An interdisciplinary cruise dedicated to understanding ocean eddies upstream of the Prince Edward Islands

I.J. Ansorge[a*], P.W. Froneman[b], J.R.E. Lutjeharms[a], K. Bernard[b], A. Bernard[b], L. Lange[b], D. Lukáč[b], B. Backeburg[a], J. Blake[b], S. Bland[a], N. Burls[a], M. Davies-Coleman[c], R. Gerber[b], S. Gildenhuys[a], P. Hayes-Foley[d], A. Ludford[b], T. Manzoni[a], E. Robertson[a], D. Southey[a], S. Swart[a], D. Van Rensburg[a] and S. Wynne[b]

A DETAILED HYDROGRAPHIC AND BIOLOGICAL survey was carried out in the region of the South-West Indian Ridge during April 2004. Altimetry and hydrographic data have identified this region as an area of high flow variability. Hydrographic data revealed that here the Subantarctic Polar Front (SAF) and Antarctic Polar Front (APF) converge to form a highly intense frontal system. Water masses identified during the survey showed a distinct separation in properties between the northwestern and southeastern corners. In the north-west, water masses were distinctly Subantarctic (>8.5°C, salinity >34.2), suggesting that the SAF lay extremely far to the south. In the southeast corner water masses were typical of the Antarctic zone, showing a distinct subsurface temperature minimum of <2.5°C. Total integrated chl-*a* concentration during the survey ranged from 4.15 to 22.81 mg chl-*a* m^{-2}, with the highest concentrations recorded at stations occupied in the frontal region. These data suggest that the region of the South-West Indian Ridge represents not only an area of elevated biological activity but also acts as a strong biogeographic barrier to the spatial distribution of zooplankton.

Introduction

Mesoscale eddies and meanders are among the dominant sources of flow variability in the ocean. Suitable observational coverage of such anomalies in space and time is severely limited by the difficulty of sampling using conventional ship-borne instruments.[1] The advent of satellite altimetry and a combination of satellite platforms has facilitated the study of such features, particularly in parts of the ocean otherwise difficult to reach. Regions of high mesoscale variability correlate closely with either the terminal region of a major western boundary current such as the Agulhas Current or the Gulf Stream, or where the Antarctic Circumpolar Current (ACC) interacts with prominent bottom topography such as in the Drake Passage or at the Crozet and Kerguelen Plateaux in the Southern Ocean.[2]

Altimetry and hydrographic data[3,4] have identified the region of the South-West Indian Ridge (30°E) as an area of high flow variability, which may extend as far eastwards as 37°E. Hydrographic data collected during the South-West Indian Ocean Experiment (SWINDEX) surveys in 1993 and 1995 showed that, close to the South-West Indian Ridge, the ACC fragments into several branches,[5] possibly resulting in enhanced eddy generation in the lee of the ridge. These observations agree with the inertial jet model of Robinson and Niiler, which shows the influence the bottom topography has on the separation of the ACC in the region of the South-West Indian Ridge.[6] At 30°E the ACC transport is concentrated within the Subantarctic Polar Front (SAF) and Antarctic Polar Front (APF). Further eastwards, there appears to be a distinct separation in the two branches, with the SAF topographically deflected northeastwards, thus widening the Polar Frontal Zone by up to 5° of latitude. Extensive expendable bathythermograph (XBT) transects south of New Zealand have shown that, in this region, the SAF bifurcates into a northern (6°C, at 200 m) and a southern (3.5°C, at 200 m) branch as a result of the topographical influence of the Macquarie Ridge.[7]

Recent investigations at 30°E, 50°S during the first of the Dynamics of Eddy Impacts on Marion's Ecosystem (DEIMEC) surveys in 2002[4] have identified a southern SAF, formed as the SAF fragments during its displacement northwards.[5] Studies on the grey-headed albatross[8] have shown that these birds exploit this region and the mesoscale anomalies generated in the lee of this ridge during their foraging excursions away from the Prince Edward Islands. In addition, sea-surface temperature (SST) data collected over the past 50 years have revealed a gradual increase of 1.4°C in surface temperatures at Marion Island.[9] Closer inspection of the SST records suggests that the island may be further influenced by the intermittent passage of both warm and cold core eddies from further upstream.[3] The clear implication of this behaviour is that the Prince Edward Island region has an enhanced anomaly presence not so much because of the interaction of the flow with the islands themselves, as has been inferred previously,[10,11] but as a consequence of the fact that they are situated at the northern border of a region of unusually high mesoscale variability in the Southern Ocean. Despite the potentially important role that this region may play in the island ecosystem, few studies have been conducted in the region of the South-West Indian Ridge. The main objective of DEIMEC is to investigate the exact nature of altimetrically observed positive and negative sea-surface height (SSH) anomalies in the region of the South-West Indian Ridge and, where possible, to follow their advection eastwards into the island's vicinity with the aid of autonomous profiling floats.

This report serves as a brief overview of the preliminary findings obtained during the DEIMEC III survey, which was conducted in April 2004. Altimetry, hydrographic and biological data are compared in order to establish a better understanding of the dynamics of the ACC in this region.

Materials and methods

Research teams from the University of Cape Town and Rhodes University participated in the annual relief voyage to the Prince Edward Islands (Voyage 116) on board the supply and research vessel *SA Agulhas* from 1 April to 6 May 2004. The cruise consisted of two main components, an inter-island study consisting of surface sampling and dredging over the shelf between the Prince Edward and Marion Island group, and an upstream, interdisciplinary oceanographic survey to investigate the physical and biological characteristics of an intense mesoscale anomaly identified within the ACC in the region of 29–33°E, 48–50°S (Fig. 1). The anomaly was identified prior to the cruise

[a]Department of Oceanography, University of Cape Town, Private Bag, Rondebosch 7701, South Africa.
[b]Southern Ocean Group, Department of Zoology and Entomology, Rhodes University, P.O. Box 94, Grahamstown 6140, South Africa.
[c]Department of Chemistry, Rhodes University.
[d]Marine and Coastal Management, Private Bag X2, Roggebaai 8012, South Africa.
*Author for correspondence.
E-mail: ansorge@ocean.uct.ac.za

from altimetry data collected using a combination of JASON-1 and TOPEX/Poseidon products. In total, 69 XBT and 27 CTD (conductivity–temperature–depth) stations were carried out. Sippican T7 XBTs were deployed to a maximum depth of 760 m. At each CTD station, vertical profiles of salinity, temperature and density were obtained with a Neil Brown Mark IIIc WOCE upgrade underwater unit to a maximum depth of 750 m. Water samples were collected on average at 9 standard depths and analysed for dissolved oxygen, salinity, and nutrient (silicate, phosphate, nitrate and nitrite) concentrations.

Total integrated chlorophyll-*a* (chl-*a*) concentration (mg chl-*a* m^{-2}) at each station was determined from water samples collected at 5 standard depths (0, 5, 20, 50 and 100 m) using a rosette of Niskin bottles attached to the CTD. Chl-*a* concentrations were determined fluorometrically and integrated chl-*a* concentrations were calculated by trapezoidal integration. In addition, size-fractionated chl-*a* studies were undertaken using water collected from the surface at each station. Water samples were serially filtered through 20-μm, 2-μm and GF/C filters to determine the micro-, nano- and the picophytoplankton concentrations, respectively. Pigment concentrations were determined as above.

Zooplankton community structure and grazing impact were investigated at 27 stations during the survey. Mesozooplankton samples (200–2000 μm) were collected using a Bongo net fitted with 200 and 300-μm nets and towed to a depth of 300 m during the day and 200 m at night. Macrozooplankton and nekton samples were collected using an RMT-8 net towed to a depth of 400 m during the day and 300 m at night. Grazing activity (herbivory) of the numerically dominant meso- and macrozooplankon at each station was estimated using the gut fluorescent technique. Carnivory by selected components of the macrozooplankton (mainly amphipod and chaetognaths) community was investigated by *in vitro* incubations.

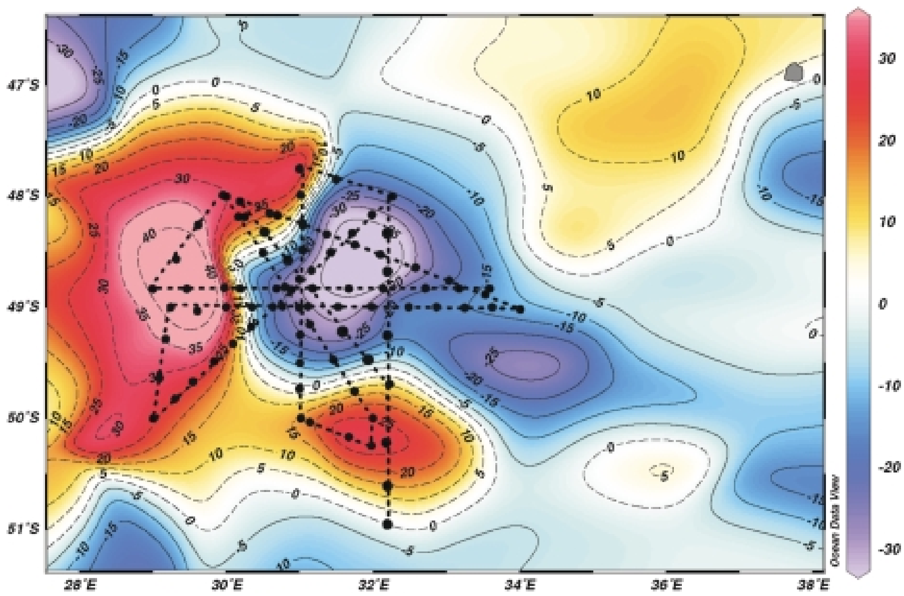

Fig. 1. Altimetry data showing sea-surface height anomalies (in cm) for the period 6–24 April 2004. The location of all hydrographic stations occupied during the DEIMEC III survey has been superimposed onto the map.

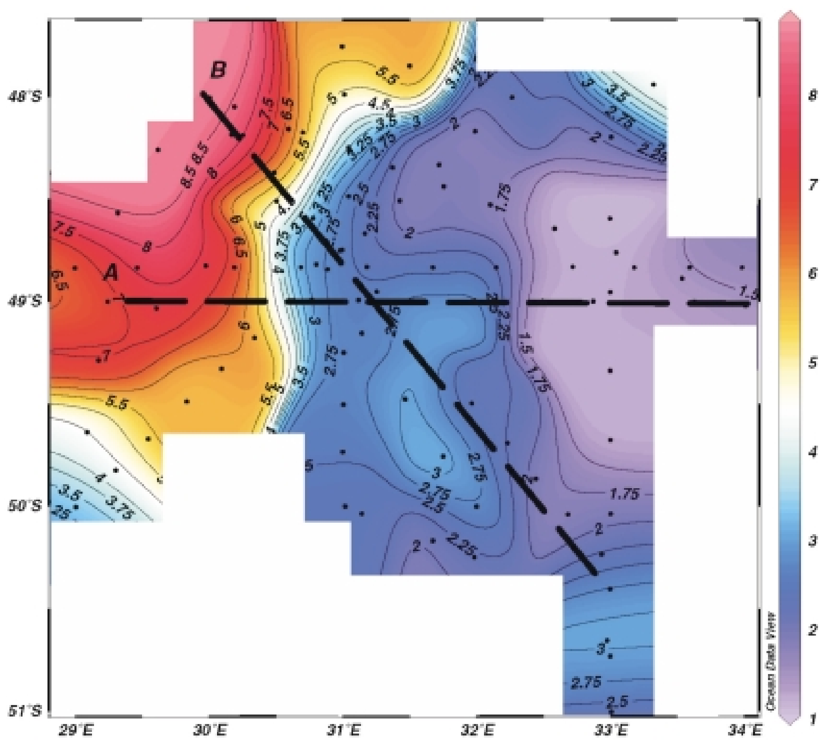

Fig. 2. Subsurface (200 m) temperature distributions (in °C) clearly showing the position of the intense frontal band between 30°30′ and 31°E. In the far eastern edge of the survey area, cold temperatures (<1.5°C) indicate the presence of an anomaly possibly spawned from south of the APF. Dashed lines represent the location of transects A and B, total integrated chl-*a* concentrations along which are discussed in the text (see also Fig. 5).

Preliminary results

Oceanographic

Blended TOPEX/ERS-2 altimetry data for the period 1993–98 reveals the formation of both positive and negative anomalies in the vicinity of the South-West Indian Ridge.[11] These anomalies may represent warm and cold eddies which have been spawned at the core of the ACC as a result of the currents interaction with the ridge. The nature of these features and the process in which these anomalies form, are poorly understood. The initial objective of DEIMEC III was to study in detail a single negative anomaly, centred at 48°30′S and 31°45E (Fig. 1), and to correlate these observations with that of a cyclonic cold core eddy, which is believed to have been spawned from south of the APF. However, the exceptionally strong SSH gradient of 75 cm between the positive (centred at 29°E, 48°45′S) and negative anomalies (centred at 48°45′S, 32°E) resulted in the survey extending further westwards than planned in order to observe the nature of this intensity (Fig. 1). Subsurface temperature distributions showed a clear correlation in the position of the SSH gradient and that of an intense frontal feature sweeping in a northeastwards direction across the survey region (Fig. 2). Previous investiga-

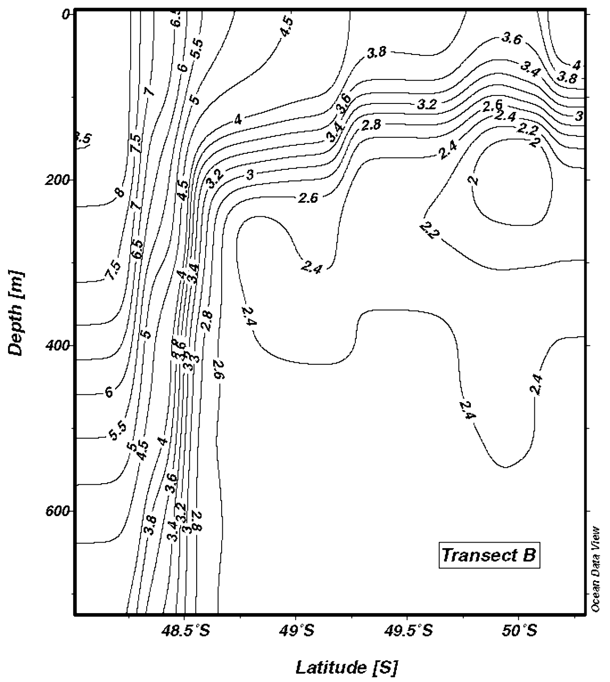

Fig. 3. Vertical temperature section (in °C) along transect B highlighting the intensity of the frontal feature observed here at 48°30′S.

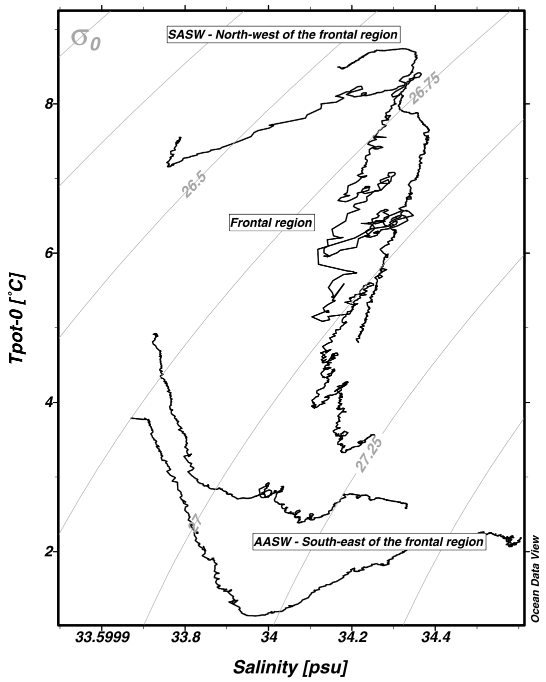

Fig. 4. Temperature/salinity (T/S) diagram showing the characteristics of stations located to the north and south of, and within, the intense frontal region.

tions in this region[12–14] showed that along the South-West Indian Ridge the position of the SAF and APF are highly variable, often temporarily converging and forming an intense double front. Subsurface temperature, salinity and sigma theta ranged from 8.5–2.5°C (Fig. 2), 34.150–33.875 and 26.8–27.05 kg m^{-3}, respectively, further support this notion. Indeed, a vertical temperature section along transect B, in which subsurface (200 m) temperature ranged by 5°C highlights the intensity of this frontal feature (Fig. 3).

Water masses identified in the survey region showed a distinct separation in properties between the northwestern and southeastern corners of the grid (Fig. 4). In the northwestern region, water masses were distinctly Subantarctic (>8.5°C, salinity >34.2), suggesting that either the SAF lay much farther to the south than in previous surveys (DEIMEC I and II) or that an eddy had become detached from north of the SAF, resulting in the advection of warmer, saltier surface water southwards. In the southeastern corner water masses were typical of the Antarctic, zone showing a distinct subsurface temperature minimum of <2.5°C. The northeastward extension of the SAF/APF at 30°30′E may explain the northward intrusion of these water masses, which would be more commonly found to the south of the APF (Fig. 4). Of particular interest is the subsurface temperature distribution in the far eastern edge of the survey grid, which may suggest the presence of a cold core eddy (Fig. 2). In this feature temperatures are less than <1.5°C and are typical of the remnants of Winter Water, suggesting that this water mass may have been entrained by a cyclonic eddy spawned at the APF. Drifter trajectories obtained during DEIMEC II showed the formation of intense cyclonic eddies in the lee of the South-West Indian Ridge at 48°S and 34°30′E. Further information, regarding the exact nature of this feature, will be gathered from a number of profiling floats deployed at select depths within the survey region and will be available over the next few months.

Biological

Total integrated chl-*a* concentration during the survey ranged from 4.15 to 22.81 mg chl-*a* m^{-2}, with the highest concentrations recorded at stations occupied in the region associated with the

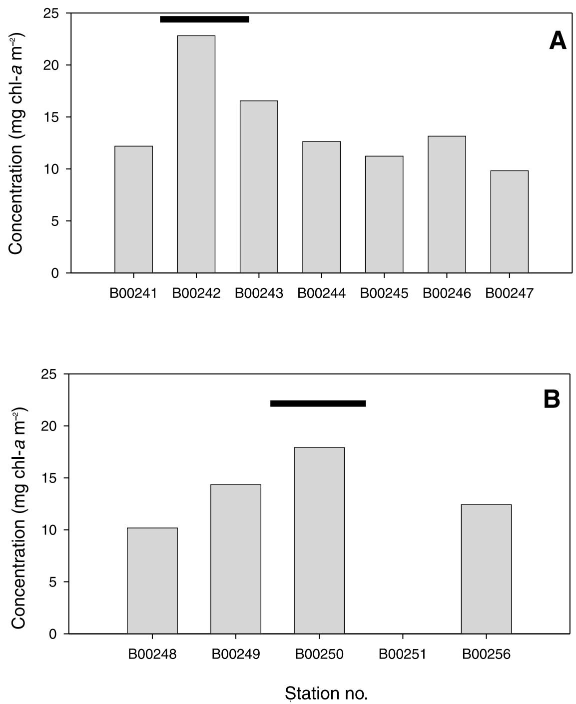

Fig. 5. Total integrated chl-*a* concentration along transects **A** and **B** of the oceanographic survey during voyage 116 of the *SA Agulhas* to the Polar Fontal Zone. Horizontal bars indicate the position of the frontal system encountered during the survey.

intense frontal system centred at 29°E, 48°45′E (Fig. 5A,B). Throughout the study, total chl-*a* concentration was dominated by the picophytoplankton (<2.0 μm), which comprised 39–59% of the total pigment. Exceptions were evident at stations occupied in the region of the frontal feature, where the nanophytoplankton (2.0–20 μm) size fraction generally represented the largest contributor to total chl-*a* concentration. The contribution of the microphytoplankton (>20 μm) to total chl-*a* concentration was always less than 10%.

Total zooplankton abundance during the entire investigation was numerically dominated by mesozooplankton (200–2000 μm) comprising small copepods of the genera *Oithona, Clausocalanus, Ctenocalanus* and *Metridia,* and by the pteropod, *Limacina* sp. In the region associated with Antarctic Surface Water south of the front, the copepod *Rhincalanus gigas* was also well represented among the copepod community. Among the macrozooplankton (>2000 μm), a distinct spatial pattern in community structure was observed. North of the frontal system, the temperate euphuasiids, *Euphausia similis* and *E.vallentini,* and the amphipod, *Themisto gaudichaudi,* numerically dominated the macrozooplankton. South of the frontal system, the macrozooplankton community was numerically dominated by the tunicate *Salpa thompsoni,* and the amphipod *T. gaudichaudi.* Chaetognaths of the genera *Sagitta* (mainly *S. gazellae* and *S. maxima*) and *Eukrohnia* (*E. hamata*) were common throughout the region investigation. A detailed investigation of the zooplankton community structure and the results of the herbivory and carnivory studies will be analysed in the laboratory.

Conclusion

Altimetry data suggest that the region in the vicinity of the South-West Indian Ridge is one of high variability. However, hydrographic data collected during the DEIMEC programme (2002–04) have shown a distinct southward deflection in the position of the frontal systems as the ACC is topographically steered across the South-West Indian Ridge. Closer inspection of sea-surface height data reveals a distinct southward curvature in altimetry, which appears to correlate with the deflection in the fronts. This suggests that the position of the SAF and APF frontal systems may in fact be quasi-stationary and act as a boundary to the passage of eddies, which are formed at the ridge and move eastwards within such a corridor into the vicinity of Prince Edward Island. Drifter data obtained from DEIMEC II further support this concept, with evidence for the formation of both anticyclonic and cyclonic eddies downstream of the ridge. In agreement with a number of previous studies conducted in the Southern Ocean,[10] the intense frontal system encountered during the survey was characterized by elevated chl-*a* concentrations and acted as a strong biogeographic barrier to the distribution of zooplankton within the study region.

1. Snaith H.M. and Robinson I.S. (1996). A study of currents south of Africa using Geosat satellite altimetry. *J. Geophys. Res.* **101**, 18141–18154.
2. Lutjeharms J.R.E. and Baker D.J. (1980). A statistical analysis of the meso-scale dynamics of the Southern Ocean. *Deep-Sea Res.* **27**, 145–159.
3. Ansorge I.J. and Lutjeharms J.R.E. (2003). Eddies originating at the South-West Indian Ridge. *J. Mar. Sys.* **39**, 1–18.
4. Froneman P.W., Ansorge I.J., Vumazonke L., Gulekana K., Webb A.M., Leukes W., Risien C.M., Thomalla S., Bernard K., Hermes J., Knott M., Anderson D., Hargey N., Jennings M., Veitch J., Lutjeharms J.R.E. and McQuaid C.D. (2002). Physical and biological variability in the Antarctic Polar Frontal Zone: report on research cruise 103 of the MV *SA Agulhas. S. Afr. J. Sci.* **98**, 534–536.
5. Pollard R.T. and Read J.F. (2001). Circulation pathways and transports of the Southern Ocean in the vicinity of the Southwest Indian Ridge. *J. Geophys. Res* **106**, 2881–2898.
6. Craneguy P. and Park Y-H. (1999). Topographic control of the Antarctic Circumpolar Current in the South Indian Ocean. *C. R. Acad. Sci. Paris* **328**, 583–589.
7. Budillon G. and Rintoul S.R. (2003). Fronts and upper ocean thermal variability south of New Zealand. *Antarct. Sci.* **15**, 141–152.
8. Nel D.C., Lutjeharms J.R.E, Pakhomov E.A., Ansorge I.J., Ryan P.G. and Klages N.T.W. (2001). Exploitation of mesoscale oceanographic features by grey-headed albatrosses *Thalassarche chrysostoma* in the southern Indian Ocean. *Mar. Ecol. Prog. Ser.* **217**, 15–26.
9. Melice J-L., Lutjeharms J.R.E., Rouault M. and Ansorge I.J., (2003). Sea surface temperatures at the Sub-Antarctic Islands Gough and Marion during the past 50 years. *S. Afr. J. Sci.* **99**, 1–4.
10. Pakhomov E.A., Froneman P.W., Ansorge I.J. and Lutjeharms J.R.E. (2000). Temporal variability in the physico-biological environment of the Prince Edward Islands (Southern Ocean). *J. Mar. Syst.* **26**, 75–95.
11. Ansorge I.J. and Lutjeharms J.R.E. (2000). Twenty-five years of physical oceanographic research at the Prince Edward Islands. *S. Afr. J. Sci.* **96**, 557–565.
12. Read J.F. and Pollard R.T. (1993). Structure and transport of the Antarctic Circumpolar Current and the Agulhas Return Current at 40°E. *J. Geophys. Res.* **98**, 12281–12295.
13. Park Y-H., Gamberoni L. and Charriaud E. (1993). Frontal structure, water masses and circulation in the Crozet Basin. *J. Geophys. Res.* **98**, 12361–12385.
14. Park Y-H. and Gamberoni L. (1997). Cross-frontal exchanges of Antarctic Intermediate Water and Antarctic Bottom Water in the Crozet Basin. *Deep-Sea. Res.* **44**, 963–986.