Antarctic Science 22(3), 211–219 (2010) © Antarctic Science Ltd 2010 doi:10.1017/S0954102010000088

Review
Oceanographic observations of eddies impacting the Prince Edward Islands, South Africa

JONATHAN V. DURGADOO*, ISABELLE J. ANSORGE and JOHANN R.E. LUTJEHARMS

Department of Oceanography, University of Cape Town, Rondebosch 7700, South Africa
**Current address: Leibniz-Institut für Meereswissenschaften (IFM-GEOMAR), Kiel, Germany*
jdurgadoo@gmail.com

Abstract: The ecosystem of the isolated Prince Edward Islands, south of the African continent, is strongly impacted by ocean eddies that are associated with the eastward flowing Antarctic Circumpolar Current. Satellite altimetry has revealed that the archipelago lies in a region of enhanced eddy kinetic energy. In the late 1990s it became apparent that in order to understand the influence of these eddies on the islands' ecosystem, the source, trajectory and nature of these eddies needed to be studied and understood. To this end a special research project with a strong ocean-going component was designed, the DEIMEC (Dynamics of Eddy Impact on Marion's ECosystem) programme. In this review we focus on the physical oceanography and summarize the aims, the results and the successes of this South African research initiative. In the vicinity of the Prince Edward Islands, an average of three intense well-defined eddies is observed per year. Their advection speeds are of the order of a few kilometres per day and longevities of 7–11 months. These features, of *c.* 100 km in diameter and reaching depths of at least 1000 m, transport anomalous water masses across the Polar Frontal Zone.

Received 26 March 2009, accepted 21 December 2009

Key words: DEIMEC, Marion Island, Mesoscale eddies, South African National Antarctic Programme (SANAP), Southern Ocean, South-West Indian Ridge

Introduction

The quasi-permanent band of low pressure around the Antarctic continent and the band of high pressure in the subtropics work in synergy to produce strong westerly geostrophic winds over the Southern Ocean. This wind stress drives the eastward flowing Antarctic Circumpolar Current (ACC), which is part of the deep transport of the global conveyor belt. It carries approximately 134 ± 13 Sv (1 Sv = 10^6 m^3 s^{-1}) of polar and subpolar water masses through the Drake Passage (Whitworth 1983, Nowlin & Klinck 1986) and 160 Sv south of Africa (Park *et al*. 2001). The flow of the ACC is concentrated at frontal bands (Orsi *et al*. 1995, Belkin & Gordon 1996). To the north, the Subtropical Convergence (STC) separates the warm sub-tropical gyres from the sub-Antarctic regime. The Sub-Antarctic Front (SAF) demarcates the northern boundary of the Antarctic Polar Frontal Zone. With a weaker surface temperature expression, the SAF is usually identified at the subsurface, typically at 200 m. The Antarctic Polar Front (APF) marks the southern boundary of the Antarctic Polar Frontal Zone and the beginning of the Antarctic Zone. Bottom topography and prevailing westerly winds, in tandem, play a major role in the temporal and spatial variability in the flow in the Antarctic Polar Frontal Zone throughout the Southern Ocean (Nowlin & Klinck 1986, Park *et al*. 1993).

The main core of the ACC is commonly associated with the SAF and APF (Rintoul & Sokolov 2001, Budillon & Rintoul 2003). South of the African continent, based on 89 hydrographic sections, the STC, SAF and APF are located on average at 41.6 ± 1.07°S, 46.4 ± 1.07°S and 50.3 ± 1.33°S respectively (Lutjeharms & Valentine 1984). Upon encountering prominent topographic features, the ACC is deflected in a way that conserves potential vorticity. South of Africa (Fig. 1), in the vicinity of the South-West Indian Ridge (SWIR), the position and structure of the SAF and APF are very variable. Read & Pollard (1993) have reported only one major intense front along 33°E. Earlier studies, however, gave the SAF and APF at distinct latitudes (Lutjeharms & Valentine 1984). Having found two branches of the SAF in their section at 30°E, Park *et al*. (2001) scrutinized Read & Pollard's results finding two expressions of the APF. The discrepancy was attributed to a possible cold eddy inducing a meandering in the front. Downstream of the SWIR, the ACC breaks up into multiple fragments (Holliday & Read 1998, Pollard & Read 2001). Kostianoy *et al*. (2004), using satellite sea surface temperature data (1997–99), mapped the fronts in the Indian sector of the Southern Ocean. In the western part (20–60°E), their results depict the latitudinal variability of the SAF and APF as well as giving a clear indication of their temporal variability and fragmentation.

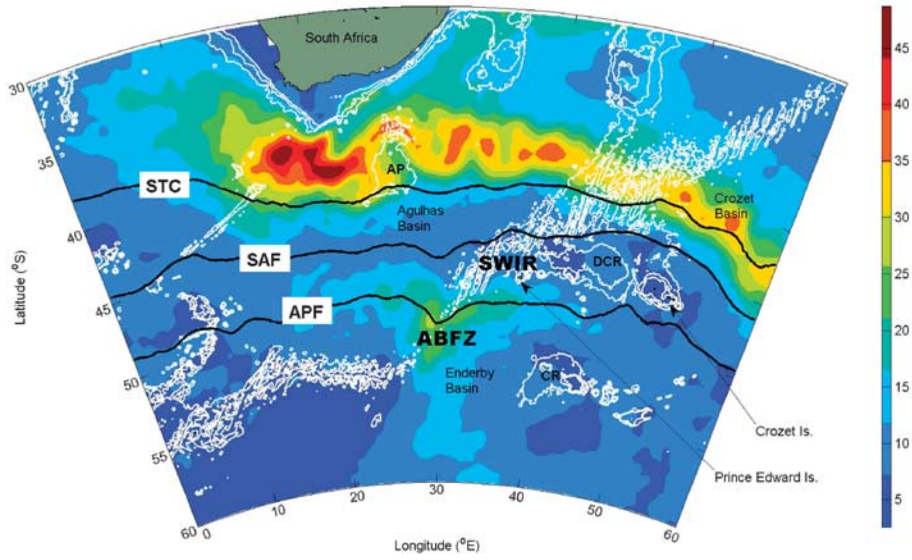

Fig. 1. The root-mean-square (rms) in Sea Level Anomaly (cm) calculated from a 13-year record of altimetry products. Bathymetric contours (-3000, -2000, -1000 m) are overlaid in white. The average position of the three major fronts associated with the ACC, derived from a five year sea surface temperature dataset from AMSR-E, is also shown: the Subtropical Convergence (STC, 14°C), the Subantarctic Front (SAF, 8°C) and the Antarctic Polar Front (APF, 4°C). Some important topographic features are shown: SWIR = South-West Indian Ridge, ABFZ = Andrew Bain Fracture Zone, CR = Conrad Rise, AP = Agulhas Plateau, DCR = Del Cano Rise.

The Prince Edward Islands are found in this highly variable environment. This island group consists of Marion Island and Prince Edward Island, the former being the largest. The islands, of volcanic origin, rise to prominence above the SWIR at 46.7°S, 37.7°E (Fig. 1). The ridge separates the African plate from the Antarctic plate and is intersected by a series of composite deep fractures. The Andrew Bain Fracture Zone centred at 50°S, 30°E is of particular importance because of its direct influence on the eastward-flowing ACC (Ansorge & Lutjeharms 2003). Approximately 110 ± 10 Sv of the current is channelled through this particular gap (Pollard & Read 2001). Over the last two decades, research around the Prince Edward Islands and the general area surrounding the SWIR has been undertaken primarily by South African scientists.

Studies leading to DEIMEC

Surveys around the SWIR prior to 1989 were sparse with most studies undertaken in the direct vicinity of the Prince Edward Islands, where an enhanced marine productivity was observed (Allanson *et al*. 1985, Rae 1989a, 1989b, 1989c, Perissinotto & Boden 1989, Perissinotto *et al*. 1990). A few transects revealed the position of the Southern Ocean fronts with respect to the location of the islands (Lutjeharms & Valentine 1984, Lutjeharms 1985, Rae 1989a, 1989b, Lutjeharms 1990). The structure of the ACC in that region was known and the temporal and spatial variability of the fronts were acknowledged (Read & Pollard 1993, Park *et al*. 1993, Ansorge *et al*. 1999). Various hypotheses have been put forward to explain the enhanced biological productivity observed in close proximity to the islands (Ansorge & Lutjeharms 2000, McQuaid & Froneman 2004). Boden (1988) suggested an 'island mass effect' where nutrient-rich runoff from the islands is contained between Marion and Prince Edward and sustain an abundant biota. The Von Kármán vortex street theory was also proposed (Allanson *et al*. 1985). This theory suggested that persistent downstream swirls would exist due to the unsteady separation of the ACC by the islands which would effectively result in successive up

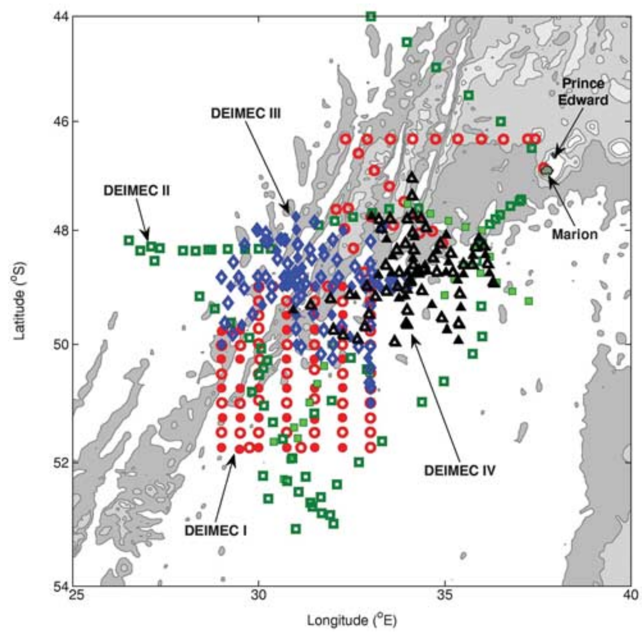

Fig. 2. The distribution of hydrographic stations for DEIMEC I (4–18 April 2002), II (6–18 April 2002), III (13–25 April 2002) and IV (14–25 April 2002) are shown using red circles, green squares, blue diamonds and black triangles respectively. The open and filled versions of the symbols represent XBT and CTD locations respectively. Bathymetric contours (< 4000 m at 1000 m interval) show the location of the stations with respect to the SWIR and the islands.

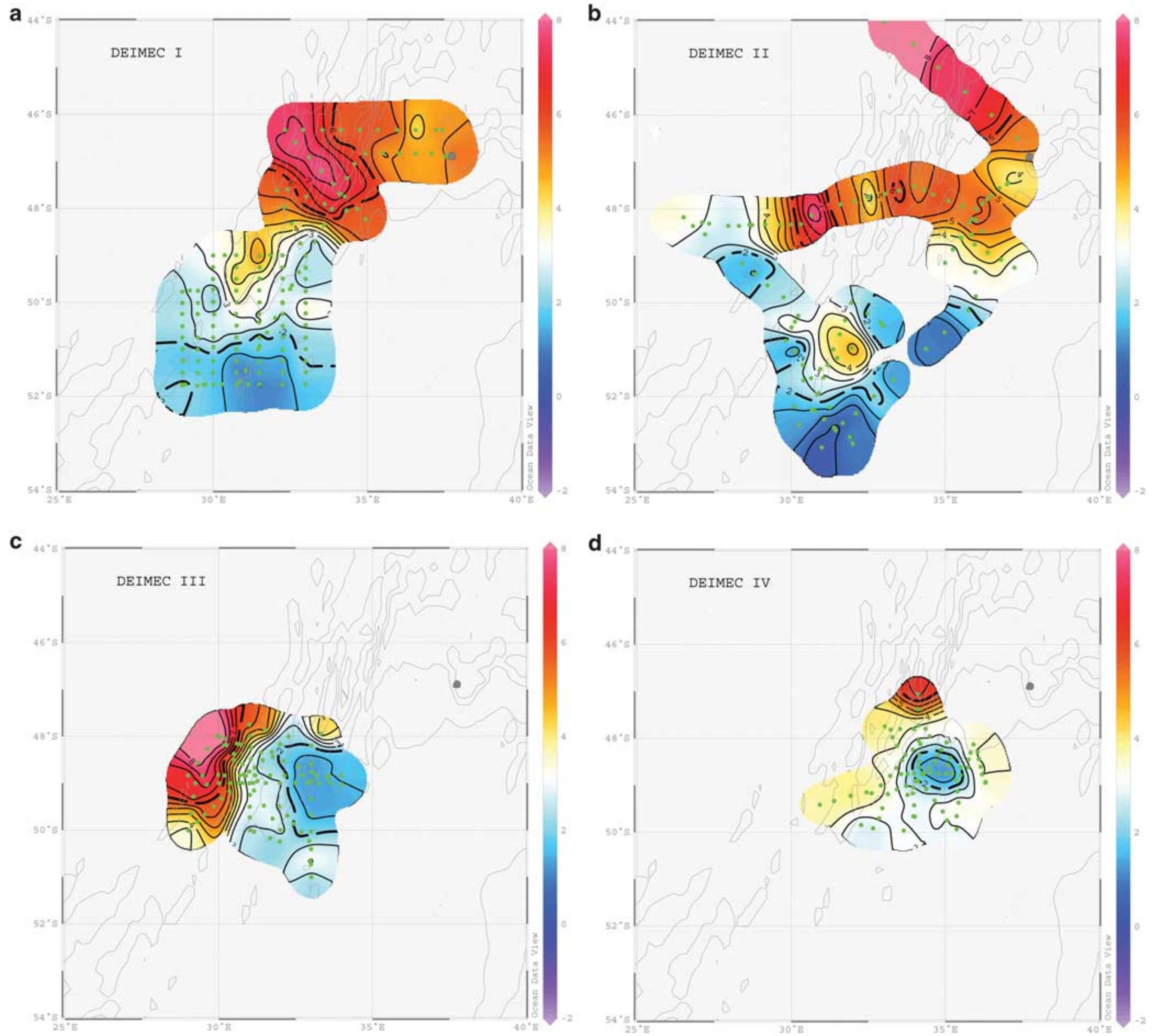

Fig. 3. Subsurface (200 m) temperature measured during the four DEIMEC cruises. Contours are drawn at 0.5°C interval and the subsurface axial position of the SAF and APF are indicated by the 6°C and 2°C dashed contours respectively. Bathymetry (2000, 3000 and 4000 m) as well as station positions (green dots) are shown.

and downwelling events. Later surveys revealed the presence of an anti-cyclonic eddy between the islands favouring retention of nutrients in a suggested Taylor column (Rae 1989b, Perissinotto & Rae 1990, Perissinotto *et al*. 1990).

The second Marion Offshore Ecological Survey (MOES-II), undertaken in April 1989, was an attempt to resolve the conundrum. MOES-II provided the first quasi-synoptic view of the general environment around the Prince Edward Islands both up and down stream (46–47.5°S, 35.9–40.5°E, see Ansorge & Lutjeharms 2000, fig. 4). It was established that the oceanographic conditions upstream of the islands were different to those downstream (Perissinotto *et al*. 2000). Upstream, the region surveyed showed a gradual change from sub-Antarctic water masses to the north to Antarctic water masses to the south. A sharp deflection of the SAF north-eastward was observed close to the islands. In contrast, downstream of the islands large deep meanders with wavelength of the order of 120 km associated with the SAF were observed (Ansorge & Lutjeharms 2002). This favoured the exchange of Antarctic and sub-Antarctic water masses across the Polar Frontal Zone. A warm eddy, resulting from the meandering SAF, was observed further downstream of the islands.

A repeat survey, the Marion Island Oceanographic Survey II (MIOS-II), was carried out eight years later covering an even wider geographic region (46–48°S, 36–42°E, Ansorge & Lutjeharms 2000). The oceanographic conditions turned out to be very different from those seen during MOES-II. In the western side of the survey area the SAF was intensified, deflecting north-eastward on approaching the islands. Further downstream, two branches of the SAF were observed (Ansorge & Lutjeharms 2002). Amidst the meandering SAF, eddies were still present downstream of the islands. However, eddies were also present upstream of the islands, which therefore nullified the hypothesis of a Von Kármán vortex street being the main circulation system at the islands. The recurring eddy activity triggered much interest, especially with respect to the meridional exchange of water masses and associated plankton activity. The enhanced biological activity observed very close to the islands was found to be closely related to these eddies (Ansorge *et al*. 1998, Pakhomov *et al*. 1998, 2000a, 2000b, Froneman *et al*. 1999, Ansorge & Lutjeharms 2002). Water masses entrained in these features were either of sub-tropical/sub-Antarctic (for warm eddies) or Antarctic (for cold eddies) origin.

Satellite altimetry provided evidence that the SWIR region was one of high mesoscale variability (Fig. 1) with the Prince Edward Islands lying at the northern border of that region (Ansorge & Lutjeharms 2003). An attempt to correlate Sea Surface Height Anomaly (SSHA) to sea surface temperature in that region was made (Ansorge & Lutjeharms 2000, 2003). Positive anti-cyclonic anomalies were found to correspond closely to warm eddies, while negative cyclonic anomalies corresponded to cold eddies. Because of the inherent advantage of satellite remote sensing to provide a continuous data set, it was possible to look at the trajectories and decay of the anomalies as well as to determine their origin. The anomalies were found to originate at the SWIR, roughly centred at 50°S, 30°E, corresponding to the axial position of the Andrew Bain Fracture Zone. Once formed, these features follow a north-eastward direction, along the eastern flank of the ridge until about 47°S where they drift pass the islands. Thereafter, the anomalies are in the final stage of decay and move eastward in the Enderby Basin. An eddy corridor was empirically defined between 48–49°S and 34–38°E (Ansorge & Lutjeharms 2003). Intense anomalies (eddies) were characterized having SSHA $> +30$ cm (or $<$ -30 cm) (Pakhomov *et al*. 2003, Ansorge & Lutjeharms 2003, 2005). However, comprehensive hydrographic data were not available to draw significant conclusions. The collocation of SSHA and eddies in that region remained to be confirmed. Moreover, the vertical structure of the features as well as their precise decay mechanisms were unknown. Nonetheless, it was clear that eddies observed during MOES-II and MIOS-II were present not only as a result of the islands' interaction with the ACC, but also because of the complex dynamics between the frontal systems and the bathymetry further afield.

The DEIMEC surveys

Hydrographic validation of results obtained from satellite altimetry was the next logical step to better understanding the circulation near the Prince Edward Islands. The Dynamics of Eddy Impact on Marion's ECosystem (DEIMEC) programme started in 2002 with the aim to characterize these eddies. Under the programme, four surveys were undertaken (2002–05) during autumn (April/May) on board the South African supply and research vessel, the *SA Agulhas*. The physical setting of the SWIR region as well as its biological community distribution were investigated with transects consisting of alternating Conductivity-Temperature-Depth (CTD) and eXpendable Bathy-Thermograph (XBT) stations with chlorophyll *a* measurements taken at every CTD station (Fig. 2). A total of 121 CTD and 265 XBT stations were occupied during the four DEIMEC cruises. Drifters and floats were deployed at strategic positions within eddies. Bongo and WP-2 nets, RMT-8 trawls and bottom dredges were also used to study the zooplankton community structure, complementing the physical description of the extended environment around the islands.

The first DEIMEC cruise (4–18 April 2002) surveyed the area around the Andrew Bain Fracture Zone, source region of the eddies. Eleven sections were occupied and two frontal features were encountered, the southern branch of the SAF and the APF. The former exhibited a high degree of meandering while the latter was concentrated within a narrow band at 51°S (Fig. 3a). More importantly, it was established that the fracture zone constricted the flow of the ACC, acting as a choke point (Froneman *et al*. 2002). A rich mesozooplankton community structure was also observed in the region, particularly close to the APF (Bernard & Froneman 2003). No eddies were encountered during the survey. DEIMEC-I provided further evidence of the dynamic and variable nature of the ACC in that region, the direct impact this has on the biology and the increased speed of the ACC through the fracture zone.

Satellite altimetry was used to locate three sea surface height anomalies that could be investigated during the DEIMEC-II cruise (6–18 April 2003). The anomalies were all found to coincide with eddies, confirming earlier hypothesis of such a relationship (Pakhomov *et al*. 2003). Water masses at the core of these features were characteristic of either Sub-Antarctic Surface Water (SASW) or Antarctic Surface Water (AASW). Two positive anti-cyclonic SSHA were associated with relatively warmer SASW while the negative cyclonic SSHA entrained fresher and colder AASW. Of the two warm eddies, the one closer to the islands, had a weaker temperature/salinity signature, giving an indication of the decay of the feature. Detailed study of the zooplankton composition showed a clear distinction in the origins of these features (Ansorge *et al*. 2009). Moreover, the APF was found to show extensive meandering, in contrast to what was observed in DEIMEC-I (Fig. 3b). Two surface drifters deployed during the survey further

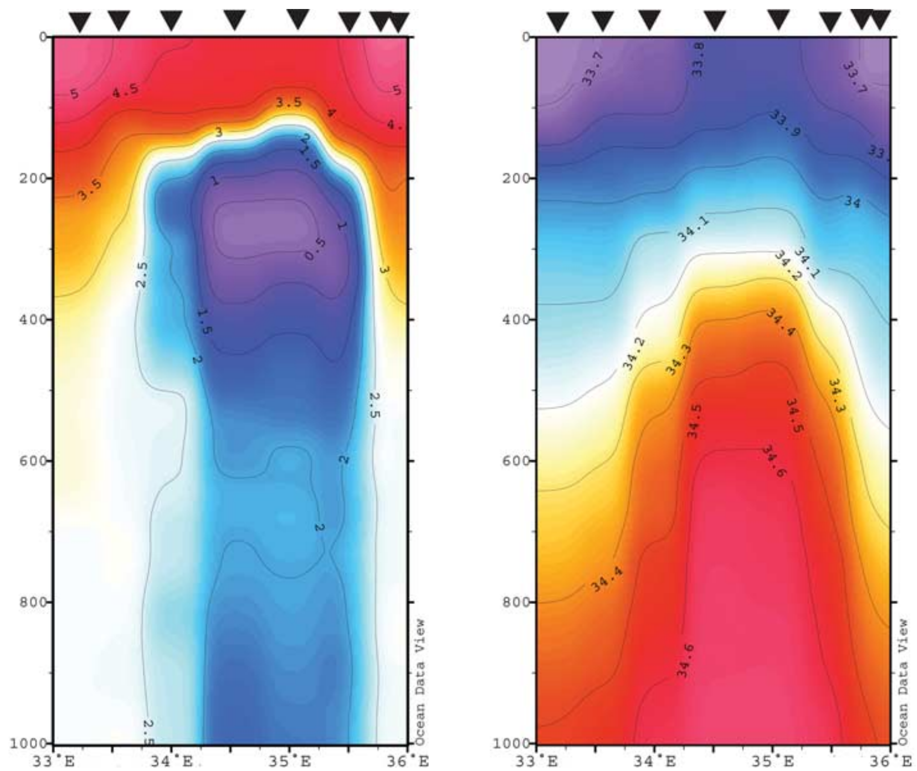

Fig. 4. Zonal sections of **a**. potential temperature (°C), and **b**. salinity (psu) across DEIMEC IV eddy. The upper 1000 m of this eddy was extensively surveyed with successive XBT and CTD stations (shown by inverted triangles) in 2005. (Adapted from Ansorge *et al*. 2006 and Swart *et al*. 2008).

demonstrated that the turbulence at the ridge consisted of eddies travelling east (Ansorge & Lutjeharms 2005).

A sharp SSH gradient, altimetrically identified, was found to correspond to an intense front during DEIMEC-III (13–24 April 2004). A detailed hydrographic study of the front revealed that it consisted of both the SAF and the APF (Ansorge *et al*. 2004). The juxtaposition of these two frontal systems once more highlighted the variable nature of the physical dynamics induced by the ridge and the fracture zone on the ACC (Fig. 3c). Highest values of total integrated chlorophyll *a* (22.8 mg chl *a* m^{-2}) were observed to coincide with the location of this double front, while elsewhere, values ranged between 4 and 11 mg chl *a* m^{-2} (Ansorge *et al*. 2004).

The last in the series of the DEIMEC cruises, IV (14–25 April 2005), extensively surveyed an intense ($<$ -40 cm) negative SSH anomaly (Ansorge *et al*. 2006). As anticipated, the anomaly was found to match the position of a cold eddy. The feature was *c.* 200 km in diameter, more than 1000 m deep (Fig. 4) and was located south of the SAF, which lay at *c.* 47.1°S (Fig. 3d). The APF was not encountered. However, water masses associated with this eddy suggested unambiguously that the feature originated south of the APF. This particularly interesting eddy was studied in great detail (Bernard *et al*. 2007, Swart *et al*. 2008). De Szoeke & Levine (1981) suggested that mesoscale features in the Southern Ocean could play a crucial role in meridional heat flux required to compensate heat loss through air-sea interactions. With that in mind, the total available heat and salt anomaly associated with the eddy relative to the surrounding waters was calculated (Ansorge *et al*. 2006, Swart *et al*. 2008). Since the eddy totally dissipated within the Antarctic Polar Frontal Zone, its heat and salt content (-5.4×10^{19} J and -6.6×10^{11} kg respectively) constituted a cross APF flux. It was estimated that this eddy accounted for 0.5% (0.25%) of the required annual circumpolar heat (salt) flux across the APF. When compared with similar studies from other regions of the Southern Ocean (e.g. Morrow *et al*. 2004), these values were shown to be larger. It was concluded that a meridional heat/salt pump exists at this location (Ansorge *et al*. 2006). Furthermore, such an intense cold eddy has the ability to modify water mass characteristics, particularly Subantarctic Mode Water, which is ventilated annually, and Antarctic Intermediate Water (Swart *et al*. 2008).

Biological observations made within the cold eddy during DEIMEC-IV (Bernard *et al*. 2007) showed that, in general, eddies play a distinct role as vehicles for zooplankton transport. In their study, Bernard *et al*. (2007) have shown from numerical analysis that the euphausiid community within the survey area consisted of three distinct groupings: those associated with the Antarctic Polar Frontal Zone waters, those at the edge of the eddy and those within the eddy core and thus typical of Antarctic species. Furthermore, they have highlighted the importance in considering eddy activity hotspots as key productive components within the food chain. Eddies located in the high latitudes increase the spatial heterogeneity of the zooplankton community.

At the culmination of the DEIMEC programme, the main objectives to study the source region of the eddies, to hydrographically characterize them and to study their biological impact had been reached. The results from these

https://doi.org/10.1017/S0954102010000088 Published online by Cambridge University Press

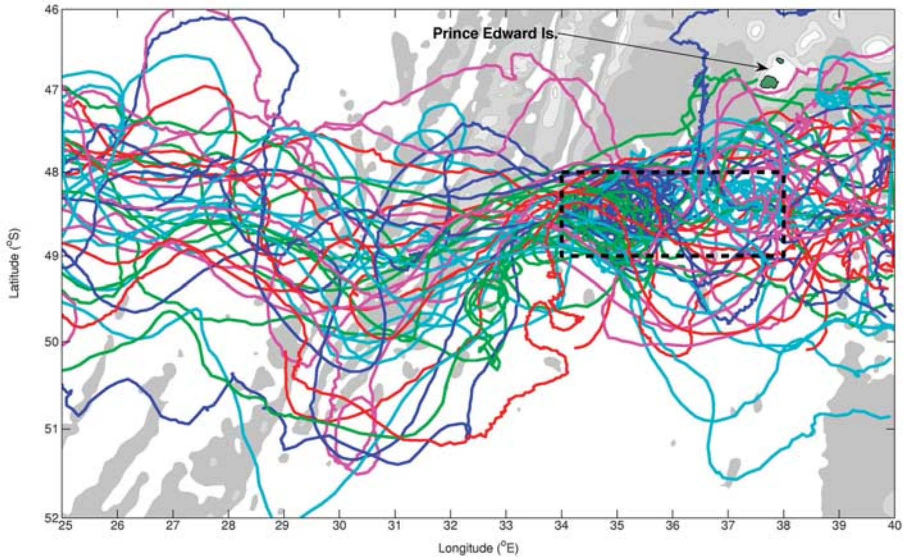

Fig. 5. Drift tracks from 43 drifters that have crossed the eddy corridor over a period of nine years (2000–08). The corridor (shown by the dashed black rectangle) has been empirically defined by Ansorge & Lutjeharms (2003) to lie between 48–49°S and 34–38°E. Bathymetric contours (< 4000 m at 1000 m interval) are also drawn.

four surveys provided the first set of direct measurements at the ridge.

Frontal dynamics at the Prince Edward Islands

Frontal dynamics in this region are complicated. It is only in recent years, during the four DEIMEC surveys, that we have been able to separate the relationship of the frontal systems occurring in close proximity of the islands from that of further afield. Figure 3 shows the subsurface 200 m temperature during each of the four cruises. Following Park *et al.* (1993), the 6°C and 2°C isotherms are used to identify the subsurface location of the SAF and APF respectively. The location of the fronts in these four snapshots attests to the

Table I. Hydrographic characteristics of cold and warm eddies based on data following MIOS-II and DEIMEC cruises. Letters in brackets indicate reference to published material: A = Ansorge & Lutjeharms (2003), B = Ansorge & Lutjeharms (2005), C = Pakhomov *et al.* (2003), D = Ansorge *et al.* (2006), E = Swart *et al.* (2008). The roman numerals within the brackets indicate the relevant DEIMEC cruise where the values were obtained, M2 = MIOS-II.

	Cold eddies		Warm eddies	
Sea surface height anomaly	Negative		Positive	
Intense SSHA	< -30 cm	(B, II)	> +25 cm	(A, M2)
	< -40 cm	(D, IV)	> +40 cm	(B, II)
Number of intense SSHA per year	3	(D, IV)		
Rotation	Cyclonic		Anti-cyclonic	
Diameter	125 km	(B, II)	250 km	(B, II)
	175–200 km	(D, IV; E, IV)		
Depth	> 1000 m	(D, IV)	> 800 m	(B, II)
Geostrophic speed (boundary)	0.69 ms^{-1}	(B, II)	0.35–0.5 ms^{-1}	(B, II)
	0.45–1.40 ms^{-1}	(D, IV)		
Geostrophic speed (core)	0.08–0.10 ms^{-1}	(D, IV)	0.08–0.10 ms^{-1}	(B, II)
Surface water	Antarctic Surface Water		Sub-Antarctic Surface Water	
	< 4°C, < 33.70	(C, II)	> 5°C, > 33.85	(C, II)
	4.2–4.4°C,	(D, IV)		
	33.77–33.83	(D, IV)		
Sub-surface water	Winter Water		Salinity maximum	
	< 0.4°C, 34.1	(D, IV)	4.09°C, 34.1	(B, II)
Advection speed	2–5 km day^{-1}	(A, M2)	2–5 km day^{-1}	(A, M2)
	4–8 km day^{-1}	(B, II)		
	2 km day^{-1}	(D, IV)		
Longevity	7–11 months	(D, IV; E, IV)	9–11 months	(A, M2)
Available heat anomaly	-5.4×10^{19} J	(E, IV)		
Available salt anomaly	-6.6×10^{11} kg	(E, IV)		

high degree of variability of the ACC structure upstream of the Prince Edward Islands. On average, the SAF is deflected north-eastwards upon encountering the ridge (Fig. 1). Yet on all four occasions during the DEIMEC surveys, the SAF was encountered south of 45°S. An attempt was made by Sokolov & Rintoul (2007) to reconcile the classical hydrographic portrayal of the ACC with the more modern multiple-filament portrayal from satellite and model data. They reached the conclusion that the multiple jet structure of the ACC fronts are aligned along streamlines of sea surface height contours. Despite the differences in datasets used to identify the ACC front in Figs 1 & 3, it is conceivable that the observed variability of the fronts at the SWIR (in Fig. 3) is integral to the multi-filament nature of the ACC.

Hydrographic conditions favouring algal blooms, as reported by Perissinotto & Rae (1990), were attributed to instances when the SAF lay north of the islands. During such periods, it has been shown that water masses are retained within the island region, encouraging bloom growth. Large populations of species typical of the Antarctic are observed (Pakhomov *et al*. 2000b) suggesting that water characteristic of modified Antarctic Surface Water dominates this region under these conditions. In sharp contrast, when the SAF lay in close proximity to the islands, a combination of sub-Antarctic and sub-tropical species indicative of such water masses has been reported (Pakhomov *et al*. 2000b). On such occasions strong advective forces predominates and water masses pass actively through the island group. Consequently, productivity in the vicinity of the Prince Edward Islands appears to be sensitive to the latitudinal position of the SAF. It seems obvious that the meandering pattern of the SAF plays an influential role on the ecosystem of the inter-island region.

Conclusion

Following the MOES-II and MIOS-II surveys, the complexity of the physical setting of the Prince Edward Islands was established. The increased biological activity previously only observed around the islands was found to be in direct response to physical dynamics at the SWIR (Froneman *et al*. 1999, Pakhomov *et al*. 2000b). The SAF and APF, carrying the core of the ACC, are highly variable east of the ridge (Pakhomov *et al*. 1998, 2003, Perissinotto *et al*. 2000, Lutjeharms *et al*. 2002). Figure 5, showing trajectories of 43 drifters, highlights the general flow at the SWIR. Two sharp deflections in trajectories are noted. Upstream of the ridge, most drifters are deflected south-eastward through the Andrew Bain Fracture Zone, and between 30° and 31°E they veer towards the north-east. Thereafter, east of 34°E, the drifters are entrained in a number of gyrations and low amplitude meanders. It is therefore evident that the region immediately south of the Prince Edward Islands is one of enhanced mesoscale turbulence. Satellite altimetry provided further insight on this turbulence. Eddies generated at the SWIR closely correlate to sea surface height anomalies from altimetry (Ansorge & Lutjeharms 2003, 2005, Pakhomov *et al*. 2003, Ansorge *et al*. 2004, 2006). The DEIMEC programme allowed detailed hydrographic studies of these mesoscale features and Table I summarizes what transpired from these surveys. Latest results further suggest that the enhanced mesoscale variability associated with the ridge could have profound climatological impact, not only for the islands downstream, but for the local heat and salt budget (Ansorge *et al*. 2006).

Despite the successes of the DEIMEC programme, many questions remain. During the four-year programme, two warm and two cold features were studied. DEIMEC-IV provided arguably the best coverage of a single cold feature in that area (Table I and Fig. 4). Unfortunately the programme failed to provide a detailed survey of a warm eddy.

The oceanic environment around the Prince Edward Islands sustains the abundant bird life and marine mammals found on the islands. Grey-headed albatrosses from the islands feed on the edges of eddies generated at the ridge (Nel *et al*. 2001). On-going research, seeking to understand the behaviour of mammals on the islands, has shown that seals adopt a similar trajectory in their foraging preference (Jonker & Bester 1998). While details of the underlying reasons for this behaviour are unclear, these and other observations suggest that the ecological role of transient mesoscale features may be profound. It is therefore imperative to understand the mechanism behind the enhanced biological activity at the edges of eddies.

Observations of behavioural changes in sub-Antarctic top predators led Weimerskirch *et al*. (2003) to postulate a system shift from one equilibrium state to another, in response to the observed 0.17°C average warming of the Southern Ocean since the 1950s (Gille 2002). Such a regime shift could impact the structure and intensity of the ACC frontal systems, and thereby affect, adversely or otherwise, the distribution of plankton usually associated with these fronts. A recent study has revealed that over the last 50 years, sea surface temperature at Marion Island has risen by 1.4°C (Mélice *et al*. 2003). Rouault *et al*. (2005) have attributed the observed warming to a change in mid-latitude climate and to the shift in phase of the semi-annual oscillation - a pronounced cycle in pressure, temperature and wind at mid-latitudes in the Southern Hemisphere. The sensitivity of eddy generation in response to this increase in sea surface temperatures remains to be investigated.

All four DEIMEC surveys were undertaken in autumn. Consequently, observations were limited to only a temporal snapshot of the eddies during the time of the respective cruises. It would be very useful to study the life history of a few eddies. This would be of particular importance in understanding the biological changes within a feature over time. It can be achieved by using a combination of satellite products and a succession of direct hydrographic observations. However, because of the unfeasibility of continuous sea-going monitoring, a mooring array upstream of the islands could be used to monitor passing eddies over a few years.

Little information is available on the decay of eddies at the ridge. Numerical modelling of processes in the SWIR region is the next logical step in understanding the observed and well-documented dynamics (Durgadoo 2008). Characteristic values pertaining to eddies at the SWIR presented in Table I could be used to validate outputs from eddy resolving models.

Acknowledgements

We thank the South African National Antarctic Programme and the University of Cape Town for funding, the officers and crew of the research and supply vessel *SA Agulhas* crew for support and many keen students for participation. The collegial collaboration with biological oceanographers from the Southern Ocean group at Rhodes University is much appreciated. JVD further thanks the Social Science Research Council Mellon Mays Graduate Initiative Program for funding. Altimetry data was acquired from AVISO ftp://ftpsedr.cls.fr/pub/oceano/AVISO/SSH/duacs/global/dt/ref/msla; AMSR-E data from ftp.ssmi.com/amsre and drifter data from http://www.aoml.noaa.gov/envids/gld/. The constructive comments of the reviewers are also gratefully acknowledged.

References

Allanson, B.R., Boden, B.P. & Duncombe Rae, C.M. 1985. A contribution to the oceanography of the Prince Edward Islands. *In* Siegfried, W.R., Condy, P.R., Laws, R.M., *eds. Antarctic nutrient cycles and food webs*. Berlin: Springer, 30–45.

Ansorge, I.J. & Lutjeharms, J.R.E. 2000. Twenty-five years of physical oceanographic research at the Prince Edward Islands. *South African Journal Science*, **96**, 557–565.

Ansorge, I.J. & Lutjeharms, J.R.E. 2002. The hydrography and dynamics of the ocean environment of the Prince Edward Islands (Southern Ocean). *Journal of Marine Systems*, **37**, 107–127.

Ansorge, I.J. & Lutjeharms, J.R.E. 2003. Eddies originating at the South-West Indian Ridge. *Journal of Marine Systems*, **39**, 1–18.

Ansorge, I.J. & Lutjeharms, J.R.E. 2005. Direct observations of eddy turbulence at a ridge in the Southern Ocean. *Geophysical Research Letters*, **32**, 10.1029/2005GL022588.

Ansorge, I.J., Froneman, P.W., Pakhomov, E.A. & Lutjeharms, J.R.E. 1998. Hydrographic and biological data report on the Marion Island Oceanographic Survey 2 (MIOS 2). *UCT Oceanography Report*, **98-1**.

Ansorge, I.J., Lutjeharms, J.R.E., Swart, N.C. & Durgadoo, J.V. 2006. Observational evidence for a cross frontal heat pump in the Southern Ocean. *Geophysical Research Letters*, **33**, 10.1029/2006GL026174.

Ansorge, I.J., Pakhomov, E.A., Kaehler, S., Lutjeharms, J.R.E. & Durgadoo, J.V. 2009. Physical and biological coupling in eddies in the lee of the South-West Indian Ridge. *Polar Biology*, **33**, 10.1007/s00300-009-0752-9.

Ansorge, I.J., Froneman, P.W., Pakhomov, E.A., Lutjeharms, J.R.E., Perissinotto, R. & van Ballegooyen, R.C. 1999. Physical-biological coupling in the waters surrounding the Prince Edward Islands (Southern Ocean). *Polar Biology*, **21**, 135–145.

Ansorge, I.J., Froneman, P.W., Lutjeharms, J.R.E., Bernard, K., Bernard, A., Lange, L., Lukac, D., Backeburg, B., Blake, J., Bland, S., Burls, N., Davies-Coleman, M., Gerber, R., Gildenhuys, S., Hayes-Foley, P., Ludford, A., Manzoni, T., Robertson, E., Southey, S., Swart, S., Van Rensburg, D. & Wynne, S. 2004. An interdisciplinary cruise dedicated to understanding ocean eddies upstream of the Prince Edward Islands. *South African Journal Science*, **100**, 319–322.

Belkin, I.M. & Gordon, A.L. 1996. Southern Ocean fronts from the Greenwich meridian to Tasmania. *Journal of Geophysical Research*, **101**, 3675–3696.

Bernard, K.S. & Froneman, P.W. 2003. Mesozooplankton community structure and grazing impact in the Polar Frontal Zone of the south Indian Ocean during austral autumn 2002. *Polar Biology*, **26**, 268–275.

Bernard, A.T.F., Ansorge, I.J., Froneman, P.W., Lutjeharms, J.R.E., Bernard, K.S. & Swart, N.C. 2007. Entrainment of Antarctic euphausiids across the Antarctic Polar Front by a cold eddy. *Deep-Sea Research I*, **54**, 1841–1851.

Boden, B.P. 1988. Observations of an island mass effect in the Prince Edward archipelago. *Polar Biology*, **9**, 1–8.

Budillon, G. & Rintoul, S.R. 2003. Fronts and upper ocean thermal variability south of New Zealand. *Antarctic Science*, **15**, 141–152.

de Szoeke, R. & Levine, M. 1981. The advective flux of heat by mean geostrophic motions in the Southern Ocean. *Deep-Sea Research I*, **28**, 1057–1085.

Durgadoo, J.V. 2008. *Circulation at the South-West Indian Ridge in a high-resolution global ocean model*. MSc thesis, University of Cape Town, South Africa, 88 pp. [Unpublished.]

Froneman, P.W., Ansorge, I.J., Pakhomovo, E.A. & Lutjeharms, J.R.E. 1999. Plankton community structure in the physical environment surrounding the Prince Edward Islands (Southern Ocean). *Polar Biology*, **22**, 145–155.

Froneman, P.W., Ansorge, I.J., Vumazonke, L., Gulekana, M.K., Bernard, K., Webb, A.M., Leukes, W., Risien, C.M., Thomalla, S., Hermes, J., Knott, M., Anderson, D., Hargey, N., Jennings, M., Veitch, J., Lutjeharms, J.R.E. & McQuaid, C.D. 2002. Physical and biological variability in the Antarctic Polar Frontal Zone: report on research cruise 103 of the MV *SA Agulhas*. *South African Journal of Science*, **98**, 534–536.

Gille, S.T. 2002. Warming in the Southern Ocean since the 1950s. *Science*, **295**, 1275–1277.

Holliday, N.P. & Read, J.F. 1998. Surface oceanic fronts between Africa and Antarctica. *Deep Sea Research I*, **45**, 217–238.

Jonker, F.C. & Bester, M.N. 1998. Seasonal movements and foraging areas of adult southern female elephant seals, *Mirounga leonina*, from Marion Island. *Antarctic Science*, **10**, 21–30.

Kostianoy, A.G., Ginzburg, A.I., Frankignoulle, M. & Delille, B. 2004. Fronts in the Southern Indian Ocean as inferred from satellite sea surface temperature data. *Journal of Marine Systems*, **45**, 55–73.

Lutjeharms, J.R.E. 1985. Location of frontal systems between Africa and Antarctica: some preliminary results. *Deep-Sea Research I*, **32**, 1499–1509.

Lutjeharms, J.R.E. 1990. Temperatuurstruktuur van die oseaanbolaag tussen Kaapstad en Marion-eiland. *South African Journal of Antarctic Research*, **20**, 21–32.

Lutjeharms, J.R.E. & Valentine, H.R. 1984. Southern Ocean thermal fronts south of Africa. *Deep-Sea Research I*, **31**, 1461–1475.

Lutjeharms, J.R.E., Jamaloodien, S. & Ansorge, I.J. 2002. The temporal displacement of ocean fronts south-east of africa. *South African Journal Science*, **98**, 304–306.

McQuaid, C.D. & Froneman, P.W. 2004. The Southern Ocean Group at Rhodes University: seventeen years of biological oceanography in the Southern Ocean reviewed. *South African Journal Science*, **100**, 571–577.

Mélice, J.-L., Lutjeharms, J.R.E., Rouault, M. & Ansorge, I.J. 2003. Sea-surface temperatures at the sub-Antarctic islands Marion and Gough during the past 50 years. *South African Journal Science*, **99**, 1–4.

Morrow, R., Donguy, J.R., Chaigneau, A. & Rintoul, S.R. 2004. Cold-core anomalies at the subantarctic front, south of Tasmania. *Deep-Sea Research I*, **51**, 1417–1440.

Nel, D.C., Lutjeharms, J.R.E., Pakhomov, E.A., Ansorge, I.J., Ryan, P.G. & Klages, N.T.W. 2001. Exploitation of mesoscale oceanographic features by grey-headed albatross *Thalassarche chrysostoma* in the southern Indian Ocean. *Marine Ecology Progress Series*, **217**, 15–26.

NOWLIN JR, W.D. & KLINCK, J.M. 1986. The physics of the Antarctic Circumpolar Current. *Reviews of Geophysics*, **24**, 469–491.

ORSI, A.H., WHITWORTH, T. & NOWLIN, W.D. 1995. On the meridional extent and fronts of the Antarctic Circumpolar Current. *Deep-Sea Research I*, **42**, 641–673.

PAKHOMOV, E.A., ANSORGE, I.J. & FRONEMAN, P.W. 1998. Prince Edward Islands' offshore oceanographic study: report of research cruise April–May 1997. *South African Journal of Science*, **94**, 153–156.

PAKHOMOV, E.A., ANSORGE, I.J. & FRONEMAN, P.W. 2000a. Variability in the inter-island environment of the Prince Edward Islands (Southern Ocean). *Polar Biology*, **23**, 593–603.

PAKHOMOV, E.A., FRONEMAN, P.W., ANSORGE, I.J. & LUTJEHARMS, J.R.E. 2000b. Temporal variability in the physico-biological environment of the Prince Edward Islands (Southern Ocean). *Journal of Marine Systems*, **26**, 75–95.

PAKHOMOV, E.A., ANSORGE, I.J., KAEHLER, S., VUMAZONKE, L.U., GULEKANA, K., BUSHULA, T., BALT, C., PAUL, D., HARGEY, N., STEWART, H., CHANG, N., FURNO, L., MKATSHWA, S., VISSER, C., LUTJEHARMS, J.R.E. & HAYES-FOLEY, P. 2003. Studying the impact of ocean eddies on the ecosystem of the Prince Edward Islands: DEIMEC II. *South African Journal Science*, **99**, 187–190.

PARK, Y.-H., GAMBERONI, L. & CHARRIAUD, E. 1993. Frontal structure, water masses and circulation in the Crozet Basin. *Journal of Geophysical Research*, **98**, 12361–12385.

PARK, Y.-H., CHARRIAUD, E., CRANEGUY, P. & KARTAVTSEFF, A. 2001. Fronts, transport, and Weddell Cyre at 30° E between Africa and Antarctica. *Journal of Geophysical Research*, **106**, 2857–2879.

PERISSINOTTO, R. & BODEN, B.P. 1989. Zooplankton-phytoplankton relationships at the Prince Edward Islands during April/May 1995 and 1986. *South African Journal of Antarctic Research*, **19**, 26–30.

PERISSINOTTO, R. & DUNCOMBE RAE, C.M. 1990. Occurrence of anti-cyclonic eddies on the Prince Edward Plateau (Southern Ocean): effects on phytoplankton biomass and production. *Deep-Sea Research I*, **37**, 777–793.

PERISSINOTTO, R., LUTJEHARMS, J.R.E. & VAN BALLEGOOYEN, R.C. 2000. Biological-physical interactions and pelagic productivity at the Prince Edward Islands, Southern Ocean. *Journal of Marine Systems*, **24**, 327–341.

PERISSINOTTO, R., DUNCOMBE RAE, C.M., BODEN, B.P. & ALLANSON, B.R. 1990. Vertical stability as a controlling factor of the marine phytoplankton production at the Prince Edward Archipelago (Southern Ocean). *Marine Ecology Progress Series*, **60**, 205–209.

POLLARD, R.T. & READ, J.F. 2001. Circulation pathways and transports of the Southern Ocean in the vicinity of the Southwest Indian Ridge. *Journal of Geophysical Research*, **106**, 2881–2898.

RAE, C.M.D. 1989a. Frontal systems encountered between southern Africa and the Prince Edward Islands during April/May 1987. *South African Journal of Antarctic Research*, **19**, 21–25.

RAE, C.M.D. 1989b. Data report of the first cruise of the Marion Off-shore Ecological study (MOES-I). *South African Natural Scientist Programs Report*, **159**, 384 pp.

RAE, C.M.D. 1989c. Physical and chemical marine environment of the Prince Edward Islands (Southern Ocean) during April/May 1987. *South African Journal of Marine Science*, **8**, 301–311.

READ, J.F. & POLLARD, R.T. 1993. Structure and transport of the Antarctic Circumpolar Current and Agulhas Return Current at 40° E. *Journal of Geophysical Research*, **98**, 12281–12295.

ROUAULT, M., MÉLICE, J.-L., REASON, C.J.C. & LUTJEHARMS, J.R.E. 2005. Climate variability at Marion Island, Southern Ocean, since 1960. *Journal of Geophysical Research*, **110**, 10.1029/2004JC002492.

RINTOUL, S.R. & SOKOLOV, S. 2001. Baroclinic transport variability of the Antarctic Circumpolar Current south of Australia (WOCE repeat section SR3). *Journal of Geophysical Research*, **106**, 2815–2832.

SOKOLOV, S. & RINTOUL, S.R. 2007. Mutiple jets of the Antarctic Circumpolar Current south of Australia. *Journal of Physical Oceanography*, **37**, 1394–1412.

SWART, N.C., ANSORGE, I.J. & LUTJEHARMS, J.R.E. 2008. Detailed characterisation of an Antarctic eddy in the subantarctic. *Journal of Geophysical Research*, **113**, 10.1029/2007JC004190.

WEIMERSKIRCH, H., INCHAUSTI, P., GUINET, C. & BARBRAUD, C. 2003. Trends in bird and seal populations as indicators of a system shift in the Southern Ocean. *Antarctic Science*, **15**, 249–256.

WHITWORTH, T. 1983. Monitoring the transport of the Antarctic Circumpolar Current at Drake Passage. *Journal of Physical Oceanography*, **13**, 2045–2057.