CHAPTER 2

OCEANOGRAPHIC SETTING OF THE PRINCE EDWARD ISLANDS

JOHANN R.E. LUTJEHARMS AND ISABELLE J. ANSORGE

The Prince Edward Islands are the most southerly part of South Africa's official territory. They consist of Marion Island and Prince Edward Island, two volcanic outcrops approximately 500 000 years old, but still active. Marion Island covers an area of 270 km²; whereas Prince Edward Island – 19 km to the north-east – is only about 45 km². The nearest landfall is Crozet Island, 950 km to the east, whereas contiguous South Africa lies over 2 000 km to the north-west. The islands were annexed by the South African government in 1947 for strategic reasons (Crawford 1982, 1999), but they are important for a number of other reasons as well. These have a lot to do with their oceanographic setting.

First, the islands are important because they are a haven for a large number of breeding birds and marine mammals. Some of these are critically dependent on the ambient oceanic conditions during their stay on the islands. It has for instance been demonstrated (Nel *et al.* 2001) that at least one bird species, the Grey-headed Albatross *Thalassarche chrystomota*, feeds preferably on specific mesoscale circulation features found nearly exclusively in the general vicinity of the Prince Edward Islands. Other birds, such as penguins, are unable to range so far afield and are dependent to a greater degree on the conditions

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in the immediate environment of the islands (e.g. McQuaid & Froneman 2004). There are therefore two aspect of the oceanic setting of the Prince Edward Islands that are of importance for the ecosystem of the islands: first, the biological productivity of the wider surrounding ocean and, second, the productivity close to the islands.

The wider ocean environment of the Prince Edward Islands is low in primary productivity, as expressed by the density of chlorophyll-*a*. The greatest exception to this oligotrophy is a zone of higher chlorophyll-*a* equatorward of the islands, largely coincident with the Agulhas Front and the Subtropical Convergence (Comiso *et al.* 1993). The physico-chemical nature of these fronts is discussed in greater detail in following sections. The chlorophyll-*a* concentrations are highest at the Subtropical Convergence, but have been shown (Weeks & Shillington 1996) to vary considerably from year to year. This variation is most pronounced in the zone where the primary productivity is highest. Farther to the south, in the sub-Antarctic zone in which the Prince Edward Islands lie, the primary productivity is much lower. Here the inter-annual variations are also much smaller. Using satellite remote sensing as well as numerical models, it has furthermore been shown (Machu & Garçon 2001; Llido *et al.* 2004) that the chlorophyll-*a* concentrations at the Agulhas Front-Subtropical Convergence exhibit a distinct seasonal variation. Values are high during the period that includes spring, summer and autumn. A distinct minimum is however seen in winter. On even shorter time scales, it has now been demonstrated (Llido *et al.* 2005) that the enhanced primary productivity at the Subtropical Convergence takes place as distinct bloom events with limited spatial and temporal scales. This process has considerable consequences for scavenging birds that cannot rely on high concentrations of phytoplankton – or primary productivity – at the fronts in the same location at all times. This unexpected variability has been observed on numerous crossings of the fronts (e.g. Lutjeharms *et al.* 1986).

On one of the first South African research cruises between South Africa and Antarctica during which biological activity was measured in the upper ocean layers (Allanson *et al.* 1981), distinct peaks in chlorophyll-*a* values were observed close to the Subtropical Convergence and the Antarctic Polar Front. However, subsequent cruises in the same (Laubscher *et al.* 1993) as well as in other parts of the Southern Ocean south of Africa (Lutjeharms *et al.* 1985) have shown that on occasion high values of chlorophyll-*a* may be found at these fronts, but at other times there is no evidence of such enhancement at all. These results adumbrated the abovementioned work and results by Llido *et al.* (2005) on the intermittency of blooms at the fronts. They demonstrated unequivocally that the physical processes occurring at these fronts are of considerable importance to the ecosystems not only of the fronts themselves (e.g. Barange *et al.* 1998), but also for birds feeding far from the Prince Edward Islands and thus the ecosystem of the islands. In fact, correlations between high densities of marine birds and frontal systems in this general ocean region have been documented

extensively (e.g. Abrams 1983; Abrams & Lutjeharms 1986; Pakhomov & McQuaid 1996; Chown & Gaston 1999). As is to be expected from the subsequent knowledge on the intermittency of bloom events at the fronts, the increased presence of birds at Southern Ocean fronts is also sporadic. Thus, the ocean fronts and their dynamics in this part of the Southern Ocean are a key component in understanding the ecosystems of the islands. The physics of the fronts are therefore dealt with in detail in a subsequent section of this chapter.

If the Prince Edward Islands are therefore important as a bird habitat because of their larger oceanic setting, i.e. their location within striking distance of oceanic fronts with high levels of biological production, how about the effect on birds that are not able to fly such great distances? What is the oceanic situation closer to the islands that may possibly have a positive effect on the feeding opportunities of such birds with a limited feeding range?

A local process that may potentially be of considerable benefit to certain species birds on the islands might be the so called “island mass effect” (Doty & Oguri 1956). This effect can be due to runoff of nutrients from the island, the increased stratification of the water column near islands due to substantial runoff of fresh – and therefore less dense – water and the retention of water in the vicinity of islands long enough to allow a plankton bloom to occur. Such an enhancement of marine productivity has been recorded at other islands in the Southern Ocean (e.g. Perissinotto *et al.* 1992). If such blooms were to be found at the Prince Edward Islands, it would have substantial consequences for subsequent investigations concerning the oceanic setting of the islands.

One of the first to suggest an island mass effect for the Prince Edward Island was Boden (1988), but his conclusions were based on observations quite close to the islands only, preventing an appropriate comparison with the surrounding ocean regions. Subsequent observations (e.g. Perissinotto & Duncombe Rae 1990) have suggested that the mechanism responsible for enhanced primary productivity here was an anti-cyclonic eddy that was frequently to be found on the shallow bathymetric saddle between the islands. This eddy, by retaining runoff water high in nutrients in this region and by enhancing the vertical stratification of the water column (Duncombe Rae 1989; Perissinotto *et al.* 1990) could indeed lead to a pronounced island mass effect and explain the high plankton densities found on these cruises. It was, however, not observed during all cruises to the islands, nor was the perceived island mass effect persistent. In fact, the phytoplankton bloom between the islands was soon recognised as being highly intermittent (Pakhomov *et al.* 2000).

During subsequent cruises in which the surrounding ocean regions were explored to a much greater distance from the islands, the biological-physical interactions and pelagic productivity were shown to be considerably more complex (Perissinotto *et al.* 2000). The distributions of terrigenous urea and ammonia circumscribe the immediate island mass effect and it has been

demonstrated that these nutrients do not as a rule extend more than 80 km from the islands. The influence of eddies in the wake of the islands was perceived to have a considerably greater influence on the pelagic productivity and the plankton distribution of the immediate region (Froneman *et al.* 1999) than the island itself. This placed the whole concept of an important island mass effect in jeopardy.

Furthermore, investigations on the type of marine organisms to be found in the plankton of waters surrounding the islands, showed some unexpected results. Boden & Parker (1986) have shown that organisms not only of the expected sub-Antarctic types were to be found here, but that subtropical, Antarctic and even tropical species were also encountered. On certain cruises zooplankton species from Antarctic water were in fact dominant (Grindley & Lane 1979). Froneman *et al.* (1999) have demonstrated that the contrasting plankton species found in this way are excellent indicators of the origin of the water masses in which they are caught.

These observational results have thus demonstrated that the local effect of the islands may not be the most important from an ecological perspective, but that the larger oceanic setting is overriding. The complex interactions between the biology and the physics of the ocean environment has indicated the importance of a better understanding of this larger oceanic setting of the islands and this has developed through a number of stages (Ansorge & Lutjeharms 2000).

2.1 Conceptual developments

On some of the first supply cruises to the islands (Table 2.1) observations of the sea surface temperature were undertaken and the geographic location of the Subtropical Convergence relative to the islands described for the first time (e.g. Lloyd 1973). During the first dedicated cruises to the islands (Grindley 1978) the distribution of organisms and the physical readings undertaken suggested that a coastal upwelling cell existed on the eastern side of the islands, considered to be the lee due to the eastward moving waters in the Antarctic Circumpolar Current.

With the onset of the first programme of dedicated research cruises to the islands, the MOES (Marion Offshore Ecological Study, Table 2.1), this presumed upwelling was not found, but instead the seemingly enhanced primary productivity between the islands lead to the concept of a Taylor column retaining water masses on the saddle between the islands (Perissinotto & Duncombe Rae 1990). The second cruise of this research programme, the MOES II (Marion Offshore Ecosystem Studies; Van Ballegooyen *et al.* 1989) extended the area being investigated enormously (e.g. Ansorge & Lutjeharms 2002). The physical environment of the islands that was thus established suggested quite strongly that a train of eddies, alternating between cyclonic and anti-cyclonic, lay in the wake of the islands. This very suggestive portrayal led to the concept of a Von Karman vortex street being the main oceanic setting

of the islands (e.g. Allanson *et al.* 1985). The hydrographic results obtained during the subsequent cruise (MIOS II, Marion Island Oceanographic Study, Table 2.1), covering a somewhat larger area around the islands, put the cat amongst the pigeons. No vortex street was to be seen on this occasion, but instead a disparate collection of mesoscale eddies in no clearly defined order (Pakhomov *et al.* 1998).

Table 2.1 Research cruises to the Prince Edward Islands during which physical observations were made by the institution shown.

Period	Vessel	Cruise	Institute
1873	H.M.S. Challenger		
1929 - 1931	Discovery		
1933 - 1935	Discovery		
1950 - 1951	Discovery II		
Feb 1957	Ob		
Apr-May 1958	Vema		
Jun 1962	Africana II	263, IIOE	DSF
Apr 1963	Africana II	273	DSF
Jan-Mar 1974	Conrad	Conrad 17	LDGO
Sep-Oct 1978	SA Agulhas	3, Marion	NRIO, CSIR
Apr-May 1979	SA Agulhas	6, Marion/Gough	NRIO, CSIR
May-Jun 1979	SA Agulhas	7, Marion relief	
Sep 1979	SA Agulhas	9, Marion	
May-Jun 1980	SA Agulhas	14, Marion relief	NRIO, CSIR
Sep 1980	SA Agulhas	15, Marion	UCT
Feb-Mar 1981	SA Agulhas	18, FIBEX	NRIO, CSIR
Apr-May 1981	SA Agulhas	19, Marion relief	UCT
Aug-Sep 1982	SA Agulhas	25, Marion	DoT
Sep 1982	F.R.V. Africana	Marion	SFRI
Nov-Dec 1983	SA Agulhas	33, Marion relief	RU
Mar-May 1984	SA Agulhas	35, SIBEX	RU
Sep 1984	SA Agulhas	36/37, Marion	NRIO, CSIR
Apr-May 1985	SA Agulhas	40, Marion	RU
Aug-Sep 1985	SA Agulhas	Marion	NRIO, CSIR
Apr-May 1986	SA Agulhas	Marion relief	NRIO, CSIR
Apr-May 1987	SA Agulhas	49, MOES I	UCT
Dec 1986-Jan 1987	R.R.S. Discovery	Discovery, 164	IOS, NERC
Apr-May 1989	SA Agulhas	57, MOES II	NRIO, CSIR
Apr-May 1991	SA Agulhas	SAAMES I	UCT

Period	Vessel	Cruise	Institute
Apr-May 1992	SA Agulhas	Marion relief	RU
Mar-May 1993	R.R.S. Discovery	Discovery, 201	IOS, NERC
Jun-Jul 1993	SA Agulhas	SAAMES III	UCT
Jan-Feb 1995	R.R.S. Discovery	Discovery 213	ISO, NERC
Apr-May 1997	SA Agulhas	84, MIOS II	UCT
Apr-May 1998	SA Agulhas	87, MIOS III	UCT
Apr-May 1999	SA Agulhas	98, MIOS IV	UCT
Apr-May 2000	SA Agulhas	MIOS V	RU
Apr-May 2002	SA Agulhas	103, DEIMEC I	UCT
Mar-Apr 2003	SA Agulhas	108, DEIMEC II	UCT
Apr-May 2004	SA Agulhas	115, DEIMEC III	UCT
Apr-May 2005	SA Agulhas	123, DEIMEC IV	UCT

BIOMASS:	Biological Investigations of Marine Antarctic Systems and Stocks
CSIR:	Council for Scientific and Industrial Research
DEIMEC:	Dynamics of Eddy Impacts on Marion's Ecosystem
DoT:	Department of Transport
DSF:	Division of Sea Fisheries
FIBEX:	First International BIOMASS Experiment
IIOE:	International Indian Ocean Expedition
IOS:	Institute of Oceanographic Sciences
LDGO:	Lamont-Doherty Geological Observatory
MIOS:	Marion Island Oceanographic Study
MOES:	Marion Offshore Ecological Study
NERC:	Natural Environment Research Council
NRIO:	National Research Institute of Oceanology
RU:	Rhodes University
SAAMES:	South African Antarctic Marine Ecosystem Study
SFRI:	Sea Fisheries Research Institute
SIBEX:	Second International BIOMASS Experiment
UCT:	University of Cape Town

This conundrum was subsequently resolved by the use of the then new product of measurements of sea surface height from satellite altimetry. Ansorge and Lutjeharms (2003) have effectively demonstrated that the range of eddies found in the vicinity of the Prince Edward Islands is not generated by the flow past the islands themselves, but that all come from the south-west, more particularly from the Andrew Bain fracture zone in the South-West Indian Ridge. Here the Antarctic Circumpolar Current is constrained to move through a narrow gap, where it speeds up and as a result generates considerable mesoscale turbulence. This makes the oceanographic setting of the Prince Edward Islands most unusual and this is described in more detail in sections that follow.

2.2 Climate change

It is clear from the above that the Prince Edward Islands are important from a marine ecosystem point of view. A further, but crucial, point on the importance of the islands has to do with climate and climate change. The islands lie in a part of the globe where very few accurate atmospheric and ocean variables are measured on a regular basis. This makes the records of such variables observed at Marion Island, which extend over a period of 50 years, enormously valuable and nearly unique (Mélise *et al.* 2003). It has also been shown (Sumner *et al.* 2004) that recent climate change at the Prince Edward Islands has become evident in the melting of perennial snow and ice. Smith and Steenkamp (1990) have explored the implications of such climate change on the ecology of the islands, whereas Rouault *et al.* (2005) have analysed the climate change at the islands since 1960 and postulated the responsible mechanisms. Such climatic changes may have a dramatic effect on the breeding success of a number of bird species on the islands (e.g. Cooper & Lutjeharms 1992). The detail of these processes of climatic change is discussed in le Roux (2007). Suffice here to point out the importance of the islands as a bellwether for climate change in the sub-Antarctic.

2.3 General current environment of the Prince Edward Islands

As discussed below, the oceanographic setting of the Prince Edward Islands is in many ways unique. Its general setting however, is similar to other islands of their kind in the Southern Ocean. The Prince Edward Islands lie in the sub-Antarctic Zone of the Southern Ocean, between the Subtropical Convergence to the north and the Antarctic Polar Front to the south. Although a surface map shows their isolated location, a chart of the bottom topography (Plate 2.1) demonstrates how they fit into the general bathymetric background.

The major feature in this part of the ocean is a mid-ocean ridge, the South-West Indian Ridge, that extends from the south-west to the north-east and lies to the immediate west of the islands. As in the case of all mid-ocean ridges it is criss-crossed by fracture zones (Plate 2.1). A particularly well-developed one in this region is the Andrew Bain fracture zone that can be seen as a relatively shallow part of the ridge at about 50° S, 30° E. As will be seen below, it plays a crucial part in the ocean currents of the region. The Prince Edward Islands lie directly east of the South-West Indian Ridge on a distinct and independent pinnacle that rises from about 5 000 m depth. This is particularly clear to the south, whereas to the north it is somewhat complicated by other seamounts that do not break the sea surface (Plate 2.1). To the north-east lies an extensive shallow feature, the Crozet Plateau. A large part of this zonal rise is shallower than 2 000 m. The Crozet Islands lie on its easternmost extremity. It is clear that these ridges and rises will form important restrictions to the flow of the dominant current in the region, the Antarctic Circumpolar Current.

The Antarctic Circumpolar Current, generally flowing zonally in an eastward direction, is the main background current affecting the general environment of the Prince Edward Islands. It lies between the Subtropical Convergence to the north and the East Wind Drift, a westward setting current at the continental shelf of Antarctica (e.g. Ledenev 1964; Tchernia & Jeannin 1980), to the south. Although generally zonal in this region, the flow does exhibit small meridional excursions (e.g. Harris & Stavropoulos 1978). Furthermore, the bottom topography has a substantial effect on the current trajectory at certain locations. This is the case east of the Crozet Islands (Park *et al.* 1993) and particularly in the general vicinity of the Prince Edward Islands. Pollard & Read (2001) have shown that a major part of the flow is forced equatorward at the South-West Indian Ridge and that another large part is constrained to move through the Andrew Bain fracture zone. This is also evident from studying the geostrophic flow based on all existing hydrographic data (Park *et al.* 2001).

In general, the geostrophic volume transport of the Antarctic Circumpolar Current in the Southern Ocean is concentrated at the embedded frontal systems, to wit, the Subtropical Convergence, the sub-Antarctic Front and the Antarctic Polar Front (Hoffman 1985). This is also the case in the general vicinity of the Prince Edward Islands. Park *et al.* (2001) have calculated a zonal geostrophic speed of 0.9 m s^{-1} at the Subtropical Convergence, about 0.2 m s^{-1} at the sub-Antarctic Front and about 0.6 m s^{-1} at the Antarctic Polar Front. The latter may not be representative since it was obtained in the Andrew Bain fracture zone where the current moves more rapidly. In the ocean regions between these high velocity jets the speed of the Antarctic Circumpolar Current lies between $5\text{--}10 \text{ cm s}^{-1}$ (Park *et al.* 1993). In the vicinity of the Prince Edward Islands about 20 Sv ($\text{Sv} = 10^6 \text{ m}^3 \text{ s}^{-1}$) is transported by the stronger currents at the Subtropical Convergence (Pollard & Read 2001), with an attendant 60 Sv in the Agulhas Return Current; about 40 Sv is to be found at the Antarctic Polar Front. It is estimated that a total of 100 Sv moves through the Andrew Bain fracture zone.

To recapitulate, the Subtropical Convergence lies equatorward of the Prince Edward Islands, at about 42°S on average, and is reinforced by the juxtaposition of the Agulhas Return Current. This current carries the remnants of the Agulhas Current proper eastward (Stramma 1992; Sparrow *et al.* 1995) but gets steadily weaker along its path (Park *et al.* 1993; Stramma & Lutjeharms 1997). By about 70°E it has completely petered out (Lutjeharms & Ansorge 2001), but by 40°E , i.e. equatorward of the Prince Edward Islands, the Agulhas Return Current is still fairly strong. Here it carries at least 60 Sv and creates a number of eddies of different dimensions (Pollard & Read 2001). This process is important, since it is in the regions where the Agulhas Return Current is still strong and the flow is still turbulent and as a result the primary productivity is highest. This may attract certain marine animals.

Of some importance to the movement of immotile organisms in the Southern Ocean is the water movement not of the bulk of the ocean described above, but in the upper few centimetres. This has been studied over a period of three years using plastic drift cards (Lutjeharms *et al.* 1988). Average drift rates at the latitude of the Prince Edward Islands were about 16 cm s⁻¹; those of drifters drogued at 50 m were about 15% higher.

2.4 General hydrographic environment of the Prince Edward Islands

The most important hydrographic variables that constitute the environment of the Prince Edward Islands are the salinities, temperatures and nutrients. These also define the locations of the fronts to be found in the region. The geographic distribution of ocean temperatures at a depth of 200 m for the South-East Atlantic and for the South-West Indian sectors of the Southern Ocean, based on all existing observations, is given in Fig. 2.1. It is immediately evident that the distributions of the isotherms have a general zonal nature, but that there are substantial deviations from such a strict zonal tendency. The 10°C isotherm has been selected because it lies at the poleward extremity of the Subtropical Convergence zone, the 6°C corresponds with the location of the sub-Antarctic Front and the 2°C isotherm with the Antarctic Polar Front (Table 2.2). South of Africa the Subtropical Convergence lies farther poleward due to the influence of the termination of the Agulhas Current, but its location steadily decreases in latitude on moving eastward so that at the longitude of the Prince Edward Islands it lies at less than 39°S. By contrast the sub-Antarctic Front (~ 6°C) extends quite zonally until it reaches the South-West Indian Ridge at about 35° E after which it swings strongly equatorward (Belkin & Gordon 1996). The Antarctic Polar Front at 2°C moves through the South-West Indian Ridge at 50° S after which it seems to exhibit more meridional meanders than upstream in the Atlantic sector. This greater tendency to meander is also evident in the results of a similar analysis by Belkin and Gordon (1996). From a direct point of view for the Prince Edward Islands is the fact that these islands lie close to the sub-Antarctic Front at an average temperature of about 6°C. How does this vary temporally?

The seasonal changes in the sea surface temperature as measured at Marion Island are given in Fig. 2.2a. These are based on a record of 50 years (Mélise *et al.* 2003). These observations show the expected seasonal cycle, the temperature having a summer maximum of 6.5 (± 0.9)°C in February and a minimum of 4.3 (± 0.8)°C in the month of September, after the austral winter. This seasonal cycle is not invariant, but varies from year to year as the standard deviations in Fig. 2.2a suggest.

Furthermore, some secular changes have been noted (Mélise *et al.* 2003, 2005). These climatic changes are discussed in le Roux (2008). Suffice here to point out that the sea surface temperatures at Marion Island exhibit a cycle with an amplitude of about 1°C and a wavelength of about a decade, suggesting the influence of the Antarctic Circumpolar Wave. A long-term increase in

temperature of 1.4°C over a period of 50 years has also been observed (Fig. 2.2b). These changes in sea surface temperatures may be due to heating of the surface layers of the ocean in this region, or may be due to meridional shifts in the frontal systems.

Figure 2.1 Average ocean temperatures at 200 m depth in the general vicinity of the Prince Edward Islands. The isotherms have been selected to coincide with the subsurface expressions of the Subtropical Convergence (10°C), the sub-Antarctic Front (6°C) and the Antarctic Polar Front (2°C). The bathymetry is given in 1 000 m intervals with parts shallower than 3 500 m shaded. Data represent hydrographic measurements which have been made over the past 30 years.

Table 2.2 Thermal characteristics of the surface expression of frontal systems south of Africa (after Lutjeharms & Valentine 1984).

Latitudinal position					Temperature (°C)				
	From	To	Middle	Width (km)	From	To	Middle	Range	Gradient (°C km ⁻¹)
Agulhas Front	39°09'	40°01'	39°37'	96.3	21.0	15.7	18.4	5.4	0.102
Subtropical Convergence	40°35'	42°36'	41°40'	225.1	17.9	10.6	14.2	7.3	0.047
Sub-Antarctic Front	45°15'	47°25'	46°23'	241.4	9.0	5.1	7.0	3.9	0.018
Antarctic Polar Front	49°39'	50°47'	50°18'	126.0	1.4	2.5	3.4	1.8	0.018

2.5 Frontal systems in the vicinity of the Prince Edward Islands

A large number of hydrographic sections have been carried out in the vicinity of the Prince Edward Islands so that the location and character of the neighbouring ocean fronts are relatively well known (Jacobs & Georgi 1977; Lutjeharms 1990; Belkin & Gordon 1996; Moore *et al.* 1999).

As mentioned above, the most intense front here is the Subtropical Convergence, sometimes enhanced by the Agulhas Front – part of the Agulhas Return Current – sometimes distinctly separate (e.g. Lutjeharms & Valentine 1984; Belkin & Gordon 1996). As intimated by the isotherms in Fig. 2.1, this system of fronts lies roughly at 40°S but can be quite complex, consisting at times of a number of fronts and sub-fronts (Lutjeharms 1985). Much of this complexity may be due to the formation of a range of eddies of different sizes and circulation direction at the fronts (e.g. Lutjeharms & Valentine 1988a, b). This turbulent tendency is evident at this front as far east as 70°E and seems to be important for creating a specific biological habitat at this front. Eddies, both cyclonic and anti-cyclonic, would have the tendency to eventually move back to the fronts from which they were generated, to be re-absorbed and to strengthen this front. This has in fact been observed in other, comparable, parts of the Subtropical Convergence (Boebel *et al.* 2003). This process of eddy shedding from fronts has also been observed at the other fronts in the region. Detail of this is given in the section on the eddy behaviour in the vicinity of the Prince Edward Islands. So what are the hydrographic characteristics of the Subtropical Convergence?

The basic thermal nature of the front is given in Table 2.2. It should be recognised that these values are averages obtained for a wider extent of the Southern Ocean south of Africa (Fig. 2.1) and therefore not for the fronts near the Prince Edward Islands only. Furthermore, the variations in these values are quite large. So, for instance, the mean thermal gradient across

the Agulhas Front is $0.102^{\circ}\text{C km}^{-1}$, but the standard deviation based on 24 crossings is $0.106^{\circ}\text{C km}^{-1}$. A very strong gradient of $0.2^{\circ}\text{C km}^{-1}$ is therefore not uncommon (Lutjeharms & Valentine 1984). As mentioned, this front may on many occasions be found in conjunction with the Subtropical Convergence, making the resultant front one of the most intense to be found in the world ocean. The temperature gradient across the Subtropical Convergence on its own is much weaker than across the Agulhas Front by itself, but remains quite formidable for an ocean front (Table 2.2). By contrast the sub-Antarctic Front and the Antarctic Polar Front are much weaker. The nature of these fronts with depth is shown in Plate 2.2.

Figure 2.2 Trends in the sea surface temperatures as measured on a daily basis at Marion Island since the 1950s. The upper panel shows the average seasonal cycle of temperature with the standard deviations observed over this period for each calendar month (after Mélice *et al.* 2003). The lower panel shows the actual monthly averages of sea surface temperature for this period with a linear trend superimposed. The latter indicates a general rise of 1.4°C (after Mélice *et al.* 2003).

The Subtropical Convergence north of the Prince Edward Islands was on this occasion very sharply defined (Plate 2.2a) to a depth of at least 750 m with a 2°C meridional gradient up to a depth of 700 m (not shown). The surface expression on this occasion was not very intense, but consisted of a step-like structure that has also been observed elsewhere (Lutjeharms *et al.* 1993) during austral summer. This relatively simple frontal structure is unusual (Lutjeharms 1990). The more typical complexity of the frontal systems is shown clearly. Here the Subtropical Convergence was found at about 39° 30'S, but a secondary front can be seen in the figure at about 43° S. It has a reasonably strong surface expression and its surface temperatures lie on the lower end of what could be expected (Table 2.2). A third front can be identified just south of 44° S. This might have been the sub-Antarctic Front, but its location is unusually far north and its temperatures too high. The sub-Antarctic Front defines the northern border of the Antarctic Polar Front Zone. Its origin and forcing is not well understood. Perhaps the weak front at ~ 48° S would be a better candidate for the sub-Antarctic Front. This imposed subjectivity illustrates the complexity of the system. The Antarctic Polar Front is more easily defined. It is the farthest equatorward extent of 2°C water at a depth of 200 m. At times this subsurface expression agrees well with a small surface gradient of about 0.018°C at a middle temperature of 3.4°C. This is the case in the vertical temperature section shown in Plate 2.2b where it was observed at 49° 15'S while a secondary front lay at 53° 45'S.

The locations of the different fronts near the Prince Edward Islands, based on measurements made on research cruises between 1978 and 1986 (Table 2.1), is shown in Fig. 2.3. It is quite apparent that the latitude of the fronts show substantial meridional shifts (Nagata *et al.* 1988; Lutjeharms 1990). The Antarctic Polar Front does not exhibit such extensive movements as the other two fronts, but this may in this case be an artefact of only a small number of crossings of the Antarctic Polar Front to the south of the islands. This front actually lies quite close to the islands to the south, whereas the meridional range of the sub-Antarctic Front includes the islands (Lutjeharms 1985; Holliday & Read 1998). The presence of the front at the islands has in fact been observed a number of times (e.g. Duncombe Rae 1989) and even short-term shifts documented (e.g. Lutjeharms *et al.* 2002) fairly extensively. No clear short-term or inter-annual movement patterns have to date been established. This intermittency of the sub-Antarctic Front passing between Marion and Prince Edward islands has given rise to the hypothesis that a trapped eddy may be formed in between the islands when the front and its associated currents – with higher speeds – are not present, but that this eddy may be swept away when the front returns (Perrisintonto *et al.* 2000). The continuation of these fronts farther east in the vicinity of Crozet Island has been amply described by Belkin & Gordon (1996) and by Park *et al.* (1991, 1993) as well as by Park & Gambèroni (1995, 1997). To some degree these described fronts in the vicinity of the Prince Edward Islands also indicate the borders of specific water masses. These are shown in Plate 2.3.

Figure 2.3 Geographic locations of the main ocean fronts in the general surrounding of the Prince Edward Islands. The fronts are: the Subtropical Convergence (solid line); the sub-Antarctic Front (broken line) and the Antarctic Polar Front (dotted line). Details of the characteristics of the surface expressions of these fronts are given in Table 2.2. These locations are based on data collected at closely spaced oceanographic stations during the period 1978 to 1986 (Table 2.1).

2.6 Water masses in the vicinity of the Prince Edward Islands

The characteristic temperature/salinity relationships of the waters in the vicinity of the Prince Edward Islands are little different from those found at the same latitude at other locations in the Southern Ocean. In Plate 2.3a they have been colour distinguished according to their location (Plate 2.3b) between different fronts along a meridional line extending across the islands.

The blue curve shows the water masses north of the Subtropical Convergence. Clearly there is much warmer water with surface temperatures of 20°C. The very surface water is slightly less saline, indicating Subtropical Surface Water. The slight subsurface salinity maximum at slightly lower temperatures denotes Subtropical Surface Water and the salinity minimum at 5°C represents Antarctic Intermediate Water. This is the more saline Indian Ocean variety of Antarctic Intermediate Water with a salinity of about 34-35 whereas the Atlantic variety has a salinity of only 34.2 (Read & Pollard 1993). This eastward increase in the salinity of Antarctic Intermediate Water is due to mixing with more saline waters along its route. According to Fine (1993) the Antarctic Intermediate Waters at the Prince Edward Islands come directly from the west.

The rectilinear curve between the two extremes of Subtropical Surface Water and Antarctic Intermediate Water is the Central Water. The salinity maximum at about 34.8 represents Circumpolar Deep Water and below that is found

Antarctic Bottom Water. The next two stations (yellow and red traces in Plate 2.3a), in the sub-Antarctic, no longer exhibit the presence of Subtropical Surface Water, as one would expect. Their surface salinities are below 34.3, denoting sub-Antarctic Surface Water. This is the water mass that forms the low salinity Antarctic Intermediate Water once it has moved equatorward and been subducted beneath the lighter Subtropical Surface Waters at the Subtropical Convergence. At depth the Circumpolar Deep Waters are slightly colder to the south than in the curves for the water masses to the north. Last, the water to the south of the Antarctic Polar Front (green trace in Plate 2.3a) is consistently colder than 2.5°C and relatively fresh due to the melting of pack ice. The highest salinity values are found for the Circumpolar Deep Water in the Antarctic zone.

These temperature/salinity characteristics define the different water masses and indicate their origins. In the direct vicinity of the Prince Edward Islands it is only the two middle curves representing the sub-Antarctic waters that are of greatest importance since this is the band in which the islands are situated. However, it has been noted that water and organisms with Antarctic characteristics and even with Subtropical characteristics are intermittently found near the islands, carried there by eddies (Boden & Parker 1986; Froneman *et al.* 1999). This is discussed at greater length in the section below. For the ecosystem of the islands as well as for its weather and climate it is only the very upper layers of the ocean that are of importance. Nonetheless, it is known that marine mammals from the Prince Edward Islands, such as elephant seals, dive to depths of 1 000 m, so deeper water masses may conceivably be of importance to such animals. The temporal variability in water characteristics at these depths would be minute however.

2.7 Eddy behaviour in the vicinity of the Prince Edward Islands

As stated previously in this chapter the general oceanic environment of the Prince Edward Islands is in most respects, very similar to that of other islands in the sub-Antarctic. This aspect has now been dealt with. It was also stated that in certain respects the Prince Edward Islands are in a unique location and environment. This is amply illustrated in Plate 2.4.

Throughout the Southern Ocean there are regions of high mesoscale variability in a background of generally low variability. These regions of high variability were first identified from statistical analyses of historic hydrographic data (Lutjeharms & Baker 1980), but subsequently with much greater detail using the trajectories of drifters (Daniault & Ménard 1985) and from satellite altimetry (e.g. Colton & Chase 1983). Increased current variability may be caused by ring shedding (e.g. Gouretski & Danilov 1994) or by the meandering of fronts. A few regions of extreme variability stand out in this ocean as a whole. These regions are where the Subtropical Convergence is intensified by other currents such as at the Falkland-Brazil Current confluence and where the Agulhas Return Current flows along this front, e.g. equatorward of the

Prince Edward Islands. South of these regions, in the Southern Ocean proper, the variability is enhanced at the cores of the Antarctic Circumpolar Current and where this current interacts with shallower bottom topography such as mid-ocean ridges (e.g. Park & Saint-Guilly 1992). It can be shown from theory that the Antarctic Circumpolar Current is very sensitive to changes in the bottom topography and to bottom currents (e.g. Craneguy & Park 1999). Such a case of the current interacting with the bottom topography is illustrated in Plate 2.4. Whereas the general ocean environment here is relatively quiescent as measured by sea surface height variability (representing variability in ocean currents), the region at 50°S, 30°E has very high values of variability. From there a band of higher variability than the surroundings extends north-eastward in the direction of the Prince Edward Islands. This geographic configuration of the variability is most unusual for the Southern Ocean. It varies slightly intra-annually and inter-annually, but the key elements remain invariant. This particular region of high variability has a significant impact on the islands' environment and potentially on the ecology of the islands (e.g. Nel *et al.* 2001). What would bring about such an unusual circulation?

Ever wider observational grids of hydrographic stations around the Prince Edward Islands (Table 2.1) have shown unequivocally that the region is characterised by the presence of an ever-changing population of eddies (Plate 2.5a) of different sizes and contrary circulation directions (Ansorge & Lutjeharms 2000). These eddies have been shown to extend to depths of more than 1 000 m and many have remnant Antarctic characteristics (Plate 2.5b). Even more important, it has been demonstrated that the intensity of these eddies is in all observed cases strongly correlated with changes in sea surface height as observed by satellite altimetry (Ansorge & Lutjeharms 2000). This means that sea surface height anomalies in the region can be assumed to represent eddies and can be followed in time and their life history studied. Such investigations have produced some seminal results.

It has been shown (Ansorge & Lutjeharms 2003) that the origin of these eddies is with few exceptions the Andrew Bain fracture zone. This is apparent if the bathymetry of Plate 2.1 and the variability shown in Plate 2.4 are compared. The most extreme variability in sea surface height is found at the location where the Antarctic Circumpolar Current is constrained to move through the South-West Indian Ridge. From there eddies move into the Enderby Basin, downstream of the ridge, but with tracks that are predominantly in a north-easterly direction (Plate 2.6). In the case shown in this figure, the eddy moved from the ridge where it had been spawned and eventually passed the islands. It became indistinguishable soon after, suggesting that it had been totally eroded. It is clear from the distribution of variability shown in Plate 2.4 that little remains of the mesoscale turbulence east of 40°E. This implies that the eddies start their life at the ridge, but decay by mixing with the ambient waters before they reach this longitude (Ansorge & Lutjeharms 2005). These eddies may carry Antarctic biota along with their water masses and cause a substantial

negative heat transfer in an equatorward direction (Ansorge *et al.* 2006). What do these eddies look like hydrographically?

As may be expected they have a range of features. Some are warm, anti-cyclonic eddies; others are cold and rotate cyclonically. To a large degree this shows their origin. A well-studied example of a cold eddy is shown in Plate 2.5. A horizontal cut through the eddy at a depth of 200 m (Plate 2.5a) gives its dimensions and demonstrates the contrast between the temperature of its waters and that of the surrounding waters. The core of the eddy had temperatures of less than 1°C whereas the surrounding water was warmer than 3°C. The eddy was not entirely circular, but had a mean diameter of about 220 km. This, and satellite altimetry, shows unambiguously that its waters had their origin south of the Antarctic Polar Front. This is also evident from a vertical hydrographic section through the eddy (Plate 2.5b).

The observed temperatures to a depth of 920 m demonstrate the sharp distinction of waters in the eddy and those outside it. This was when the eddy was still fairly young and had not undergone much mixing with its environment. The temperature minimum at roughly 240 m depth is Antarctic Winter Water still intact so shortly after the eddy had formed. The eddy was first observed in satellite altimetry in October 2004 and by August 2005 has sufficiently dissipated that it was no longer observable as a distinct sea surface height anomaly. This lifetime of less than a year is typical for this type of eddy. Its speed of translation in a north-easterly direction (Plate 2.6) was 2 km day⁻¹. When observed hydrographically (Plate 2.5) its peripheral speeds were up to 1.4 m s⁻¹, extremely high for such features in the Southern Ocean. So what are the implications of this unusual eddy street for the Prince Edward Islands?

2.8 Conclusions

Due to the eddies that continually traverse the islands, the direct environment of the islands is much more variable in current speeds, current directions and water types than would normally be expected. This is also reflected in a much higher variety of ocean habitats that come about in the region, evident in the patchy nature of chlorophyll distribution in the vicinity of the islands (Froneman *et al.* 1999). Furthermore, these eddies carry with them organisms from their region of origin so that the surrounding waters of the Prince Edward Islands have a much more diverse spectrum of biota than one would normally expect from an island in the sub-Antarctic. Moreover, these and other eddies create unusual habitats of their own, particularly at their borders. This has become evident from the feeding behaviour of some birds (Nel *et al.* 2001). The further study of this mechanism and its implications is being planned.

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