from the east is not uncommon, or even frequent (N. W. Young, personal communication). This western boundary current has received much attention, because it forms the western limb of the deep cyclonic subpolar gyre in the Australian–Antarctic Basin (Park and Gambéroni, 1995; McCartney and Donohue, 2007), carrying equatorward cold Antarctic coastal waters and Antarctic Bottom Water (Speer and Forbes, 1994; Donohue et al., 1999; McCartney and Donohue, 2007; Rintoul, 2007; Aoki et al., 2008). The Fawn Trough Current could strengthen this gyre system. Another converging flow is the one associated with the ACC coming from the north of the Kerguelen Islands. The cold dense water made by mixing the Fawn Trough Current and the DWBC of the subpolar gyre is likely to intrude beneath the lighter waters coming from the north (McCarty and Donohue, 2007). From penguin-borne temperature data, Charraissin et al. (2004) showed the existence of a subsurface cold water tongue flowing northwestern along the eastern flank of the northern Kerguelen Plateau. From a detailed analysis of recent KEOPS hydrographic sections and associated current measurements across the eastern flank of the northern Kerguelen Plateau, Park et al. (2008a) showed that this cold tongue is a northward branch of the Fawn Trough Current. All this information shows that the presence of the Kerguelen Plateau within the ACC path induces an important meridional shift of the regional circulation, leading to substantial inter-basin exchanges and mixing of circumpolar water masses. It also indicates that the Fawn Trough is a strategic site for investigating the topographic steering effect of the Kerguelen Plateau on the circumpolar circulation.

Despite its utmost importance, a precise knowledge of the volume transport through the Fawn Trough is missing. Park et al. (1991) proposed a coarse estimate of 30 Sv from the Antiprod-1 cruise data along 66°30′E, while Sparrow et al. (1996) gave a substantially higher estimate of 65 Sv. Recently, McCartney and Donohue (2007) suggested a transport of 38 Sv based on the Antares 2 hydrographic section (Park et al., 1998a), considering the continuity of transport downstream from the Fawn Trough. Using a finite-difference inverse model of the South Indian Ocean, Sultan et al. (2007) found a very similar 35 Sv transport. Interestingly, all ACC transport estimates available across the Princess Elizabeth Trough (Heywood et al., 1999; McCartney and Donohue, 2007; Sultan et al., 2007) consistently show a lower eastward transport (≤ 15 Sv) than in the Fawn Trough, pointing it out as a secondary path for the southern ACC flow. With the aim to better document the Fawn Trough Current, its transport, and its time variability, an extensive CTD survey and 1 year-long currentmeter

Fig. 13. SeaWiFS-derived monthly mean chlorophyll concentrations (mg m⁻³) in December 2002. The trajectories of two representative Argo floats (brown solid line: 1900103, brown dashed line: 1900314) passing through the Fawn Trough are superimposed.
Fig. 14. Schematic of the large-scale circulation in the Enderby Basin as obtained from the present study. The Fawn Trough Current (FTC) results from the channelling of most of the Antarctic Circumpolar flow crossing the Enderby Basin. We tentatively called the two main branches of flow converging to form the FTC as the northern and southern affluents of the FTC (respectively the N-FTC and S-FTC). The N-FTC (S-FTC) is best characterized by the 2.2 °C (2 °C) 700 m deep isotherm. The Deep Western Boundary Current (DWBC) flowing along the eastern flank of the southern Kerguelen Plateau is also converging with the FTC at the outlet of the Fawn Trough sill. Circulation features deduced from the literature, namely the Weddell Front (WF: Park et al., 2001) and the Antarctic Slope Front (ASF) along the Antarctic coast which bifurcates in the area of the Princess Elizabeth Trough (McCartney and Donohue, 2007), are shown dark grey. The Antarctic Divergence (AD) and the Ice Limit (IL) are also shown (grey dashed lines).

Moorings across the Fawn Trough sill during 2009 are being planned in the framework of the International Polar Year (Y.-H. Park, unpublished document, 2007). Our results shall serve as a useful guide for this field experiment.

In addition to an up-to-date description of the frontal structure in the Fawn Trough area, we pursued further analysis in the entire Enderby Basin using different supplementary data in order to track the origin of the Fawn Trough Current. This revealed several distinctive branches of deep-reaching currents strongly controlled by prominent topographic features such as the Southwest Indian Ridge, Conrad Rise, Elan Bank, and Kerguelen Plateau. These deep currents all converge into the Fawn Trough Current, in contrast to surface-intensified fronts that cross the plateau through shallower gaps developed south of the Kerguelen and Heard Islands. This newly emerged frontal structure reconciles and refines considerably previous suggestions in the literature (see Fig. 4), which is summarized in a schematic in Fig. 14.

The present study is the first demonstration that the hydrographic data collected by the Southern Ocean elephant seals can address with success important issues on the regional circulation, despite the still insufficient quality of SRDL data. Significant improvements in sensor accuracies have recently been achieved, which may allow us to address other key climate issues in the future, such as the interannual variability of water properties and transport, or the wintertime water mass formation processes within the pack ice.

Acknowledgements

The French component of SEaOS (CG as the PI) was financially supported by the program TOSCA of the CNES (Centre National d’Études Spatiales). Financial and logistic support was also provided by IPEV (Institut Polaire Français Paul-Emile Victor) and the Groupe de Mission Mercator Coriolis. All elephant seal data are available on the CORIOLIS database (http://www.coriolis.eu.org/). We thank B. Ollivier and N. Metzl for allowing us to perform the at-sea instrument tests onboard the R/V Marion-Dufresne, and M. Le Menn (SHOM) for his assistance in the SRDL calibration. The CMDT of Rio and Hernandez (2004) was produced by CLS Space Oceanography Division. We are grateful to all colleagues involved in the SEaOS project, particularly M. Fedak, C. McMahon, P. Lovell, M. Biuw, M. Hindell, L. Boehme, C.-A. Bost, and I. Field. We are also grateful to I. Belkin, A. V. Romanov and three anonymous reviewers for their constructive comments that helped to much improve the manuscript.

References


