The hydrography and dynamics of the general oceanic environment of the Prince Edward Islands

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Chapter 5

Chapter 6

Chapter 1

The circulation in the Southern Ocean

The Southern Ocean is the name given to the oceanic region that surrounds the entire Antarctic continent. It comprises the southern extents of the Atlantic, Indian and Pacific Oceans. The Antarctic continent forms the southern boundary of the Southern Ocean, while the northern border is not physiographically fixed, but is usually considered to coincide with the geographic location of the Subtropical Convergence (STC) (Lutjeharms 1985). The unique geography of the Southern Ocean makes it the only place where ocean currents run completely around the globe.

In a narrow zone around most of the continent there is a westward flowing coastal current termed by Deacon (1937) the "East Wind Drift" after the prevailing easterly winds near the coast. Farther north, the remainder of the Southern Ocean is dominated by a strong, deep, eastward flowing current called the Antarctic Circumpolar Current (ACC) (Figure 1.1). This current has also often been referred to as the "West Wind Drift" after the strong westerly winds that prevail between the subtropical high pressure belt and the Antarctic trough, which lies between 30°S-65°S (Taylor et al. 1978). The surface flow of the ACC is driven primarily by the frictional stress of the westerly wind, however combined with the Coriolis force a northward component to the surface current is responsible for the formation of frontal bands.

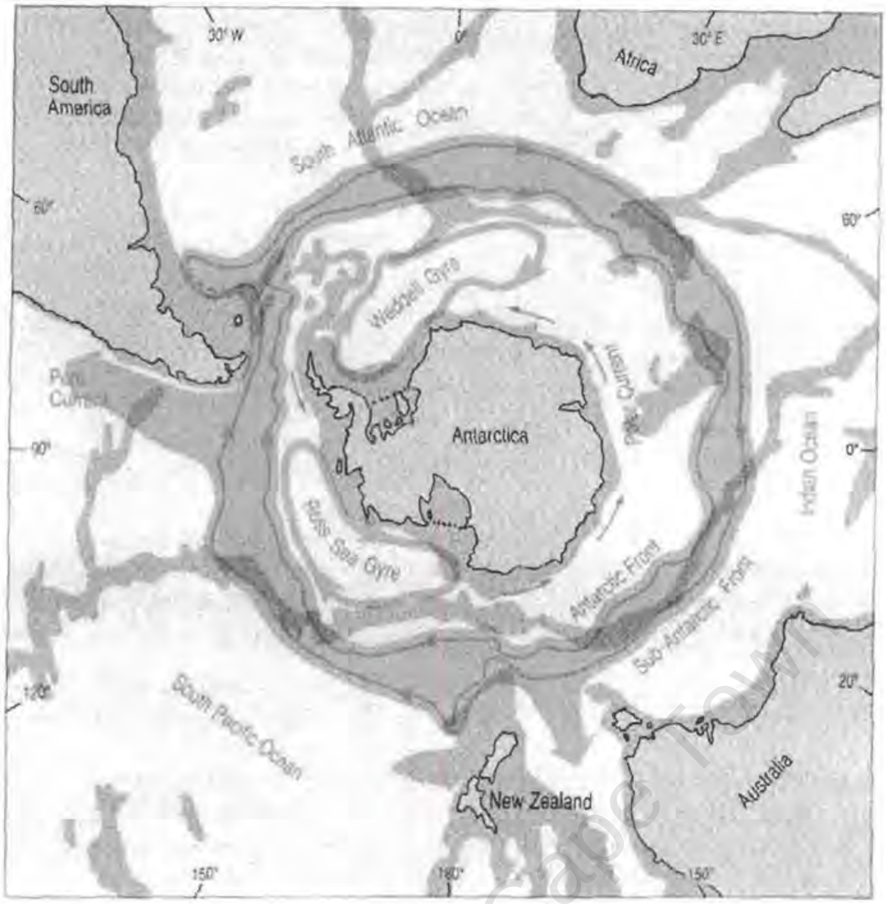


Figure 1.1: Schematic map showing the circulation in the Southern Ocean. The path of the Antarctic Circumpolar Current (ACC) is shown by the dark grey tone, the two dark lines representing the average northern (Subantarctic Front) and southern (Antarctic Polar Front) boundaries of the ACC. In addition, the approximate positions of the Weddell and Ross Sea gyres are shown, as well as the coastal Polar Current or East Wind Drift. Grey shading indicates water depths less than 3000 m (from Ocean Circulation – Open University Press).

The Antarctic Circumpolar Current

The Antarctic Circumpolar Current (ACC) is a complex system comprising of narrow regions of sharp horizontal density gradients, which extend through the entire water column as frontal bands separated by broad zones with less intense gradients (Nowlin et al. 1977, Nowlin and Klinck 1986) (Figure 1.2). Deacon (1937) has noted that the poleward rise of isohalines and isotherms is not uniform with distance south, but occurs as steps coinciding with the position of thermal fronts. Transects across the ACC (such as the Drake Passage) show this current to consist of zones of several quasi-uniform water masses separated by fronts in which horizontal gradients of properties are relatively large (Nowlin and Clifford 1982) (Figure 1.2).

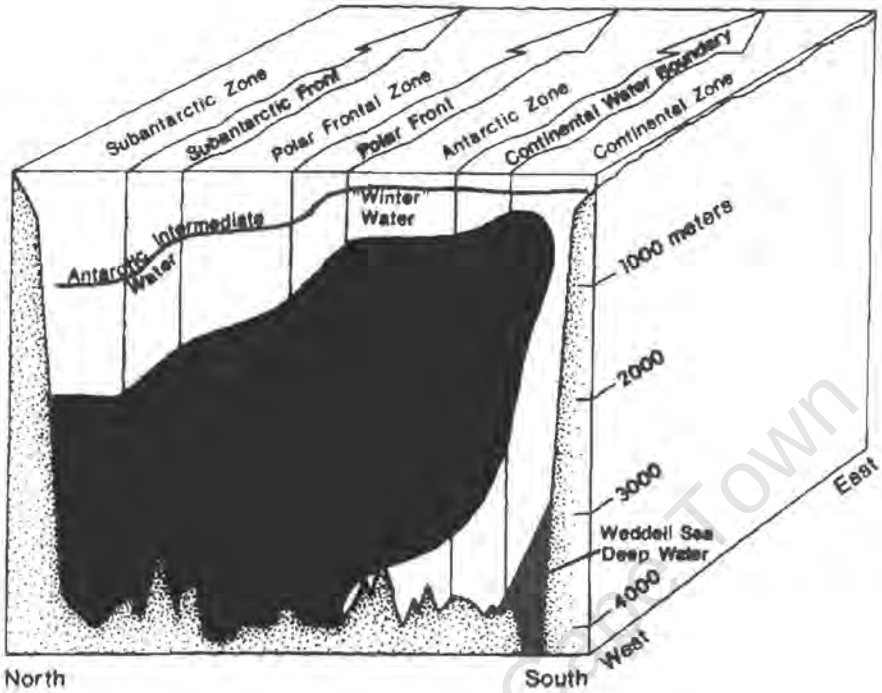


Figure 1.2: Schematic representation of the four relatively quiescent zones, which are separated by three fronts across the Drake Passage from Cape Horn to Antarctica (from Nowlin and Clifford 1982).

According to Whitworth (1980), these broad zones are the Subantarctic Zone, Polar Frontal Zone, Antarctic Zone and the Continental Zone (Figure 1.2). The major recognised circumpolar fronts of the ACC have been extensively defined throughout the Southern Ocean as the Subantarctic Front (SAF) and the Antarctic Polar Front (APF) (Lutjeharms and Valentine 1984, Lutjeharms 1985, Whitworth and Nowlin 1987, Read and Pollard 1993, Park et al. 1991, 1993, Belkin and Gordon 1996).

Definition of the Polar Frontal Zone fronts

Identification of the main ACC fronts is essential in order to trace the upper level circulation associated with the baroclinic shear. However, accurate identification of the fronts is not always simple especially in regions where they remain merged (Read and Pollard 1993, Park et al. 1993, 1997). One major difficulty is the various definitions that have been given for the characterisation of these fronts. Depending on authors, these definitions are based on either surface or subsurface property values, whereas others have used phenomenological definitions (Park et al. 1993). In order to unambiguously place the fronts before describing the frontal features observed in the region surrounding the Prince Edward Islands, each front will be defined using their representative axial values at 200 m where generally each front is marked best.

Subantarctic Front (SAF)

The Subantarctic Front was first identified south of Australia and New Zealand and termed the "Australasian Subantarctic Front" by Burling in 1961. It was only in later years when Emery (1977) traced this front from Australia to the Drake Passage that the more generic term, the Subantarctic Front was adopted.

The SAF forms the northern boundary of the Polar Frontal Zone (PFZ) and marks the southern extent of Subantarctic Surface Water (SAW). However, unlike the Subtropical Convergence (STC) and the Agulhas Front (AF), which are characterised by sharp consistent surface expressions that make identification easy (Lutjeharms and Valentine 1984), the SAF is less clear at the surface in terms of temperature and salinity gradients. Its definition varies considerably between authors and geographical locations (Park et al. 1993). Sievers and Emery (1978) have defined the subsurface expression of the SAF to be the most vertically orientated isotherm within a temperature gradient lying between 3°C and 5°C. Whitworth and Nowlin (1987) use the sharp descent of the salinity minimum to depths between 500-600 m to locate the SAF; Holliday and Read (1998) found the SAF to change in structure west and east of the Crozet Plateau. West of the Crozet Plateau, it appears as a wide band typically 200-300 km in width and consisting of a series of steps.

More detailed definitions have been given by Belkin and Gordon (1996) during their study of all the fronts between the Greenwich meridian and Tasmania. As the surface expression is generally weak or ill defined, the subsurface structure is usually the preferred indicator. Consequently, for the purpose of this study the definition used by Park et al. (1993), in which the T-S ranges between 4-8°C and 34.1-34.5 at 200 m, with axial values of 6°C and 34.3, will be used. Extensive analysis by Belkin and Gordon (1996) have found the subsurface SAF axial indices to remain fairly stable between 0°E and 150°E.

South of Africa, the SAF has been shown, from over 89 crossings, to have a mean location of 47° 25' S (Valentine and Lutjeharms 1984).

Antarctic Polar Front (APF)

The Antarctic Polar Front or Antarctic Convergence forms the southern boundary of the PFZ and marks the location where Antarctic Surface Water (AASW) moving northwards sinks below Subantarctic waters (Deacon 1933). The APF is a region of elevated current speeds and strong horizontal gradients in density, temperature and salinity (Deacon 1933, 1937). It is best defined as the northernmost extent of the 2°C isotherm associated with the winter remnant of Antarctic Surface Water, a temperature minimum layer (Clifford 1983, Lutjeharms 1985, and Orsi et al. 1993). South of the APF it is found at approximately 100 m descending to 500-600 m at the SAF. North of the SAF it becomes weak or absent. In the PFZ, a salinity minimum is also evident either at the surface or as a subsurface feature (slightly above the temperature minimum) between 200-300 m. At the SAF, it descends rapidly forming a distinct salinity minimum characteristic of the Antarctic Intermediate Water. Although the northern limit of the 2°C isotherm below 200 m is the definition most commonly used, some instances have shown that the surface and subsurface expressions do not always coincide (Lutjeharms and Valentine 1984). South of Africa, distances of approximately 50 km (Lutjeharms and Valentine 1984) separate the subsurface and surface expressions of the APF. Consequently, the definition used by Ostapoff (1962), where the surface expression of the APF lies at the maximum gradient between 2° - 6°C, will also be used.

South of Africa, Valentine and Lutjeharms (1984) have shown the APF to have a mean location of 50° 47'S, whereas Treshnikov et al. (1980) consider the circumpolar average location of the APF to lie between 52° and 53° S.

Belkin and Gordon (1996) have extensively defined the SAF and APF throughout the Southern Ocean. In order to address the position of the fronts in relation to the islands it is essential that definitions given remain consistent throughout this study. Thus, the following definitions outlined in Table 1.1, for both surface and subsurface (200 m) will be used.

Surface	Property range	Reference
SAF	8.4°-5.6°C; 33.91 – 33.87	Holliday and Read 1998
APF	Maximum gradient of SST regime between 2° and 6°C	Ostapoff 1962
Sub-Surface		
SAF	T-S ranges of 4°-8°C and 34.1-34.5 at 200 m with axial values of 6°C and 34.3	Park et al. 1993
APF	Axial T_{200} is 2°C	Orsi et al. 1993

Table 1.1: Definitions for the surface and subsurface expressions of the Subantarctic and Antarctic Polar Fronts.

Current measurements at the Drake Passage have shown the ACC to include a third frontal feature south of the APF, called the Southern Antarctic Circumpolar Current Front (SACCF) (Nowlin et al. 1977, Roether et al. 1993, Orsi et al. 1995, Veth et al. 1997). This feature has been repeatedly observed near the southern flank of the Drake Passage (Orsi et al. 1995) and at 52°S at the Greenwich meridian (Whitworth and Nowlin 1987). Unlike the SAF and APF, it is not known whether this frontal feature is circumpolar, as suggested by Orsi et al. 1995, or whether it lies only in the western Atlantic sector of the Southern Ocean (Belkin 1993). Extensive investigations in the region south of Africa (Lutjeharms and Valentine 1984, Read and Pollard 1993) have thus far failed to recognise this front.

Extensive investigations have been carried out in the past decades to understand the flow pattern of the ACC and the extent of its temporal and spatial variability throughout the Southern Ocean. Clifford (1983) has made the first study of the circumpolar nature of zonation of the ACC. Using historical hydrographic data results Clifford has shown that the two main fronts of the ACC, the SAF and APF, are continuous over the entire Southern Ocean as seen in Figure 1.1. As part of the First Global Garp Experiment (FGGE) during the same period, 300 Argos satellite-tracked buoys were deployed in the Southern Ocean between 30° and 65°S (Garrett 1981). These could, in principle tell us that the circulation in the Southern Ocean is predominantly concentrated at the frontal bands.

The objectives of this global study were threefold:

(1) To determine the meridional structure of the ACC by comparing the buoy trajectories with the location of fronts obtained from historical hydrographic data.

(2) To determine if the buoys became entrained into the high flow associated with the frontal regions.

(3) To estimate the near surface velocities within the fronts and zones of the Southern Ocean.

Hofmann (1985) has shown from the buoy tracks that there exists a good correspondence between the increased surface speeds and the locations of the three main fronts: STC, SAF and APF. Drifter densities clearly showed a banded current structure within the ACC, with greater densities observed along the fronts rather than in the broad zones separating them. Meridional excursions from the otherwise zonal flow occurred in regions of prominent bathymetric features, suggesting that lateral motions of fronts may be controlled by the sea floor.

In addition, the study of GEOSAT altimetry data (Chelton et al. 1990, Morrow et al. 1994) further demonstrated large mesoscale variability within the ACC. Chelton et al. (1990) found a close relationship between the level of mesoscale sea surface variability and bottom topography (Figure 1.3).

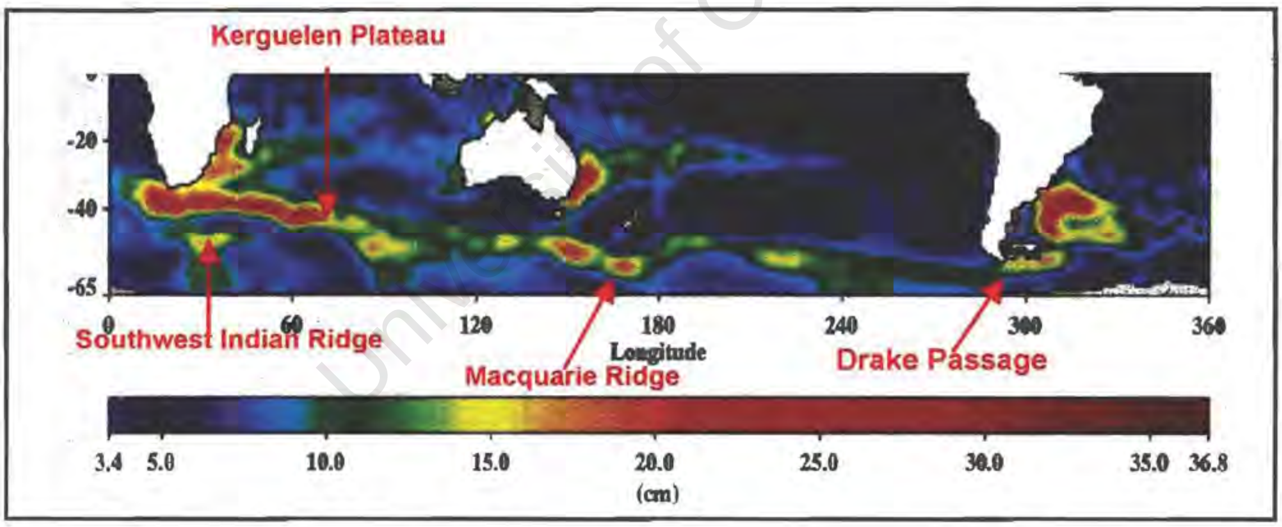


Figure 1.3: RMS of sea level variability for the Southern Ocean from blended TOPEX/Poseidon data (cycles 2 to 51) (from Nerem et al. 1994).

Such correlation suggests that hydrodynamic instability of the ACC is responsible for observed mesoscale variability. Daniault and Ménard (1985) studied the eddy kinetic energy distribution in the Southern Ocean, comparing data obtained from a Seasat altimeter to the drift patterns of buoys deployed during the First Garp Global Experiment (FGGE) between 1978 and 1980. The general pattern determined from both the drifter trajectories and satellite altimetry appeared to be similar, with strong mesoscale activity in the form of meanders and eddies occurring near western boundaries and shallow topographic features.

The summary of the circulation pattern given above represents a generalised picture of the dynamics of the Southern Ocean system, however it should be emphasised that any small-scale temporal or spatial variability is effectively smoothed out in the actual circulation (Gordon 1988). The Southern Ocean is not radially symmetric and regions of high mesoscale variability are found to closely correlate either to the terminal region of a major western boundary current, prominent bottom topography or along the core of the ACC (Lutjeharms and Baker 1980). Consequently, since 1975 greater attention has been given to measure the mesoscale variability in such regions. Several programmes were designed: the International Southern Ocean Studies (ISOS) and the Polar Experiment (POLEX-south) (Sarukhanyan 1980). Within these experiments concerted efforts were made to describe the frontal and transport structure in regions where mesoscale activity associated with the flow of the ACC were significant.

Mesoscale Variability in the Southern Ocean

Regions of high mesoscale variability appear to closely correlate to either the terminal region of a major western boundary current such as the Falkland and Agulhas Currents or where the ACC crosses prominent bottom topography (Figure 1.3). Such areas have been identified as the Drake Passage and the Scotia Ridge in the South Atlantic, the Southwest Indian Ridge and the Crozet and Kerguelen Plateaux in the South Indian Ocean and the Macquarie Ridge in the Pacific (Figures 1.3 and 1.4) (Lutjeharms and Baker 1980).

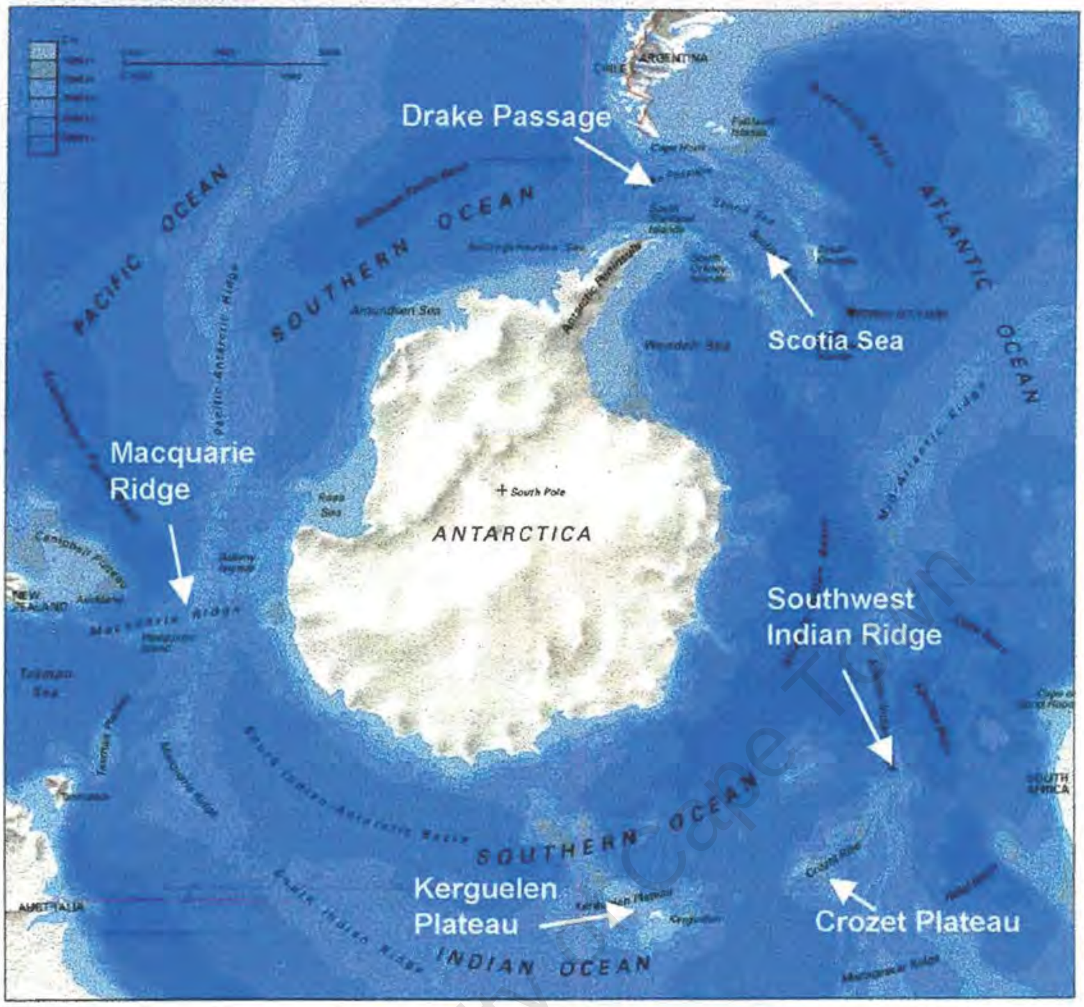


Figure 1.4: Bathymetry of the Southern Ocean (from Philip's Atlas of the Oceans).

Spatial structure of the ACC in the Drake Passage and the Scotia Sea

In order to understand the spatial structure of the ACC and the impact prominent bathymetry has on its flow, it is best to start with the Drake Passage and the Scotia Sea region with its long period of current observations. The narrow constriction of the Drake Passage and the close proximity between the South American and Antarctic continents has resulted in this region being extensively surveyed during the past 40 years (Legeckis 1977, Joyce and Patterson 1977, Sievers and Emery 1978, Patterson and Sievers 1978, Patterson 1978, Sciremammano 1980, Hofmann and Whitworth 1985, Sprintall et al. 1997) (Figure 1.5).

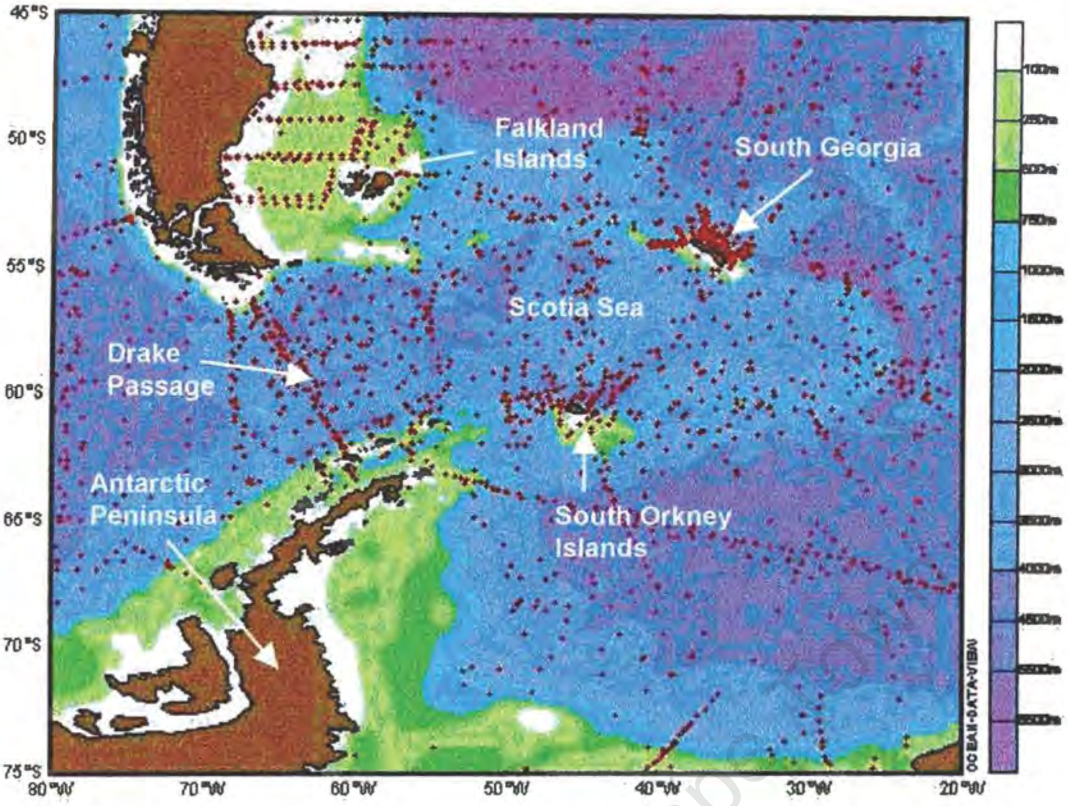


Figure 1.5: Distribution of CTD stations in the southwest Atlantic sector of the Southern Ocean, currently available to the Ocean Climatology Research Group at the University of Cape Town.

The first observation of mesoscale activity in the Drake Passage occurred in the early 1970s when Joyce and Patterson (1977) observed a cyclonic ring at the Antarctic Polar Front. It was believed that a large meander had developed in the APF and subsequently a cold feature was pinched off producing an eddy 60-80 km in diameter. Calculated geostrophics showed this eddy to move northeastwards at a rate of 10 cm s^{-1}. These eddies appear to be recurrent having been observed on 8 out of 12 occasions (Sievers and Emery 1978). Hofmann and Whitworth (1985) have described a warm core ring that remained near the Drake Passage for 4 weeks, while a cold core ring lasted over 20 weeks. This extended period may be due to the rugged topography associated with the surrounding islands such as the South Orkney, Falkland and South Sandwich Islands, which hamper the eastward progression of such features. Sievers and Emery (1978) have shown that these eddies widen the PFZ to over 300 km in a matter of a few weeks. Recent studies conducted in the Drake Passage have also revealed the seasonal variability of the SAF and APF. A series of six XBT/XCTD transects across the Drake Passage were conducted between September and April 1996-1997 (Sprintall et al. 1997). During the course of these surveys the APF remained at 58°S, whereas the SAF fluctuated considerably between 55°S and 58°S often combining with the APF. In comparison to previous investigations (Joyce and Patterson 1977, Sievers and Emery 1978), a cold eddy or meander was observed in the PFZ during the first transect occupied in the austral spring (September 1996). However, this feature was only seen during the one occasion contradicting the results reported by Sievers and Emery (1978), who have observed a high frequency of eddy presence in this region and Hofmann and Whitworth (1985) who observed a cold eddy to last more than 20 weeks. Sprintall et al. (1997) have also shown the effect summer warming has on the geographical position of the SAF. During the course of summer the SAF appears to migrate southwards to lie closer to the APF and narrowing the PFZ. Short-term variability in the SAF was further shown by comparisons with two transects occupied a week apart. During this period, the position of the SAF varied from 57°15'S to 56°45'S, possibly due to the sudden onset of winter (Figure 1.6).

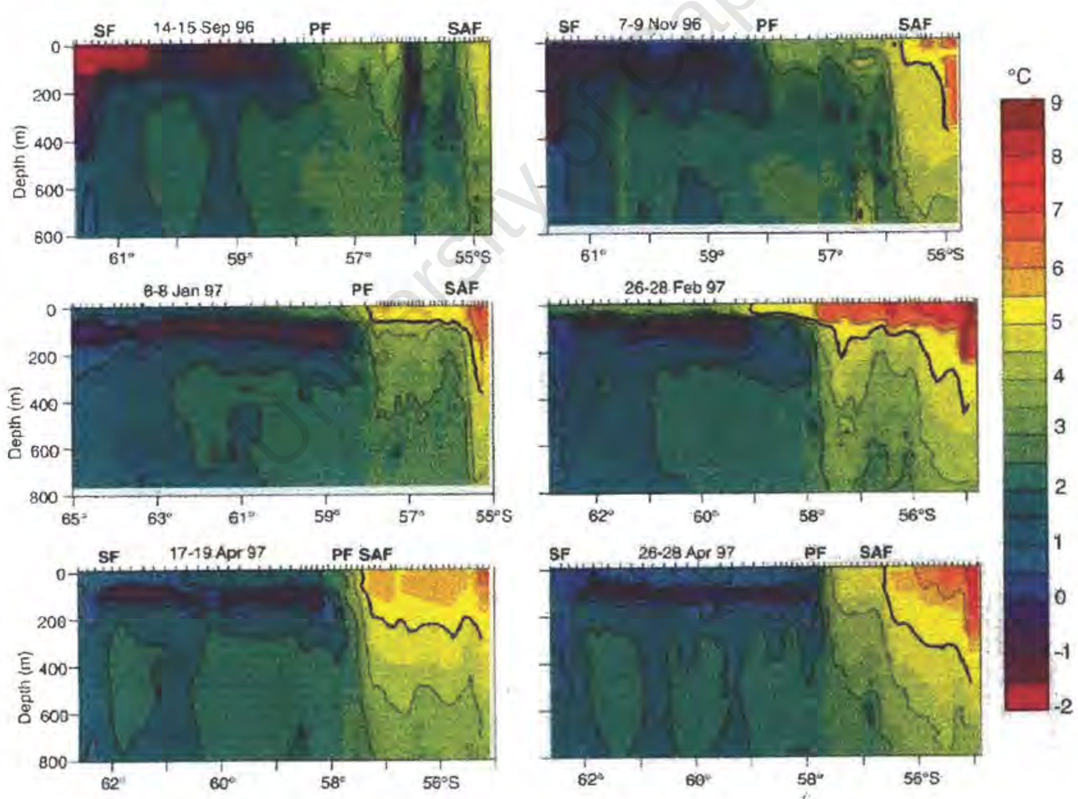


Figure 1.6: Temperature sections from six XBT cruises across the Drake Passage. The position of the Subantarctic Front (SAF) and the Antarctic Polar Front (APF) are noted along the top axis (from Sprintall et al. 1997).

Further east of the Drake Passage, the Scotia Ridge connects Antarctica with South America. The frontal structure in this region displays certain peculiarities attributed to the land mass distribution and to bottom relief (Belkin 1993) (Figure 1.7). Extensive hydrographic data has shown that in this region the SAF bends around the Falkland Islands forming a vast northward loop in the western Argentine Basin and converging at 45°S with the Brazil Current (Belkin 1993) (Figure 1.7). In the vicinity of the Ewing Bank and the Falkland Ridge, the SAF parallels the APF on many occasions merging to form a single front. East of the Ewing Bank, extensive southward meanders in the SAF and APF have been observed (Peterson and Whitworth 1989). In addition, Gordon et al. (1977) have mapped the PFZ in the western Scotia Sea and noted its highly meandered nature and the occurrence of isolated eddies.

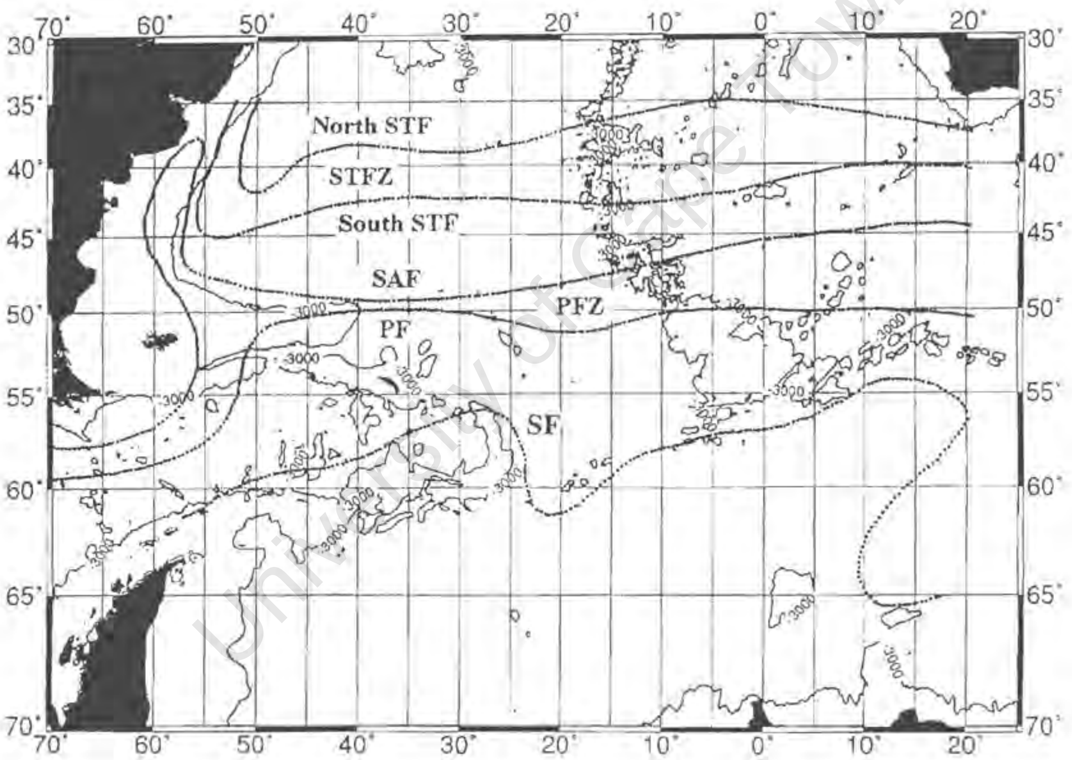


Figure 1.7: Frontal systems in the southwestern Atlantic Ocean. The impact the narrow constriction of the Drake Passage and the complex regional bathymetry has on the frontal systems, Subtropical Convergence (STC), Subantarctic Front (SAF), Antarctic Polar Front (APF) and the Scotia Front (SF) can be clearly seen (from Belkin 1993).

Recent observations conducted as part of the WOCE program carried out repeat sections across the Scotia Sea (Garcia et al. 1997). During DRAKE 95 and DRAKE 96 (February 1995 and 1996) both fronts were encountered. Comparisons between both datasets have revealed differences that may be attributed to interannual variability and enhanced mesoscale activity within the ACC. During DRAKE 95 the SAF was observed at 56°08'S, while a year later during DRAKE 96 it had migrated northwards to 55°52'S. A similar northward shift was also observed in the APF from 57°17'S to 56°56'S. Evidence of energetic cyclonic eddies were observed during DRAKE 95 and may explain the more southern position of the APF. By contrast, during DRAKE 96 the ACC appeared to be more zonal with small anticyclonic eddies lying to the south. Garcia et al. (1997) have proposed that such an eddy may have been "sucked" into the Scotia Sea by the strong jets associated with the Southern Antarctic Circumpolar Current Front (SACCF).

Klinck (1985) has shown that an important factor affecting the distribution of the APF is the bottom topography and the location of seamounts, although Pakhomov et al. (1997) have suggested that the seasonal and short term changes in the fronts position may be wind driven. One area that exhibits such complexity lies to the north of South Georgia. Recent investigations (Trathan et al. 1997) in the region between South Georgia, the Maurice Ewing Bank (MEB) and the Falkland Islands have shown the ACC to flow in a southwestward direction opposite to the prevailing flow, suggesting the existence of a meander or a warm anticyclonic ring at 50°S.

The position of the APF in relation to South Georgia and the Falkland Islands and the degree of mesoscale activity in this region has an important impact on the zooplankton community structure (Atkinson and Peck 1988, Priddle et al. 1988). During occasions when the APF lies to the north of the islands, a scenario termed "cold year" (Hardy and Gunther 1935, Priddle et al. 1986, 1988), in which Antarctic species dominate. Cold years appear to be the normal situation around South Georgia, however, during a recent cruise the APF lay 100 km further south than its normal position and consequently a predominance in Subantarctic zooplankton species was found (Pakhomov et al. 1997).

It is therefore clearly apparent that in the Southwest Atlantic Ocean, the Drake Passage and the Scotia Sea have been relatively well investigated. Both regions represent choke points in the flow of the ACC, resulting in extensive mesoscale activity and enhanced cross-zonal exchange of water masses. Hydrographic surveys further east over the south central Atlantic region are sparse, but dynamic height maps (Wytrki 1977, Gordon et al. 1978) suggest that the SAF and APF, once removed from prominent bottom relief, return to their zonal positions. Indeed, hydrographic stations occupied at the Greenwich meridian (Whitworth and Nowlin 1987) show the ACC to exhibit a banded nature of flow with two thirds concentrated along the SAF and the APF (Figure 1.7). In the Southeast Atlantic, only the African sector (10° - 20°E) has been studied relatively well (Lutjeharms and Valentine 1984, Lutjeharms 1985) but here too the ACC displays similar structural features.

Spatial structure of the ACC in the region between Africa and Antarctica

Further east, the Indian sector of the Southern Ocean extends between 20° - 170°E and is bounded by Australia and South Africa to the east and west and by Antarctica to the south. In this region, the prominent bottom topography is the Atlantic-Indian mid-ocean Ridge (Figure 1.4). This Ridge extends northwards towards southern Madagascar, where it is broken into a series of deep (> 4000 m) fracture zones such as the Prince Edward Fracture Zone at 27°- 28°E. To the east of this Ridge lies the shallow Del Cano Rise, which stretches eastwards towards the Crozet Plateau. South of the Del Cano Rise, a deep abyssal plain extends southwards to the Antarctic continent and depths increase to 5 500 m (Figure 1.4).

In this sector, oceanographic research has mainly focussed on the impact the Southwest Indian Ridge and the Crozet and Kerguelen Plateaux have on the path of the ACC (Read and Pollard 1993, Pollard and Read 1997, Park et al. 1991, 1993, 1997) (Figure 1.8).

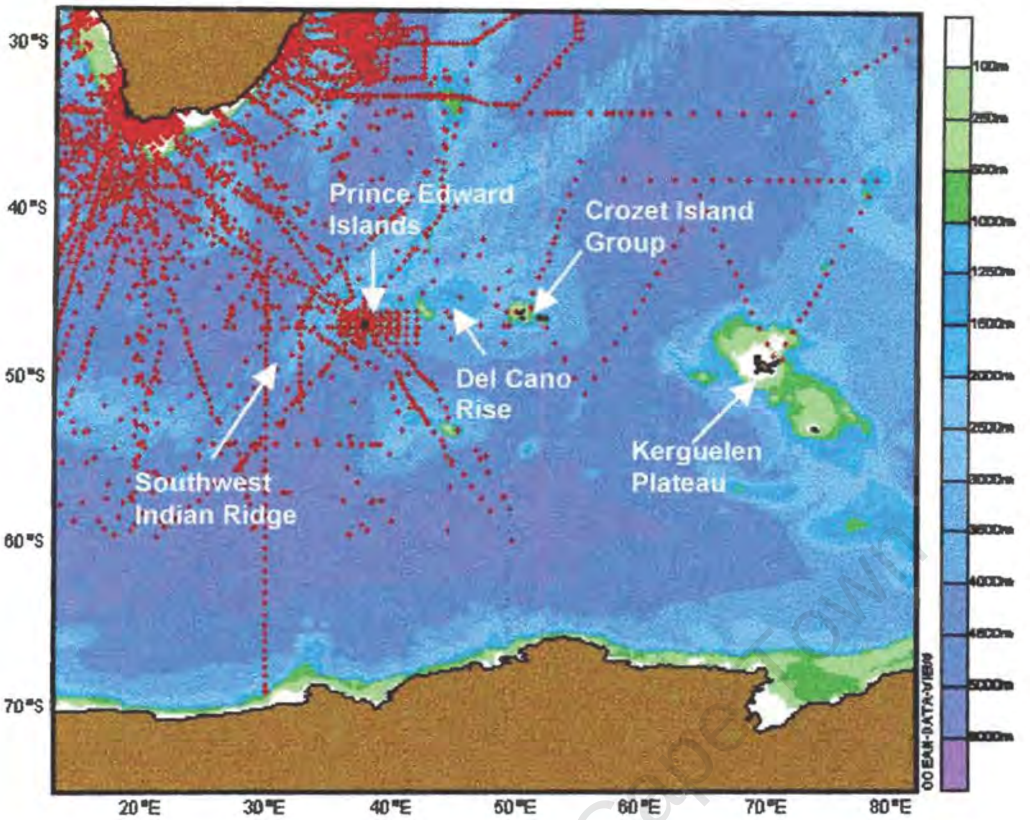


Figure 1.8: Distribution of CTD stations in the southwest Indian sector of the Southern Ocean, currently available to the Ocean Climatology Research Group at the University of Cape Town.

In 1986-87 a survey along the crest of the Southwest Indian Ridge between 23° - 52°S was undertaken (Read and Pollard 1993). The main objective of this cruise was to examine the frontal systems of the South Indian Ocean and their associated water masses. During this survey the Agulhas Return Current and it's associated front, the Agulhas Front (AF), appeared as a strong, single feature separate from the STC. The Agulhas Return Current, formed by the retroflection of the western boundary Agulhas Current (Lutjeharms and Ansorge submitted) marks the initiation of a major zone of intense baroclinicity, which extends across the entire South Indian Ocean to the Campbell Plateau south of New Zealand (Figure 1.3).

Previous surveys in this region (Jacobs and Georgi 1977, Poisson and Caschetto 1987) failed to distinguish the AF from the STC. Wide station spacing of 2° and 4° of latitude may be accountable. In contrast, the SAF and APF appeared to form a merged narrow front between 48°S and 49°S. A repeat survey at 30°E along the Southwest Indian Ridge (Park et al. 1997) has shown this area to exhibit extreme temporal and spatial variability. During CIVA-1 in 1993, the SAF existed as a single structure at 48°S, while a meandering APF forming two branches was observed at 50°S and 52°S. However, data collected during CIVA-2 in 1996 (Figure 1.9) failed to show this. Instead, the SAF appeared to meander forming two branches, a single structure at 47°S, while the more southern branch merged with the APF at 50°S.

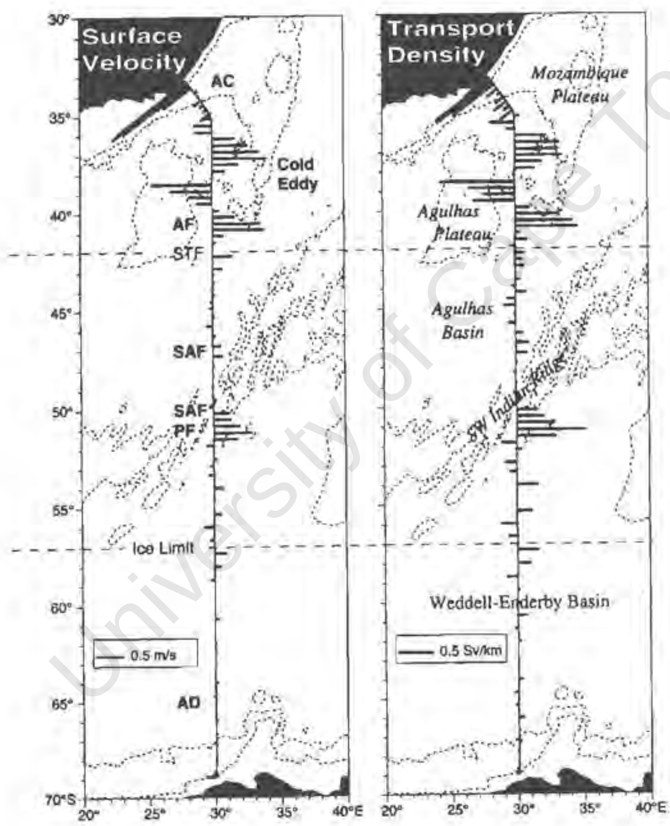


Figure 1.9: Geostrophic observations obtained during CIVA-2 (from Park et al. 1997). The position of the fronts can be clearly seen.

The impact the Southwest Indian Ridge has on the ACC can be clearly seen. This region is an area of high variability with the position and structures of the main frontal systems changing considerably between surveys. Concerted efforts have been made to study the formation of these mesoscale features. An intense cold cyclonic eddy within the ACC between 47° - 48°S and 25° - 27°E has been intensely studied by Koshlyakov et al. (1985). The water mass characteristic, indicative of Antarctic Surface Water, suggests that this eddy may have been spawned at the APF. However, T/S properties also reveal evidence of Subantarctic water masses with increasing depth, which may have been drawn into the feature by its cyclonic rotation (Koshlyakov et al. 1985). This observation is consistent with studies on cyclonic rings carried out in the Gulf Stream (Kamenkovich et al. 1982). The numerous observations of cold eddies in this region (Sarukhanyan 1980) suggest that these features may be quasi-stationary, blocked by the shallow topography associated with the Southwest Indian Ridge.

Further investigations (Gouretski and Danilov 1994) have also revealed the presence of a warm anticyclonic eddies at 57°S, 28°E. Anticyclonic eddies appear to have been shed from poleward meanders in the APF. This behaviour in the APF has been extensively modelled by Wolff et al. (1991) and Gouretski and Danilov (1994) and is in good agreement with drifting buoy data (Harris and Stravopoulos 1978, Garret 1980). Topographical control of the ACC by the Southwest Indian Ridge has also been modelled by Craneguy and Park (1999) using Niiler and Robinson's (1967) inertial jet model. A series of simulations based on observed values of current velocity were able to show the effect the Southwest Indian Ridge had on the flow and separation of the SAF and APF. Four jets at 49°S, 50°S, 51°S and 52°S were placed at 25°E. Results have shown that the Southwest Indian Ridge induces a northward deflection of the 2 northern jets (49°S and 50°S), whereas the Enderby Basin induces a southward shift of 2 southern jets (51°S and 52°S). These results are comparable to hydrographic observations (Park et al. 1991, 1993, 1997) in this region. It appears that the frontal bands shift southwards through a narrow (300 - 400 km) corridor in the Southwest Indian Ridge between 26° and 32°E. The rings tend to drift southwards to between 55° - 56°S were they stagnate and slowly decay over a period of a year.

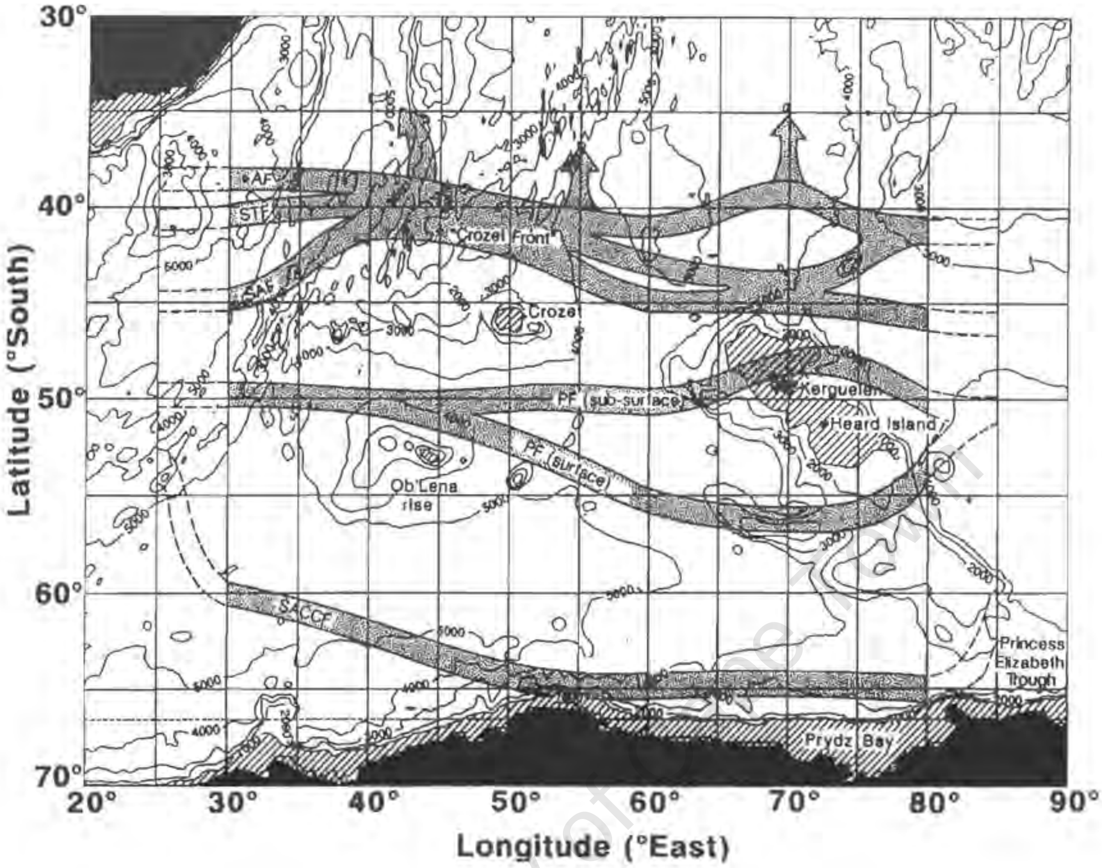


Figure 1.10: Position of the main frontal systems in the southwestern sector of the Indian Ocean. The effect of the complex bathymetry associated with the Southwest Indian Ridge can be seen by the northward deflection of the SAF to form the Crozet Front (after Sparrow et al. 1995).

Dynamic topography distributions of the Southern Ocean (Gordon et al. 1978, Park et al. 1993) and hydrographic data (Read and Pollard 1993, Pollard and Read 1997), suggest that a strong northward deflection in the path of the ACC occurs at the Del Cano Rise, east of the Southwest Indian Ridge (Figure 1.10). In order to establish how and where the ACC crosses this topographic barrier SWINDEX (Southwest Indian Ocean Experiment) was undertaken and a large number of moorings spanning the Del Cano Rise were deployed. Results have shown that between 50-60% (80 – 90Sv) of the ACC continues eastwards south of the Del Cano Rise, however, approximately 13% (20Sv) of the ACC deflects northwards along the Prince Edward

Fracture Zone. A further 25-40 Sv (30-40%) flows northwards through the passage separating the Crozet Island group from the Del Cano Rise (Pollard and Read 1997).

The oceanic region surrounding the Crozet and Kerguelen Islands corresponds to one of the major "choke points" (Park et al. 1993), where the ACC exhibits maximum mesoscale variability in it's flow (Figure 1.3) (Cheney et al. 1983, Daniault and Ménard 1985). Extensive efforts such as measuring bottom pressures at Kerguelen and Amsterdam Islands (Lamy 1988, Saint Guily and Lamy 1988, 1990), conducting multidisciplinary surveys (ANTARES and SUZIL) (Park et al. 1991, 1993) and GEOSAT altimetry data (Park et al. 1995) have all clearly indicated the ACC to be highly variable in this region.

The ACC upstream of the Crozet Island group is unique. Unlike other regions of the Southern Ocean where it forms a multi-band feature separated by broad zones (Hofmann 1985), the ACC near these islands is an intensive single narrow jet. Formed by the confluence of three fronts, the AF, STC and the SAF, this frontal band has often been referred to as the "Crozet Front" (Belkin and Gordon 1996) (Figure 1.10). It is here at 47°E that the horizontal temperature (19° - 7°C) and salinity (35.5 - 33.6) gradients are the sharpest in the Southern Ocean with all 3 fronts lying on average between 41° - 43°S (Park et al. 1991).

This regional peculiarity of the ACC core appears to be correlated to the close proximity of the Agulhas Return Current and it's associated Agulhas Front (Lutjeharms and Ansorge in review). This current, the eastern extent of the Agulhas Current system, extends into the Crozet Basin carrying warm, saline, subtropical water masses and initiates a zone of enhanced baroclinicity downstream of the Agulhas Plateau. With distance east the Agulhas Return Current slowly recirculates northwards feeding into the anticyclonic subtropical gyre (Figure 1.10) (Wyrtki 1971, Lutjeharms and Ansorge in review), its waters separating from the intense frontal feature associated with the ACC (Park et al. 1993).

While the main branch of the ACC appears to be concentrated north of the Plateau, the APF lies south of the islands between 49° - 50°S. Consequently, the PFZ in this region is exceptionally wide 7°S, almost twice as wide as in other regions (Nowlin and Klinck 1986). Recent investigations (Belkin and Gordon 1996, Sparrow et al. 1995, Holliday and Read 1998) have shown the APF to split into two branches (Figure 1.10). The subsurface expression of the APF is forced north of Kerguelen

Island by the shallow topography, whereas the surface expression swings southwards passing over the Kerguelen Plateau through the deep channel south of Heard Island (Sparrow et al. 1995). However, during the ANTARES and SUZIL surveys (Park et al. 1991, 1993), which were conducted in the vicinity of the Crozet-Kerguelen Island group, the APF was found to lie south of Kerguelan where it remained a weak front with no noticeable baroclinic shear (Figure 1.10).

Comparisons of altimetry (TOPEX/POSEIDON), modelled data (using FRAM - Fine Resolution Antarctic Model) and hydrographic data (Park and Gamberoni 1995) have shown a remarkable resemblance to the sluggish flow associated with the APF. In contrast to studies carried out further upstream (Read and Pollard 1993, Park et al. 1997), the majority of the flow in this region is associated with the STC and SAF and not with the APF. Recent investigations along the 62°E meridian (ANTARES 2 - Park et al. 1998) have identified the APF as a very slow flow, its passage hindered by the topographic barrier of the Kerguelen Plateau. Current meters moored at 50°40'S and 68°25'E (KERFIX - Park et al. 1998) confirm the existence of this negligible flow. Geostrophic velocities associated with the APF south of the islands are on average < 5 cm s^{-1} (Park et al. 1991, 1993) in comparison to other regions of the Southern Ocean where it is usually the strongest flow (Park et al. 1997).

As expected from the high variability of this region depicted in the sea surface height anomaly in Figure 1.3, alternating east and west current flow at 42°S and 43°S suggest the existence of eddies or meanders. Rossby waves in the Crozet basin have been observed on numerous occasions (Projet MARISONDE 1979, Park and Saint-Guily 1992) (Figure 1.11).

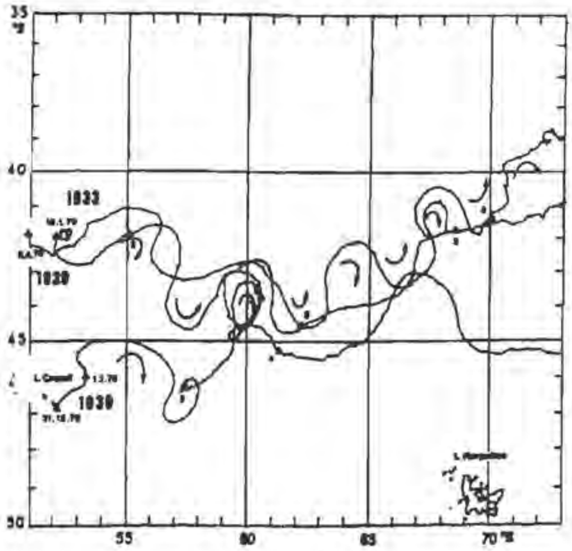


Figure 1.11: The trajectories of three FGGE buoys which have been deployed downstream of the Crozet Islands. The formation of meanders and eddies is clearly evident (from Park and Saint Guily 1992)

These features appear to be quasi-permanent and have been observed during investigations in which either satellite tracked buoys (Projet Mariosonde 1979, Daniault 1984), sea level variability (Cheney et al. 1983, Daniault and Mènard 1985, Park 1990) or hydrographic data (Gamberoni et al. 1982, Park et al. 1989,1991,1993) were studied. Planetary waves generated over the shallow topography of the Southwest Indian Ridge and the Crozet Plateau seem to be responsible for the generation of these features (Daniault 1984, Park and Saint Guily 1992).

In the Indian sector of the Southern Ocean, the ACC loses its zonal character as a result of its northward deflection around the Crozet and Kerguelen Plateaux. As it approaches the region between Australia and Antarctica the basic flow of the ACC deflects southwards again to lie between 45° and 65°S.

Spatial structure of the ACC at the Macquarie Ridge

The study of the ACC spatial structure in this region is limited because very few large-scale oceanographic surveys with the required spatial resolution have ever been carried out (Sarukhanyan 1980) (Figure 1.12).

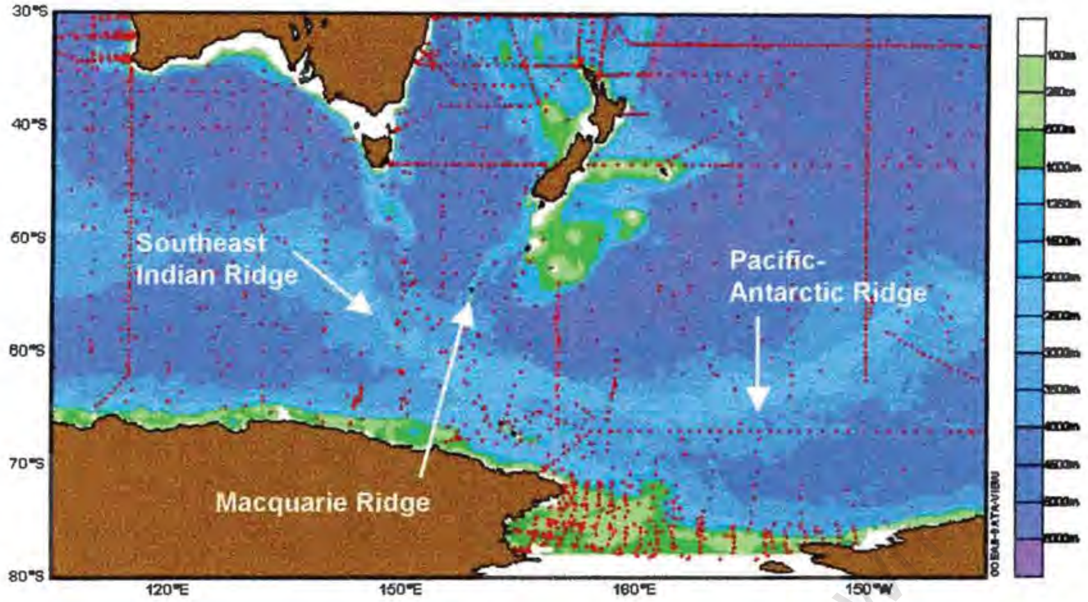


Figure 1.12: Distribution of CTD stations in the Australian and southwest Pacific sector of the Southern Ocean, currently available to the Ocean Climatology Research Group at the University of Cape Town.

In the region south of Australia (120°E – 170°E) FGGE buoy trajectories have shown a distinctive banded pattern with high buoy densities correlating to the latitudinal location of the STC (46° - 49°S), SAF (53° - 56°S) and APF (57° - 61°S) (Hofmann 1985). Analysing the dynamic height topography, Gordon et al. (1978) have shown intense variability within the ACC. Laboratory and numerical models (Boyer and Guala 1972) have attributed this variability to the shedding of eddies as the current interacts with the Southeast Indian, Macquarie and the Pacific-Antarctic Ridges to form a significant obstacle to the flow of the ACC (Figure 1.12). Further confirmation has been given by Heath et al. (1978), who have observed from the trajectory of a satellite tracked buoy, large meanders and a deep (> 2000 m) anticyclonic eddy.

Further investigations in this region (Bryden and Heath 1985) focussed on the ACC between 48° and 65°S. An array of current meters and a series of drifters were deployed in the vicinity of 49°30'S, 170°W, (Figure 1.13) and the passage of a large number of eddies were tracked over 2 years. These eddies are believed to vary over temporal scales of 20 days and horizontal scales of 60 km. Propagating southeastwards at a rate of 12 cm s^{-1}, these features carry substantial amounts of heat polewards (Sciremammano 1980). Savchenko et al. (1978) have also found evidence of a cold cyclonic ring, similar to one observed in the Drake Passage (Joyce and Patterson 1977) in this region.

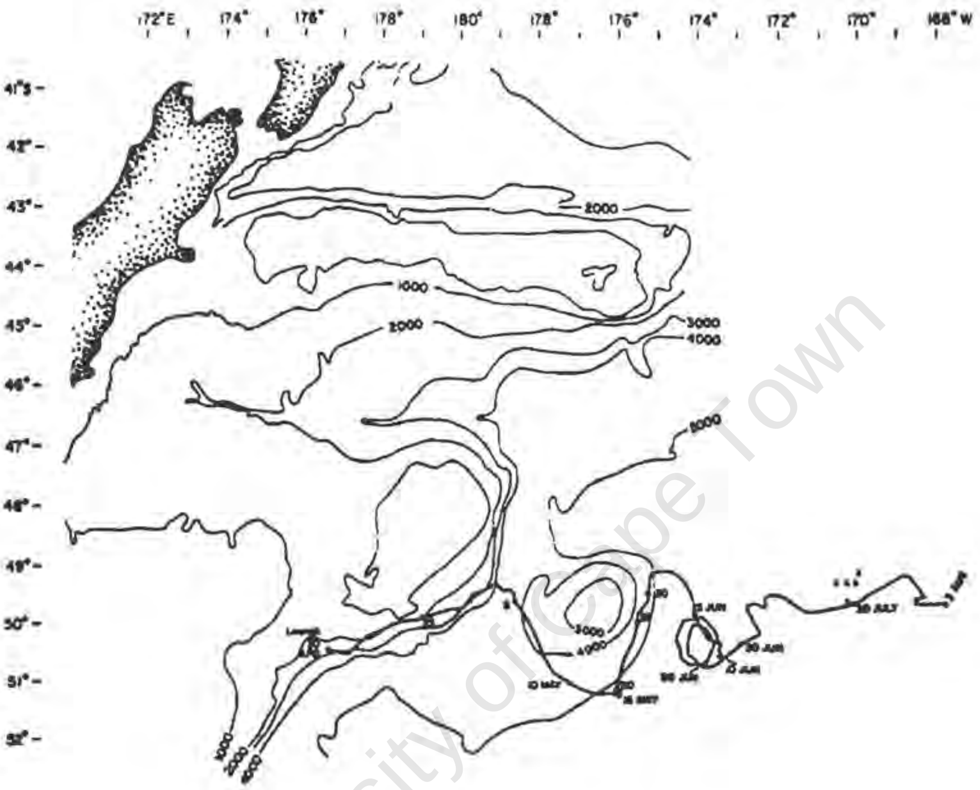


Figure 1.13: Path of a satellite tracked surface buoy southeast of New Zealand (from Bryden 1983).

Although numerous observations of cyclonic eddies in this region of the Southern Ocean have been made, no hydrographic data exists on the presence of warm rings within the ACC. The only observation ever made was by Legeckis (1977) who using satellite thermal imagery identified several warm eddies, stretching 150 km in width, south of the APF. These observations lend further support to the influence the shallow Macquarie Ridge has on path of the ACC.

It is evident from the existing literature that many of the characteristics of the ACC have been well documented. Past experiments using satellite imagery (Cheney et al. 1983), buoy trajectories (Hofmann 1985) and hydrographic data (Gordon et al. 1977, Nowlin et al. 1977, Park et al. 1993, Read and Pollard 1993, Trathan et al. 1997) have identified and concentrated on regions were sea level height variability is significant. These regions coincide with areas of prominent topographic relief, Drake Passage, Southwest Indian Ridge, Crozet and Kerguelen Plateaux and the Macquarie Ridge. However, the complex bathymetry of the Southern Ocean shown by Figure 1.4, suggests that there are also other regions of prominent relief, which lie directly in the path of the ACC. Some of these regions remain, despite the advent of enormous multidisciplinary surveys undertaken during WOCE and JGOFS programs, scientifically 'untapped'. One such example is the Prince Edward Island Group lying in the Indian sector of the Southern Ocean at 46°50'S, 37°50'E. These islands lie directly in the path of the ACC, sandwiched between the SAF to the north and the APF to the south. The circulation in this region has up until now been poorly studied.

It has long been hypothesised that these islands may form an additional barrier to the prevailing flow. One assumption, is that, mesoscale disturbances resulting in enhanced cross-zonal exchange of water masses may be further generated downstream of these islands. The purpose of this study is therefore to acquire time-variable information of the oceanic environment surrounding the Prince Edward Islands and to study for the first time the impact these islands may have on the hydrography and dynamics of the general oceanic environment.

Chapter 2

Introduction: Questioning the "island mass effect" at the Prince Edward Islands

The Prince Edward Islands, consisting of Marion and Prince Edward, lie east of the Southwest Indian Ridge and southwest of the shallow Del Cano Rise (Figure 2.1). The islands are volcanic outcrops approximately 250 000 years old (McDougal 1971). Marion Island is the larger of the two, over 270 km^2, whereas Prince Edward Island, which lies 19 km northeast, covers approximately 45 km^2. The islands are separated by a shallow saddle, which varies between 40 m and 200 m in depth. Although the islands rise steeply from a region of complex bottom topography, the group are a distinct and isolated feature in an otherwise deep (> 3 000 m) ocean. The nearest landfall is the Crozet Island Group, 950 km to the east (Figure 2.1).

The earliest study of the marine environment of the islands was conducted in 1873 when a British scientific vessel HMS Challenger visited the islands. In 1947, the British Government decided to give Marion and Prince Edward Islands to South Africa in order to prevent their falling into hostile hands. Marion Island was initially used as a meteorological station. However, it was only during the mid 1970s that a variety of other scientific endeavours such as: physical oceanography, primary productivity, plankton, fish and seabirds, were carried out by South African and French scientists aboard the French research vessel MS Marion Dufresne (Frost et al. 1976, Grindley 1978). Based on the results from this expedition in 1976, the South African Scientific Committee for Antarctic Research (SASCAR) recognised that further research should be conducted in both offshore and inshore regions in order to improve the understanding of the functioning of the islands' terrestrial ecosystem (SASCAR 1987). Six exploratory surveys to the vicinity of the islands between 1980 and 1985 emphasised the urgent need for further interdisciplinary studies of the offshore ecosystem (Pakhomov and Froneman 1999).

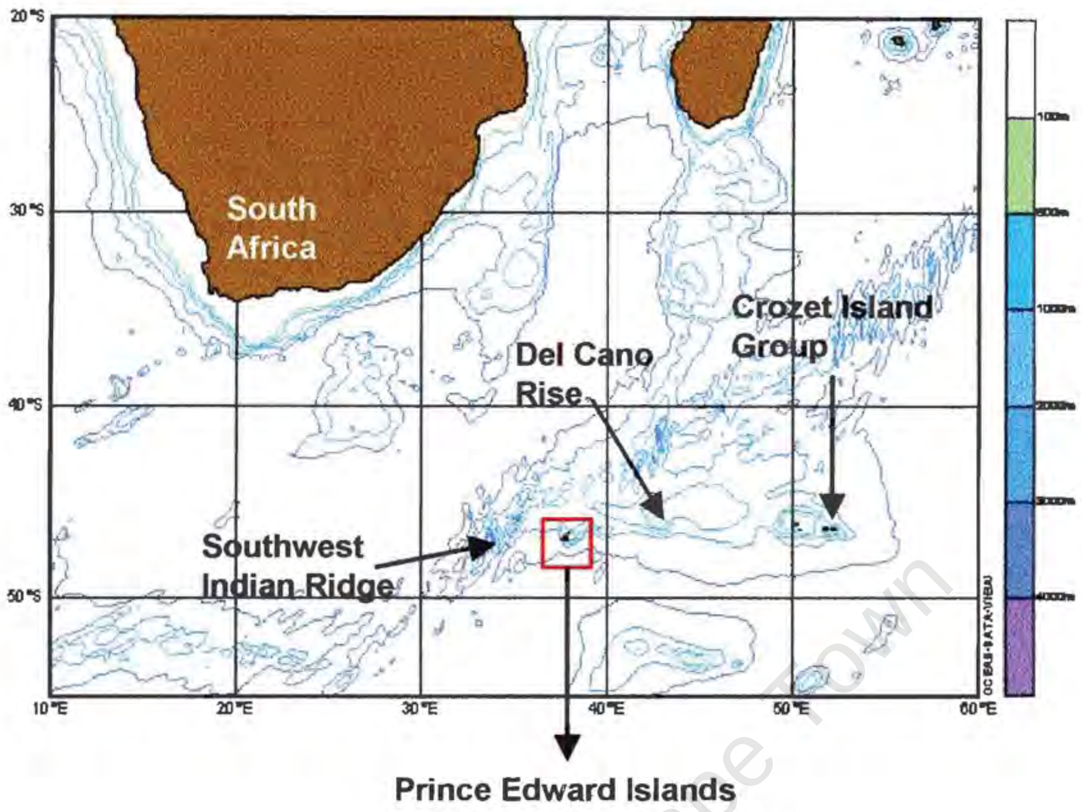


Figure 2.1: Location of the Prince Edward Islands in the Southwest Indian Ocean.

The Prince Edward Islands, in common with the Crozet and Kerguelen Island Groups (Park et al. 1993, 1997) and South Georgia (Trathan et al. 1997), lie directly in the path of the Antarctic Circumpolar Current (ACC). Extensive surveys between South Africa and the islands have already shown that they are sandwiched between the Subantarctic Front (SAF) to the north and the Antarctic Polar Front (APF) to the south (Valentine and Lutjeharms 1984, Lutjeharms and Valentine 1984). These fronts separate Subantarctic Surface Water (SASW) from Antarctic Surface Water (AASW), with a zone of transition known as the Polar Frontal Zone (PFZ) lying between the two.

Extensive oceanographic observations have shown that the SAF and APF demonstrate a high degree of latitudinal variability in this region (Valentine and Lutjeharms 1984, Lutjeharms 1990, Nagata et al. 1988, Duncombe Rae 1989 a, b). The ACC is primarily wind driven (Deacon 1982), however friction caused by bottom topography plays a major role in its flow and in the position of the PFZ (Nowlin and Klinck 1986, Park et al. 1993). Deacon (1983) has postulated that the complexity of the current regime in the vicinity of the Prince Edward Islands results in an increase in the interchange of Antarctic and Subantarctic Surface water within the PFZ.

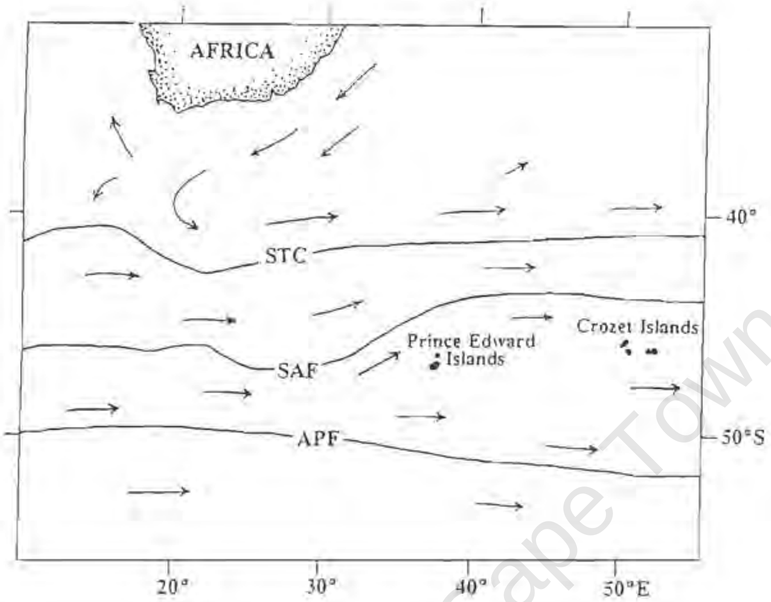


Figure 2.2: The positions of the Prince Edward Islands in relation to the African continent and major frontal systems of the Southern Ocean. STC = Subtropical Convergence, SAF = Subantarctic Front, APF = Antarctic Polar Front (after Pakhomov and Froneman 1999).

The presence of > 5 million birds and seals on the islands (Williams et al. 1979), raised the important question of whether the islands create their own enhanced biological ecosystem, the so called "Island Mass Effect" (Doty and Oguri 1956); or whether biological productivity is affected by physical processes due to the presence of these islands (Perissinotto et al. 2000). Vertical profiles of temperature and salinity showed the existence of a deep (75 – 150 m) well mixed layer depth at most stations (Allanson et al. 1985, Duncombe Rae 1989 b) thus providing stable conditions for a bloom to develop. SASCAR recognised these urgent needs to clarify the trophic links between the marine and terrestrial ecosystems and in an attempt to study the complex biological and physical interactions in the inter-island region, a dedicated program the Marion Offshore Ecological Survey (MOES) was developed. However, despite numerous hypotheses outlined below, there is still no adequate explanation of either the validity of this view or of the mechanisms involved.

1 – Upwelling theory

Hydrographic and biological studies in the lee of Marion Island (Grindley and Lane 1979) suggest, on the basis of zooplankton species, that upwelling of deep Antarctic water, as a result of predominant northwesterly winds, is the primary mechanism responsible for the high productivity in the vicinity of the islands (Allanson et al. 1985). The upwelling of nutrients would favour increased phytoplankton production. Indeed, Grindley and Lane (1985) reported the presence of a predominantly Antarctic copepod fauna in the sea surrounding the Prince Edward Islands confirming the presence of water of Antarctic origin during the period of the 1979 cruise. However, El-Sayed et al. (1979) and Deacon (1983) argue against this hypothesis on the basis of low silica concentrations in the surface waters found in this area. The upwelling hypothesis proposed by Grindley and Lane (1985) was also rejected by Allanson et al. (1985) on the basis of insufficient data. It is believed that the height of the islands would alter the wind stress curl exerted by the prevailing northwesterly winds sufficiently to prevent upwelling from occurring directly along the island shelf. Instead, Perissinotto and Duncombe Rae (1990) have suggested that upwelling would actually occur in the open ocean, as the length scale of the islands is too short.

With increased involvement from SASCAR, more opportunities of increasing the number of visits to the islands and station spacing arose, enabling Allanson et al. (1985) to propose instead a new hypothesis.

2 –von Kàrmàn Vortex Street

Allanson et al. (1985) have proposed that where wind shear is of a sufficient magnitude and when coupled with the impact the islands have on the dynamics of the ACC, vortex fields resembling a von Kàrmàn street may develop in the lee of the islands. The formation of insular eddies would result in downwelling and upwelling processes (associated with the cyclonic and anticyclonic motion of each eddy) becoming the foci of nutrient sequestration and enhanced biological productivity (Allanson et al. 1985). Such a hydrodynamic event would certainly explain the possible mechanism responsible for the development of an island mass effect. Although this hypothesis is certainly possible, changes in the zooplankton community structure may also be attributed to the advection of vagrant eddies or the development of frontal meanders downstream of the islands. These "expatriate" water masses would transport foreign plankton species into the eddy field in the lee of the island.

Further analysis by Perissinotto and Duncombe Rae (1990) suggest that rotational effects of the earth rather than frictional and advective forces dominate the flow regime associated with the islands. This new hypothesis implies that the structure of the island wake is dominated by turbulent dissipation rather than by eddy shedding.

3-Taylor column

Investigations by Perissinotto and Duncombe Rae (1990) have suggested that enhanced biological productivity may be attributed to the stabilising effect of an anticyclonic eddy with a low-density core. Such a feature would be analogous to a Taylor column entrapping nutrient rich run-off from the islands over the island plateau. Analysing hydrographic data collected from inter-island 6 cruises in the 1980s, Perissinotto and Duncombe Rae (1990) have shown that anticyclonic eddies were present on the shelf during 4 occasions. The dynamics of this eddy formation remain unresolved, but it is believed that frictional forces tend to dominate resulting in the retention of water over the island shelf. It has been suggested by Duncombe Rae (1989a) that freshwater run-off is sufficient to account for the retention of low salinity water within this feature, thereby providing further support for this theory. However, the theoretical basis for predicting such an anticyclonic eddy in the inter-island region by a Taylor column has been criticised by Attwood (1991), since the horizontal scales typical of the Prince Edward environment are far smaller than theoretical parameters. Another reason this mechanism is thought to be unfounded is that Taylor columns tend to be trapped over a shallow isolated bump such as a mid-ocean seamount, the Prince Edward Islands extend above the sea surface (Pakhomov and Froneman 1999). Indeed, Perissinotto and Duncombe Rae (1990) agree that they are unable to provide conclusive evidence of a Taylor column over the island shelf due to insufficient spatial resolution.

4-A fourth hypothesis?

A further hypothesis has been suggested by Perissinotto et al. (2000) that food necessary to sustain such an enormous community could also be washed into the island region from further upstream. Extensive research (Lutjeharms and Baker 1980) have indicated that eddies may actually be advected into the island vicinity from further afield by the Antarctic Circumpolar Current. The meandering dynamics of the ACC and the position of its associated fronts, the SAF and APF, may play a crucial role in forming the macro- and mesoscale oceanographic conditions surrounding the islands. Investigations have shown that the SAF and APF are characterised by the genesis of spinout eddies (Lutjeharms and Baker 1980, Gouretski and Danilov 1994, Lutjeharms and Valentine 1988). These eddies once trapped over the island shelf would protract residence time of water masses that would, under normal conditions, be rapidly advected through the inter-island region.

Although the concepts of the land mass effect of the Prince Edward Islands are well established, there are many areas where our understanding of these processes and the mechanisms involved are poor. As Pakhomov and Froneman (1999) point out, *"very little is known of how physical features influence the availability of food...particularly the nature of the upstream/downstream offshore source of food is completely unknown"*.

Despite a large number of hydrographic surveys in the vicinity of the islands (Miller 1982, Miller et al. 1984, Allanson et al. 1985, Boden and Parker 1986, Boden 1988, Duncombe Rae 1989 a, b, Perissinotto and Boden 1989, Perissinotto and Duncombe Rae 1990), the SAF remains to this day the least studied frontal system in the Southern Ocean (Pakhomov and Froneman 1999). The temporal meridional shifts of the position of the SAF may be responsible for the extreme variability in the plankton species composition and biomass observed in the islands ecosystem (Pakhomov and Froneman 1999). To try and resolve this it is essential to concentrate on the variability and dynamics of the SAF and to study in detail its influence on the background productivity upstream of the Prince Edward Islands.

Two cruises were designed to accomplish such an aim: the Marion Offshore Ecological Survey – MOES 2 survey in 1989 and a repeat cruise in 1997, the MIOS 2, during a follow-up programme the Marion Island Oceanographic Survey (MIOS). No comparison has, so far, ever been made of these two datasets. The MOES and MIOS mesoscale surveys combined form one of the most intensely studied regions in the Southwest Indian sector of the Southern Ocean (Figure 2.3).

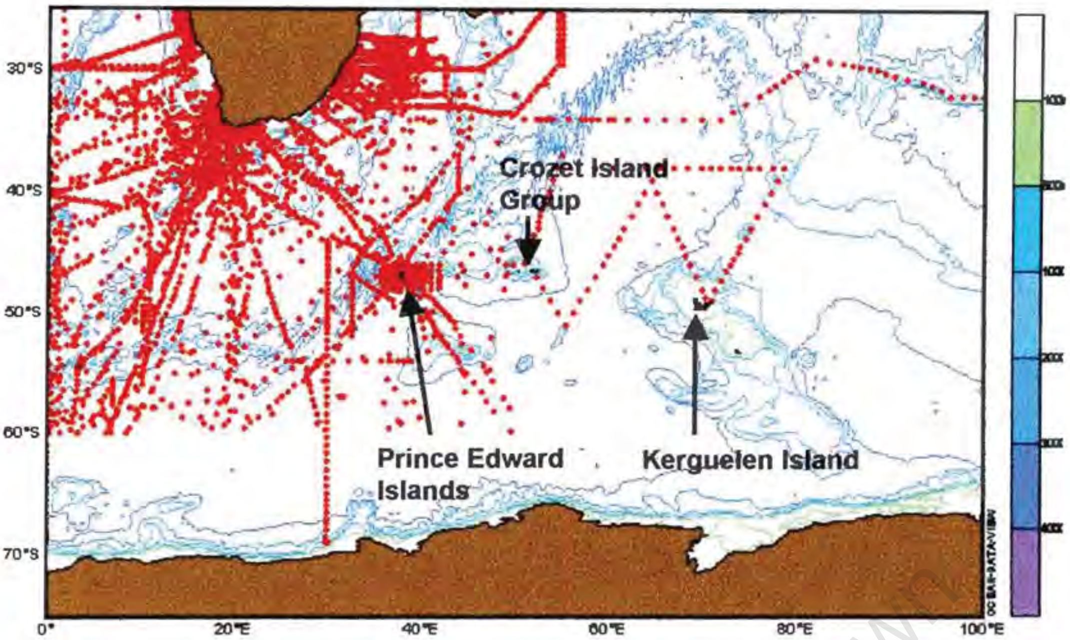


Figure 2.3: Distribution of CTD stations in the southwest Indian sector of the Southern Ocean, currently available to the Ocean Climatology Research Group at the University of Cape Town. The dense coverage of stations surrounding the Prince Edward Islands were carried out during the MOES 2 and MIOS 2 surveys and represent a strong contrast to the poorly studied regions surrounding the Crozet-Kerguelen Islands.

The broad objectives of this thesis are therefore:

1. To establish a reliable hydrographic profile of the ACC in the vicinity of the Prince Edward Islands.
2. To study what degree of impact these islands may have on the spatial and temporal variability of particularly the SAF in this sector of the Southern Ocean.
3. Finally, to describe in detail the hydrography and dynamics of the general oceanic environment of the Prince Edward Islands.

This thesis is divided into chapters, which address the following key questions that have arisen as a result of our lack of knowledge and understanding of this region.

To avoid repetition, methods common to many of these chapters are combined in the Data and Methods - Chapter 3.

1. **What water masses can be found in the ocean surrounding the Prince Edward Islands?**

2. **What impact do the Prince Edward Islands have on the flow of the Antarctic Circumpolar Current?**

3. **What impact, if any, does this have on the general oceanographic environment of the Polar Frontal Zone?**

The Prince Edward Islands lie directly in the path of the ACC, sandwiched between the SAF to the north and the APF to the south, in a region known as the Polar Frontal Zone. This is a zone of transition, in which water masses associated with the Subantarctic zone gradually modify to become characteristic with the water masses found in the Antarctic Zone. It has been hypothesised (Allanson et al. 1985, Perissinotto and Duncombe Rae 1990) that mesoscale disturbances may be generated downstream of the islands resulting in enhanced cross-zonal advection of water masses. In order to understand the oceanographic regime surrounding the Prince Edward Islands, it is necessary that water masses associated with this region and the modifications that may arise through the formation of these hypothesised disturbances be studied.

4. **What impact does the physical environment have on the distribution and community structure of the zooplankton?**

5. **Does the species distribution reflect the variability of the oceanographic regime around the islands from one year to the next?**

The zooplankton community structure in the vicinity of the Prince Edward Islands may be strongly determined by the prevailing oceanographic regime. Results from previous investigations (Boden and Parker 1986) have shown that the zooplankton community in this region is generally dominated by Subantarctic species, although shifts in the taxonomic groups suggest that water masses of different origins may have been sampled (Allanson et al. 1985, Boden and Parker 1986). The aim of this chapter is to compare hydrographic with biological data, collected during the two surveys, and to examine and compare the influence that disturbances in the ocean environment may have on the zooplankton community structure.

6. **Is there evidence of synoptic pulsing through the islands?**

The SAF has been shown to vary considerably in its latitudinal position in the region surrounding the Prince Edward Islands. Previous investigations (Perissinotto and Duncombe Rae 1990) have shown that during occasions when the SAF lies far to the north of the islands, the prevailing flow associated with the PFZ is weak and as a result, water appears to be trapped in the inter-island region. In contrast, during occasions when the SAF lies closer to the islands advective forces associated with the frontal flow dominate and consequently flow through the islands is strong. Previous investigations have shown the SAF to fluctuate considerably (Lutjeharms and Valentine 1984, Duncombe Rae 1989b), however, little is known of the impact this may have on the flow passing through the inter-island region. Investigations have certainly indicated that biological productivity varies considerably from year to year suggesting that flow-through may be irregular (Pakhomov et al. 1998). Whether, continuous advection of large plankton and nekton species occurs over the islands saddle has still not been resolved, although it has been hypothesised that pulses of water may occasionally occur between the islands (Miller 1982, Pakhomov and Froneman submitted). The main aim of this chapter is to explore the synoptic dynamics controlling the oceanographic and biological parameters over the inter-island region in order to test the pulsing hypothesis.

7. **Is TOPEX/ERS 2 a good representation of the flow dynamics found at the Prince Edward Islands?**

8. **Is it possible to track the development and/or decay of mesoscale features for an extended period of time?**

Satellite altimetry provides the most powerful tool to observe sea level variations globally and synoptically. The launch of TOPEX/POSEIDON in 1992 and ERS-1 and ERS-2 in 1995 has resulted in continual mapping of the global sea surface topography from which surface currents can be computed. However, little is known of the correlation between in-situ measurements and such images in the Southern Ocean. Persistent attempts in the past using infrared imagery to ascertain the circulation pattern in the region surrounding the Prince Edward Islands have been foiled by almost continuous cloud cover. The aim of this chapter is to compare sea surface height anomalies obtained by blended TOPEX/ERS-2 data with hydrographic data collected during MIOS 2.

In addition the extreme costliness of ship's time presents a strong limitation to the collection of in-situ measurements, particularly in the Southern Ocean. As a result hydrographic data presents only a synoptic picture of the quasi-instantaneous circulation around the islands and the gradual development or decay of mesoscale features can only be speculated. It is therefore hoped that after establishing a reliable representation between TOPEX/ERS-2 and the MIOS 2 dataset, that the decay or development of such features in the vicinity of the Prince Edward Islands may be followed over an extended period of time.

Chapter 3

Data and Methods

To address the research questions posed in the previous chapter, two mesoscale grid surveys, MOES 2 and MIOS 2, occupying a total area 100 000 km^2 were carried out. During each cruise, closely spaced hydrographic stations (approximately 16 nautical miles apart) were occupied upstream and downstream of the Prince Edward Islands. It is important to note that both MOES 2 and MIOS 2 surveys were undertaken during the annual logistical re-supply of Marion Island between April and May. Consequently, although the interannual temporal and spatial variability of the PFZ can be studied, the effects of seasonality on the oceanic environment surrounding the islands will remain unresolved.

Hydrographic Data

The region between South Africa and the Prince Edward Islands has been extensively studied from XBT stations deployed enroute to the islands (see Figure 2.3 – page 31). These XBT lines delineate the geographic location of the major frontal systems (AF, STC and SAF), as well as identify their thermal characteristics. In the past, CTD stations were restricted to either single line surveys in the upstream region (Jacobs and Georgi 1977, Read and Pollard 1993) or in the immediate vicinity of the islands (Allanson et al. 1985, Perissinotto and Duncombe Rae 1990). As a consequence, these surveys were lacking either the spatial resolution or the areal extent, necessary to resolve mesoscale oceanographic features in the wider vicinity of the islands. In order to fill this gap two research surveys: Marion Offshore Ecological Survey 2 (MOES 2) and the Marion Island Oceanographic Survey 2 (MIOS 2) were co-ordinated in the upstream, inter-island and downstream regions of the islands.

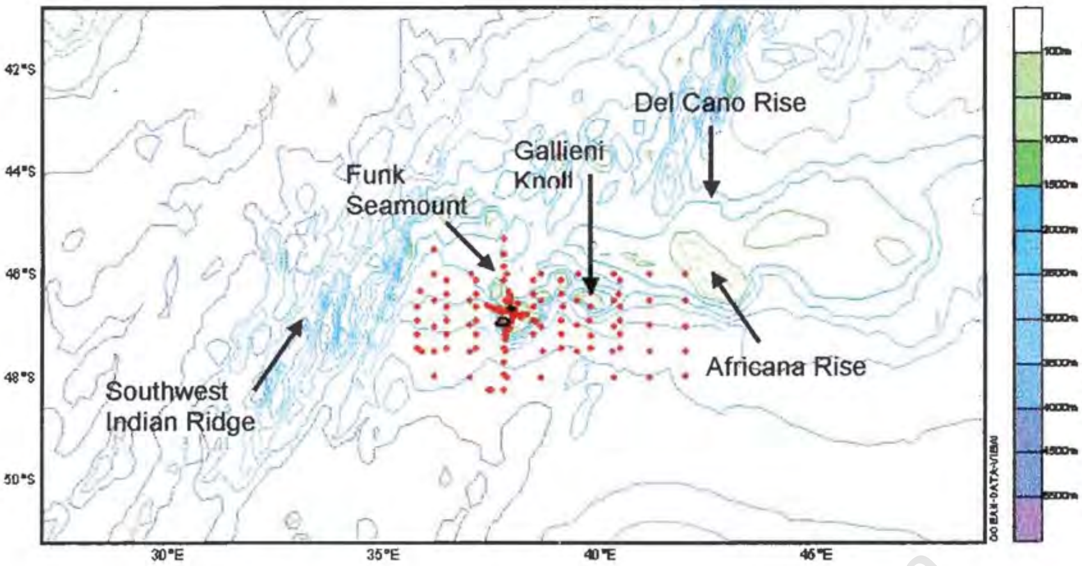


Figure 3.1: Area covered by the MOES 2 and MIOS 2 surveys. The complex topography surrounding the islands is clearly shown. Isobaths are marked at levels of 500 m.

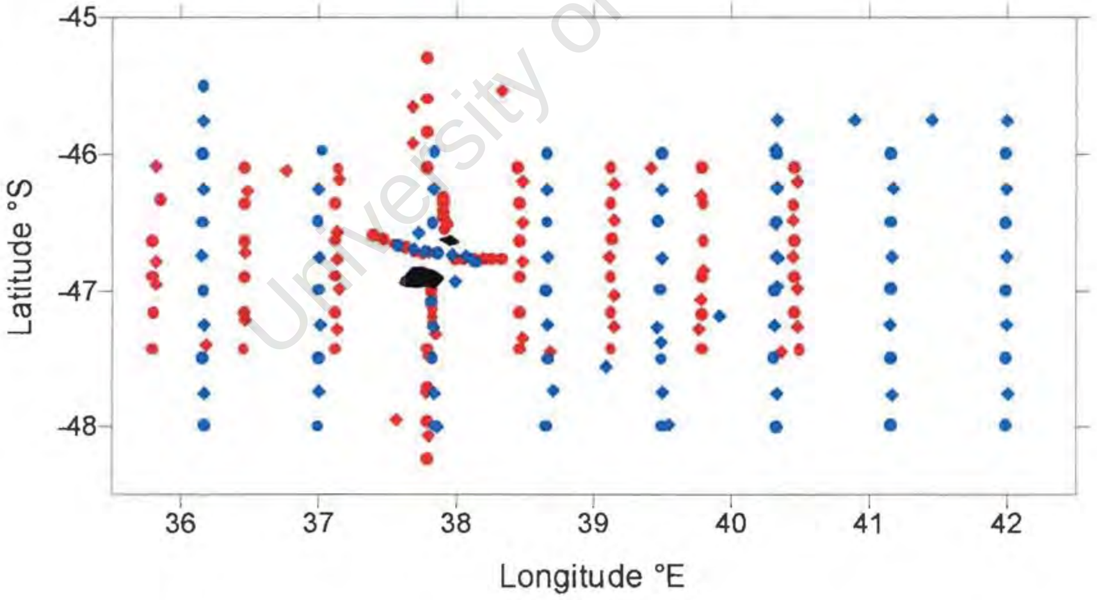


Figure 3.2: Distribution of all hydrographic stations (CTD - dots and XBT - diamonds) occupied during the MOES 2 (red) and MIOS 2 (blues) surveys.

Objectives of MOES 2

The Prince Edward islands support a large community of seabirds and marine mammals (Williams et al. 1979). Extensive biological investigations (Allanson et al. 1985) in the surrounding waters have shown the islands to demonstrate an "island mass effect" (enhanced phytoplankton production). Recent investigations suggest that food necessary to support the vast populations of predators may be advected from upstream into the vicinity of the islands (Perissinotto 1989). It is difficult to establish whether this enhanced productivity is solely due to the presence of the islands in the Southern Ocean, or whether other factors play a significant role. To clarify this uncertainty, it was considered essential to place enhanced productivity levels in the immediate vicinity of the islands into a broader geographic perspective. Thus, the main aim of the MOES 2 survey was to study the close interaction between the surrounding oceanographic regime and the islands ecosystem.

Hydrographic Dataset

The second cruise of the Marion Offshore Ecological Study (MOES 2) took place between 29 March and 8 May 1989 aboard the research vessel *SA Agulhas*. The survey consisted of a grid of eight north-south transects across the Polar Front Zone (PFZ) (Figure 3.3). Three lines were occupied upstream of the islands between 35°51'E – 37°07'E, four lines were occupied downstream between 38°27'E – 40°28'E and one line extending approximately 180 nm was occupied along the longitude of the islands (37°48'E). Each line consisted of six alternate CTD and XBT stations occupied at 16 nm intervals.

At each hydrographic station, vertical profiles of conductivity, temperature and depth were obtained to a maximum depth of 2000 m using a Neil Brown Instrument system Mark IIIB underwater unit (Van Ballegooyen et al. 1989). At each XBT station, Sippican Deep Blue XBT probes were deployed to a maximum depth of 760 m or to the bottom at shallow stations. The probes were calibrated against sea surface water temperatures obtained with a Crawford bucket (Crawford 1972).

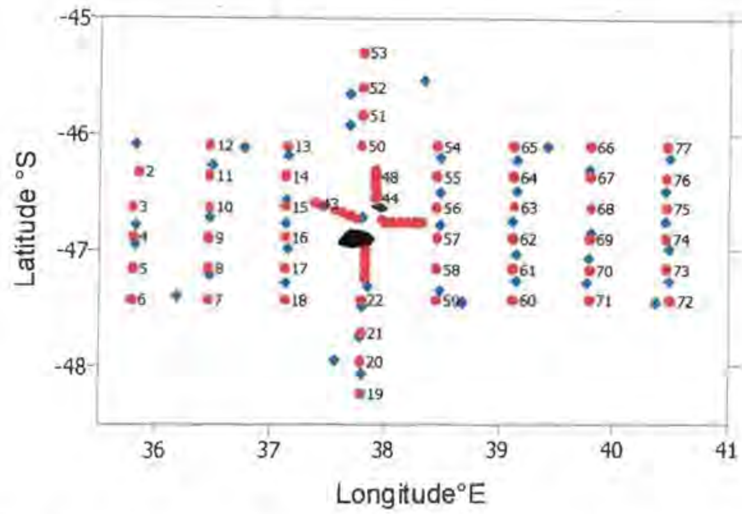


Figure 3.3: Distribution of hydrographic stations occupied in the oceanic environment of the Prince Edward Islands during MOES 2. CTD stations are denoted as red dots and the location of XBT stations are shown as blue diamonds. The Prince Edward Islands are marked in black.

Calibration Procedures

Following the cruise the CTD sensor was calibrated at the Sea Fisheries Research Institute, Roggebaai, South Africa (SFRI). The pressure sensor was calibrated against a Budenberg Dead Weight Tester Model (Model 280D), the temperature sensor against a Hewlett Packard 1804A Quartz thermometer and the conductivity sensor against IAPSO standard seawater using a minisal (Model 2110) salinometer. The conductivity to salinity conversion follows UNESCO (1983) and this was applied to the corrected CTD temperatures before further analysis took place (Van Ballegooyen et al. 1989).

Limitations of the MOES 2 dataset

Problems encountered with salinity calibrations resulted in low accuracy levels ~0.03, however, θ/S plots of the corrected MOES 2 data compare well with historical data in the region of the Prince Edward Island group. Van Ballegooyen et al. (1989) gives further information, as well as all the CTD and XBT data listings at standard depths.

Objectives of MIOS 2

The Antarctic Circumpolar Current and its associated fronts have been shown to exhibit extensive latitudinal variability (Lutjeharms and Valentine 1984, Duncombe Rae 1989a). Results from MOES 2 have suggested that the oceanic environment surrounding the islands be divided into clearly distinguishable upstream and downstream regimes. The objectives of the MIOS 2 cruise were to better understand the impact the isolated islands have on the prevailing easterly flow of the ACC. By occupying a grid survey similar to MOES 2, the inter-annual spatial variability can be established and the implications it may have on the biological community structure studied. In addition, repeat XBT lines were carried out to and from the islands in the region between 42°S and Marion Island in order to determine the geographic location of the SAF prior to the grid survey.

Hydrographic Dataset

The second cruise of the Marion Island Oceanographic Survey (MIOS 2) was undertaken between 25 April and 28 May 1997 aboard the *SA Agulhas*. The MIOS 2 was designed as a comparative study, hence the survey grid consisted of similar transects as that of MOES 2, with alternate CTD and XBT stations on average 15 nm apart. In order to increase the spatial coverage of the Polar Frontal Zone (PFZ), hydrographic transects extended farther south between 46° - 48°S and farther east between 36° 10' - 42° 00'E than for the MOES 2.The survey consisting of a similar grid of eight north-south transects across the PFZ (Figure 3.4). Two sections were occupied upstream of the islands between 36°10' E to 37° E, five were occupied downstream between 38°40' E and 42° E and one line occupied along the longitude at which the islands lie.

In addition, repeat XBT lines were carried enroute to the Prince Edward Islands between 42° - 47°S. The aim of these transects was to determine the temporal variability in the geographic location of the SAF during the period of the survey (Figure 3.4). At each hydrographic station, vertical profiles of conductivity, temperature and depth were obtained with a Neil Brown Instrument system Mark IIIC upgrade underwater unit. Where possible the CTD station extended to a maximum depth of 1500 m. Water samples were collected on the upcast at 11 standard depths with a duplicate bottle fired at 20 m. These duplicate samples were taken for biological analyses. Bottles were triggered at depths corresponding to 1500, 1250, 1000, 900, 750, 500, 400, 200, 100, 50, 20 and surface +/- 5 m. The CTD rosette was lowered through the water column at rates varying between 0.6 – 1 m s^{-1} (Ansorge et al. 1998).

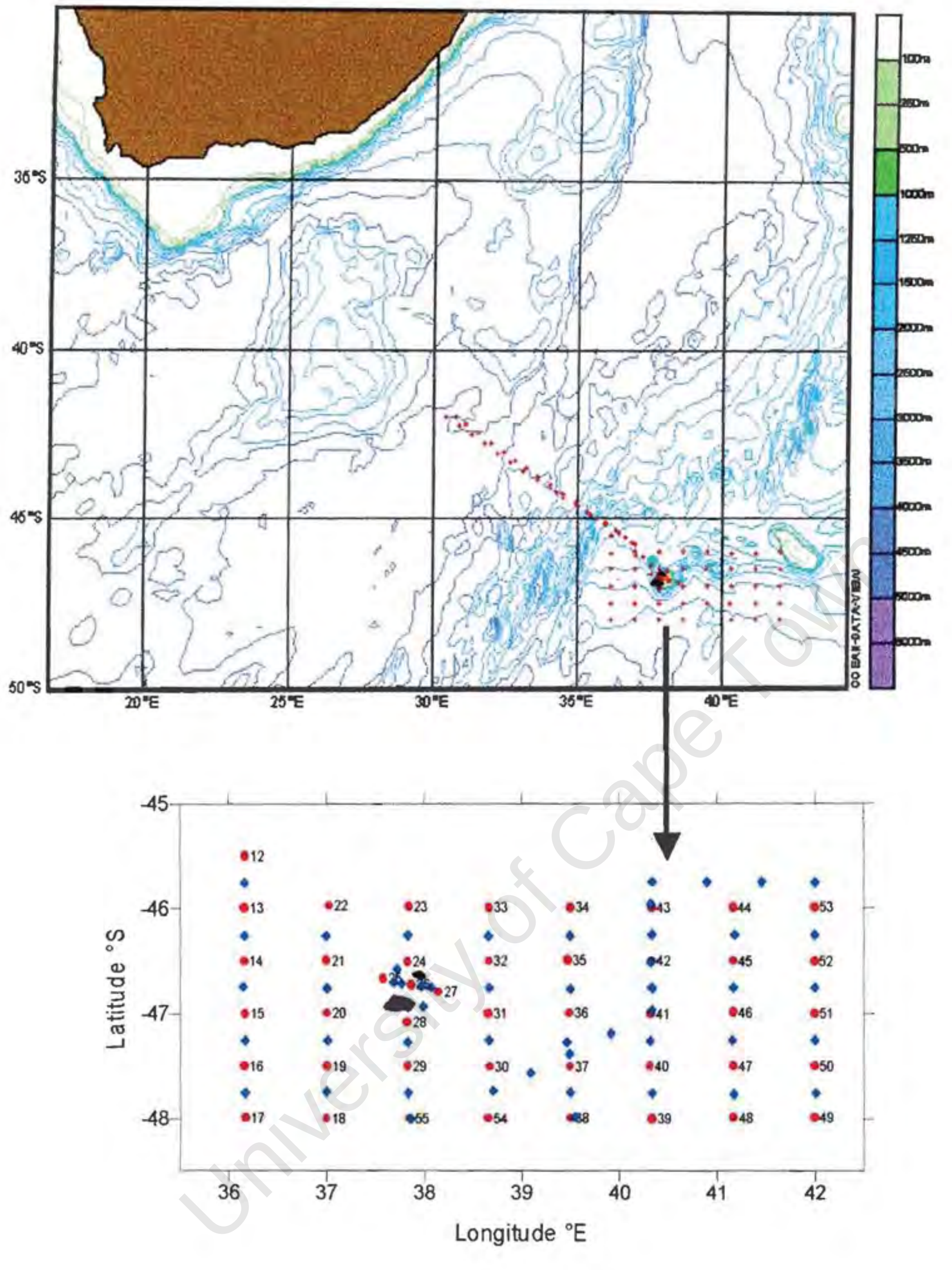


Figure 3.4: Geographic location of hydrographic stations occupied during MIOS 2. CTD stations are denoted as red dots and XBT stations as blue diamonds. The Prince Edward Islands are in black. XBT stations were occupied enroute to the islands between 42° - 47°S. A total of 173 hydrographic stations (116 XBT and 57 CTD) were undertaken during the survey.

Calibration Procedures

The following laboratory calibrations were carried out before and after the cruise at the SFRI. The pressure sensor was calibrated against a Budenberg Dead Weight Tester, the temperature sensor against a calibrated Hewlett Packard 1804A quartz thermometer and the conductivity sensor against IAPSO Standard Seawater using an Autosal. The conductivity to salinity conversion described in UNESCO Technical papers in Marine Science 44 (1983) was applied, using the corrected CTD temperatures. Further calibration of the conductivity sensor using in situ observations was also carried out. In total 390 salinity samples were obtained during CTD stations. These were used for calibration purposes and a multiple regression analysis was applied to the CTD and bottle salinity data (Figure 3.5).

Pressure corrections

The pressure calibration was checked by comparing the CTD depth at the bottom of each shallow cast (< 1500 m) with the depth derived from the onboard echo sounder. As each cast was only lowered to a maximum depth of 1500 m the number of occasions when the sea floor was within that range were limited to 12 out of 57 casts. During these occasions the CTD was lowered to within 10 m of the bottom and the echo sounder reading logged. The difference between the distance from the bottom of the CTD, the pressure reading from the CTD acquisition software and the depth recorded by the echo sounder were compared. The CTD pressure was converted to depth by using the equation of state. As a result the difference between echo sounder reading and the converted CTD reading was ± 3.3 m.

Temperature corrections

The CTD temperature corrections were based primarily upon comparisons between the CTD readings and DSRT. A five point (5°C, 10°C, 15°C, 20°C, 25°C and 30°C) calibration was carried out on the CTD prior and post cruise, using a high precision 2804A quartz thermometer with probes 18121A and 18119A. The high precision was calibrated against a precision thermometry bridge.

Salinity corrections

Bottle salinities were collected from each Niskin bottle in order to calibrate the CTD. Salinity samples were drawn into 200 ml bottles after 3 rinses and analysed within 8-25 hours of collection after equilibrating to laboratory temperature. The draw time and equilibration times were logged. Comparisons of the bottle salinities and the CTD salinities were also used to identify malfunctioning rosette bottles. These values can be found for each CTD station in Ansorge et al. (1998). A regression analysis was carried out between the CTD and bottle salinities (Figure 3.5).

In total 390 values were compared and a regression value of 0.9988 between the two was calculated.

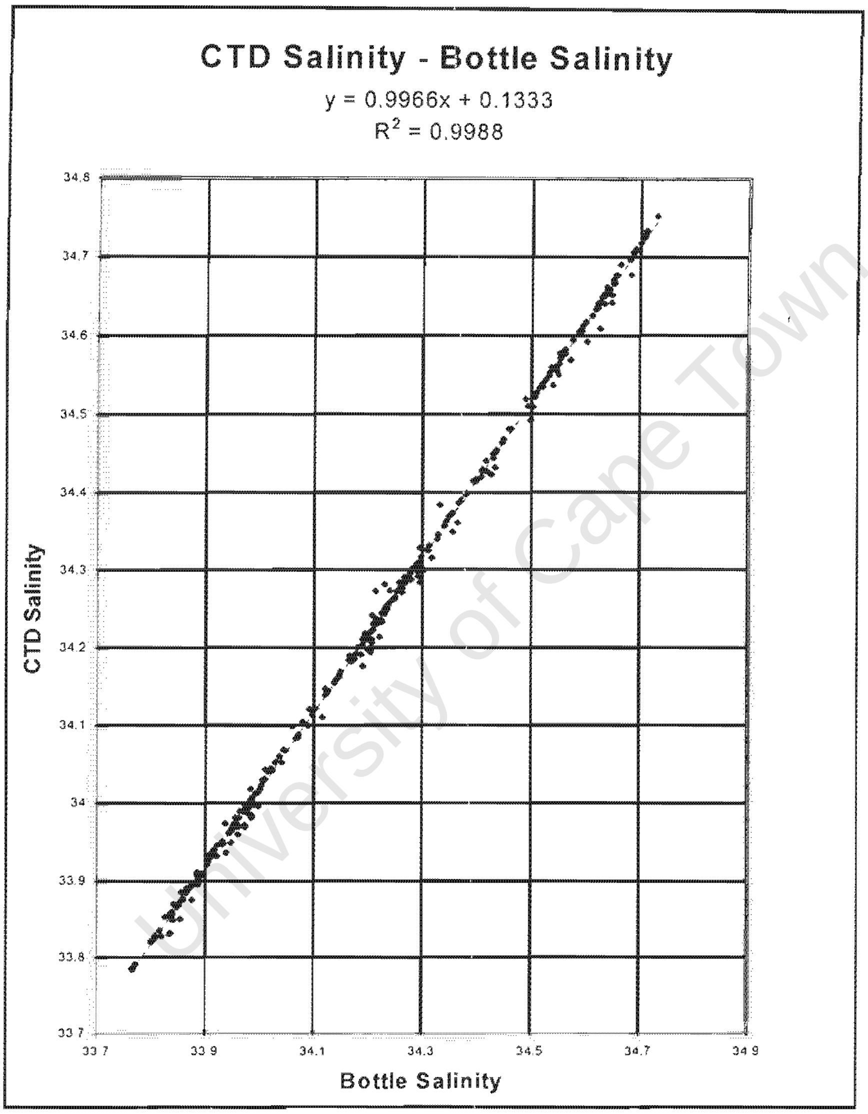


Figure 3.5: Regression line and scatter graph comparing bottle and CTD salinities.

The conductivity ratio was determined using a Guildline Autosal Model 8400A salinometer and followed the methods described in the Guildline AutoSal Operating Manual. The conductivity was converted to salinity using equations described by UNESCO (1983). The autosal had been re-calibrated and re-aligned in June 1995 at Ocean Scientific International in Great Britain. Wormley Standard Sea water batch

P119 was used to standardise the salinometer at the start and end of every two stations (24 samples). In total, the salinometer was standardised on 22 occasions during the cruise, of which 18% experienced no drift, 18% experienced a positive drift while 64% experienced a negative drift. The drift in conductivity values at the end of each standardisation varied between -0.00066 to +0.00025; this corresponds to changes in salinity of -0.0049 and +0.0010. The highest drift (conductivity -0.00175 and salinity -0.0345) occurred between stations 7 and 9, this coincides with the only problem that was encountered with the salinometer when the transformer overheated and burnt out.

XBT corrections

Sippican T7 XBTs were deployed to a depth of 760 m or to the bottom, at alternate intervals between CTD stations during the survey. The probes were calibrated against sea surface water temperatures obtained with a Crawford bucket (Crawford 1972) Each probe was placed in a water bath for 5 minutes prior to deployment in order to minimize the difference between the probes storage temperature and that of the sea surface temperature. In total a failure rate of 15.5% was experienced mainly as a result of strong winds and sea swell. During the survey, a comparison was made between CTD and XBT temperatures at station 38. Surface readings showed an offset of +0.1°C against the CTD reading.

Limitations of the MIOS 2 dataset

One limitation of this dataset is that during the cruise, spooling problems with the CTD cable prevented the CTD being lowered deeper than 1500 m, consequently only surface and intermediate water masses were sampled. Stormy conditions also prevented the most southern stations along transect 3 and 4 being occupied and as a result these missed stations were occupied (CTD 54 and 55) 3 days later (Figure 3.4).

Further information and station listings can be obtained from Ansorge et al. (1998).

Both cruises were entirely funded by the South African National Antarctic Program (SANAP) of the Department of Environment Affairs and Tourism (DEA&T).

Calculations:

Great Circle Distances

Distances between station pairs were calculated according to the formula

$$(3.1)\ \mathbf{dx = R.arctan\cdot(1/\alpha^{2})-1}$$

Where:

dx is the great circle distance in kilometres

α = cos (lat1).cos (lat2).cos (lon1-lon2)+sin (lat1).sin (lat2)

R is the radius of the earth = 6371 km.

The latitudes and longitudes are given in radians

Geostrophic Velocity

Geostrophic velocities (with reference to the deepest common depth) between two stations were calculated at every 1 db pressure level throughout the water column. It must be remembered that while the majority of stations extended to 2 000 m during MOES 2, problems with the spooling of the hydrographic wire during MIOS 2 prevented a wire out of more than 2 000 m. As a result, geostrophic velocities have been calculated to a maximum reference of 1 500 db for both surveys.

Equations (3.2) and (3.3) are used in calculating geostrophic flow between a station pair:

$$(3.2)\ \Phi = \delta.\mathbf{dp}$$

Where;

Φ (J kg^{-1}) is the geopotential anomaly calculated for each level relative to a common reference level.

δ (m^{3} kg^{-1}) is the specific volume anomaly calculated using the UNESCO (1983) algorithm.

dp (db) is the difference between the pressure levels.

$$(3.3)\ \mathbf{vAB=(1/\mathit{f}.dx)[\ \Phi B-\Phi A]}$$

Where;

vAB the geostrophic flow measured in m/s between station pairs.

f the Coriolis force at an average latitude for the two stations.

dx (m) is the distance between two stations, which is calculated using the above great circle equation (3.1).

Generation of vertical sections and horizontal distributions

Vertical sections and horizontal distributions for temperature, salinity, sigma-theta, geopotential anomalies and geostrophic velocities were plotted using a contouring package *Surfer 6.02 by Golden Software*. Surfer 6.02 is a grid-based contouring graphics program. Surfer interpolated irregular spaced data collected during both surveys into gridded data files using the geostatistical method of data interpolation "kriging". Grid limits and densities varied for each survey as a result of hydrographic transects during MIOS 2 extending farther south between 46° - 48°S and farther east between 36° 10' - 42° 00'E than for the MOES 2.

The horizontal field gridded and the spacing of data points for each survey are given below in Table 3.1. Grid density refers to the number of rows and columns in a grid file, and is a measure of the number of grid nodes in the grid. Higher grid densities increase the smoothness of the contour maps and surface plots. Grid line geometry defines the grid limits and grid density. Grid limits are the minimum and maximum X and Y coordinates for the grid. By defining the grid limits and the number of rows and columns, the spacing values are automatically determined as the distance in data units between adjacent rows and adjacent columns.

Survey	Grid limits Longitude	Grid limits Latitude	Spacing X	Spacing Y	Lines X direction	Lines Y Direction	Grid Density
MOES2	35.75-42.25	45.25-48.0	0.08	0.11	31	50	1550
MIOS2	35.55-40.75	45.05-48.5	0.12	0.11	21	50	1050

Vertical Profiles

Hydrographic profiles showing the potential temperature/salinity (θ/S) relationships for individual and group stations have been drawn using *Ocean Data Viewer (ODV)*. ODV can be downloaded from http://www.awi-bremerhaven/de/GPH/ODV.

MOES 2 and MIOS 2 datasets were easily imported into ODV and quality flags were maintained with every individual data value. These quality flags can be used by ODV as a data filter to exclude bad or questionable values.

These profiles have been drawn to identify and characterise the various water masses associated with the Antarctic Circumpolar Current according to definitions based on previous investigations (Whitworth and Nowlin 1989, Read and Pollard 1993). Boundaries between the various water masses are then defined by divisions based on a change in the slope of the θ/S plot.

Chapter 4

The hydrography of the waters surrounding the Prince Edward Islands: A comparison between MOES 2 and MIOS 2.

Results from the MOES 2 and the MIOS 2 give the first quasi-synoptic portrayals of the ocean surroundings of the Prince Edward Islands. They indicate an unusually high degree of spatial and temporal variability for this region, in contrast to comparable regions of the PFZ elsewhere in the Southern Ocean.

Oceanic environment during MOES 2

The SAF lay at 46°38'S upstream of the islands during MOES 2, on the first transect of this survey (Figure 4.1). Closer to the islands its path was deflected northwards to 45°55'S. Farther downstream, surface temperatures and sigma-theta values gradually decreased poleward - between 46°S and 48°S - from 7.5 – 5.5°C and from 26.42 – 26.60 kg m^3 (Figures 4.1 a and c). These values are typical of the transitional character of the PFZ (Perissinotto et al. 2000). In contrast, a single sharp gradient in surface salinities from 33.80 to 33.90 was observed between 46°15'S and 46°45'S (Figure 4.1b). The APF was not encountered upstream, instead a cold eddy (< 5°C) was observed immediately south of the islands (Figures 4.1a and 4.2a).

Downstream, the surface expression (7.2°C) of the SAF remained within a narrow band along the northern edge of the survey grid at 46°S (Figure 4.1a). Subsurface distributions of temperature and sigma-theta show the existence of a distinct, broad, meandering wake with a wavelength of 120 km within the PFZ (Figures 4.2a and c). Temperature distributions show this wake to be deep, extending to 1500 m (Figure 4.5a). However, at the same depth salinity and sigma-theta do not show a clear wake but instead a gradual southward shift in isohalines and isopycnals (Figures 4.5b and c). A possibility that would explain this southward shift may be the existence of an arc of shallow seamounts and rises (Gallieni Knoll and Del Cano Rise) to the northeast of the islands (Figure 3.1 page 36), restricting the advection of deeper water masses northwards. Pollard and Read (2000) find that bathymetry shallower than 2000 m has the greatest impact on flow in this region. Their study of the pathway and transport of the ACC in the vicinity of the Southwest Indian Ridge revealed that 10 Sv of the ACC turns southeast to pass between the Gallieni Knoll and the Del Cano Rise. This would certainly explain the southerly shift in properties seen in Figures 4.5 b and c.

At the eastern edge of the survey grid (40°45'E) a warm eddy was observed. Subsurface temperatures and salinities within this eddy, > 5.2°C and > 34.20, were higher than the surrounding waters suggesting an origin farther to the north (Figures 4.2a and b).

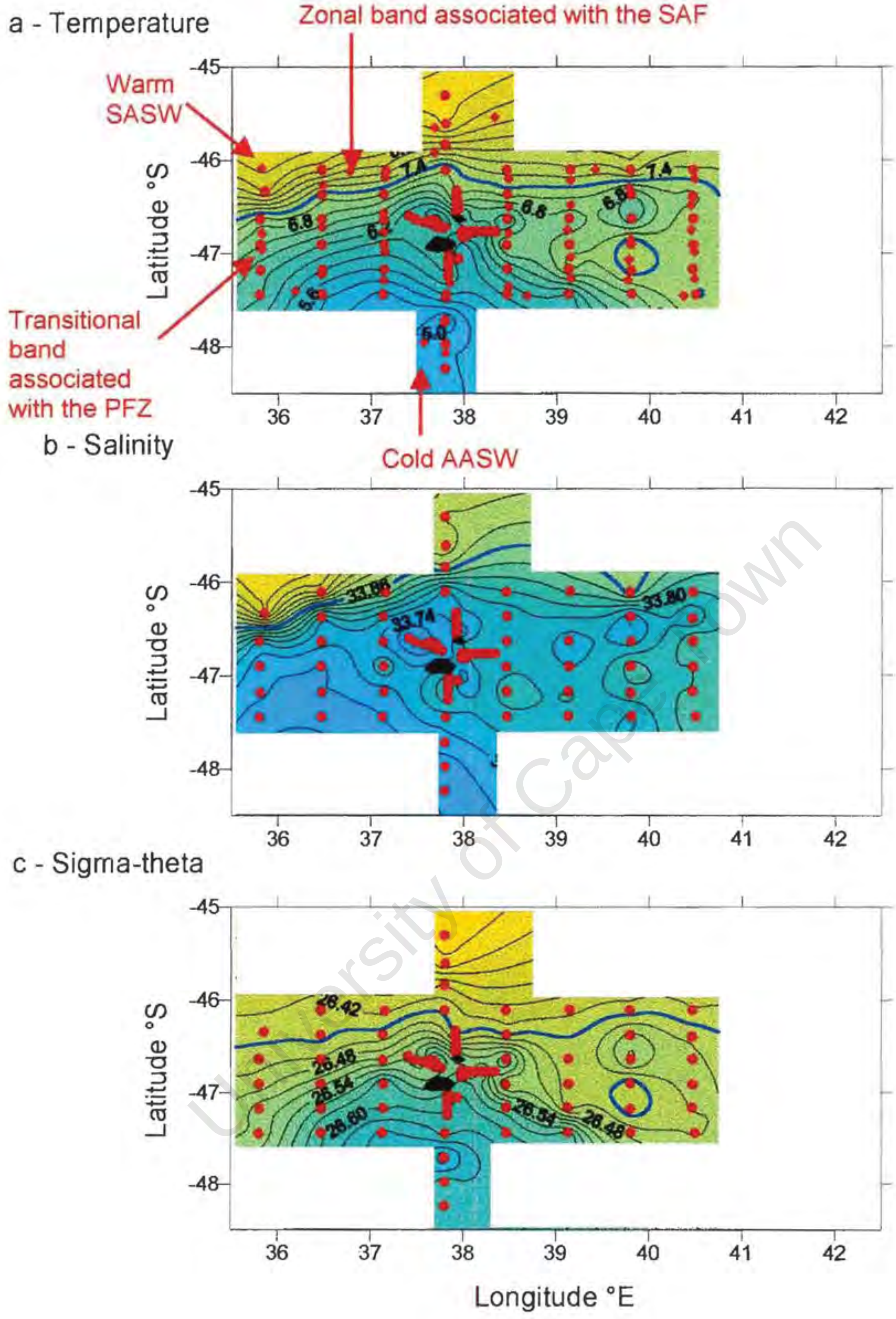


Figure 4.1 Surface horizontal distribution of (a) Temperature (°C), (b) Salinity (psu) and (c) Sigma-theta (kg m^3) observed during MOES 2. A blue line marks the surface expression of the SAF axis. It appears to be a zonal band lying to the north of the islands. Red dots represent the position of all CTD stations and red diamonds represent XBT stations (temperature only), which were deployed to a maximum depth of 750 m.

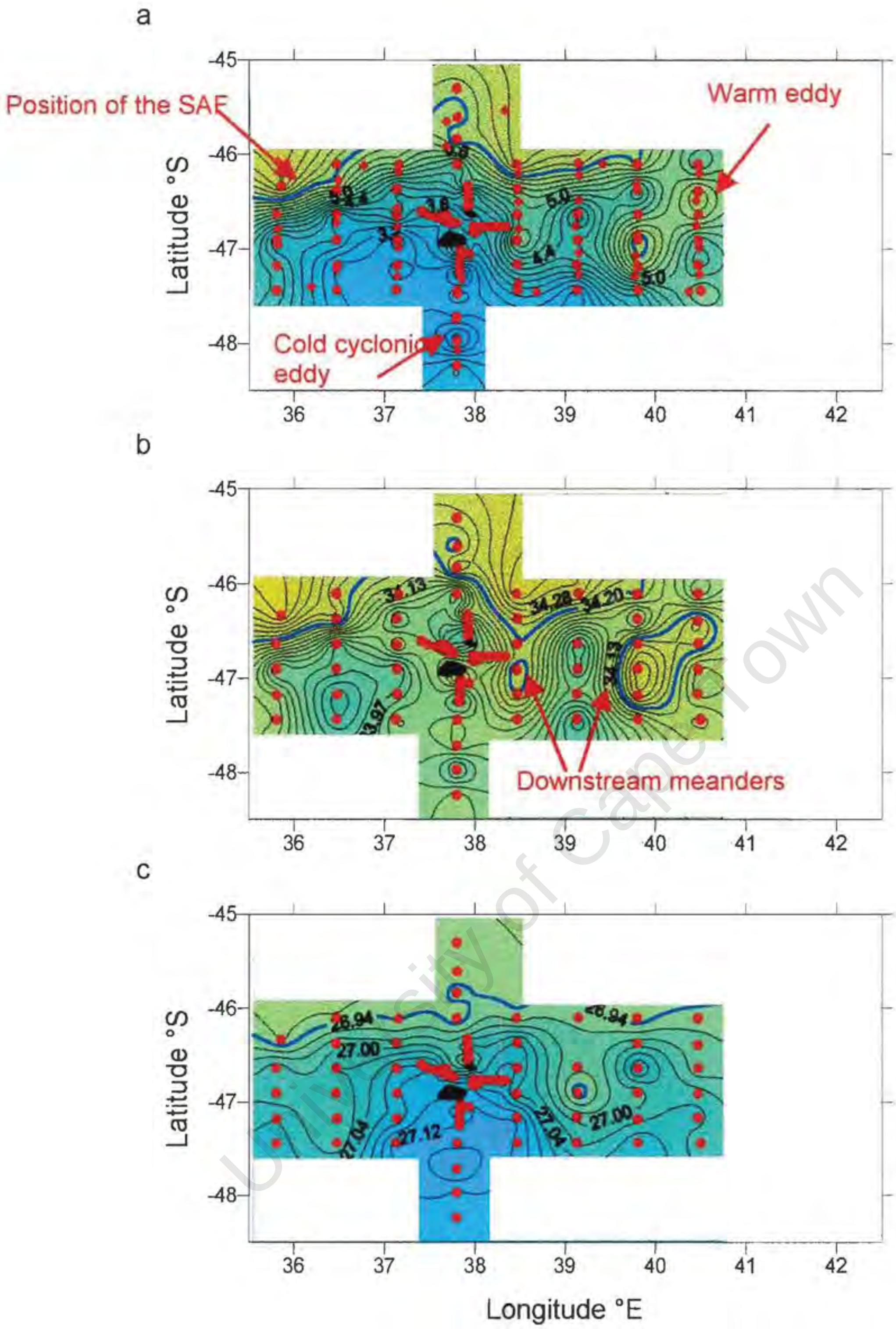


Figure 4.2: Horizontal distribution of (a) Temperature (°C), (b) Salinity (psu) and (c) Sigma-theta (kg m^3) at 200 m during MOES 2. A blue line marks the sub-surface expression of the SAF axis. The formation of a meandering wake downstream of the Prince Edward Islands is evident. It appears to be a zonal band lying to the north of the islands. Red dots represent the position of all CTD stations and red diamonds represent XBT stations (temperature only), which were deployed to a maximum depth of 750 m.

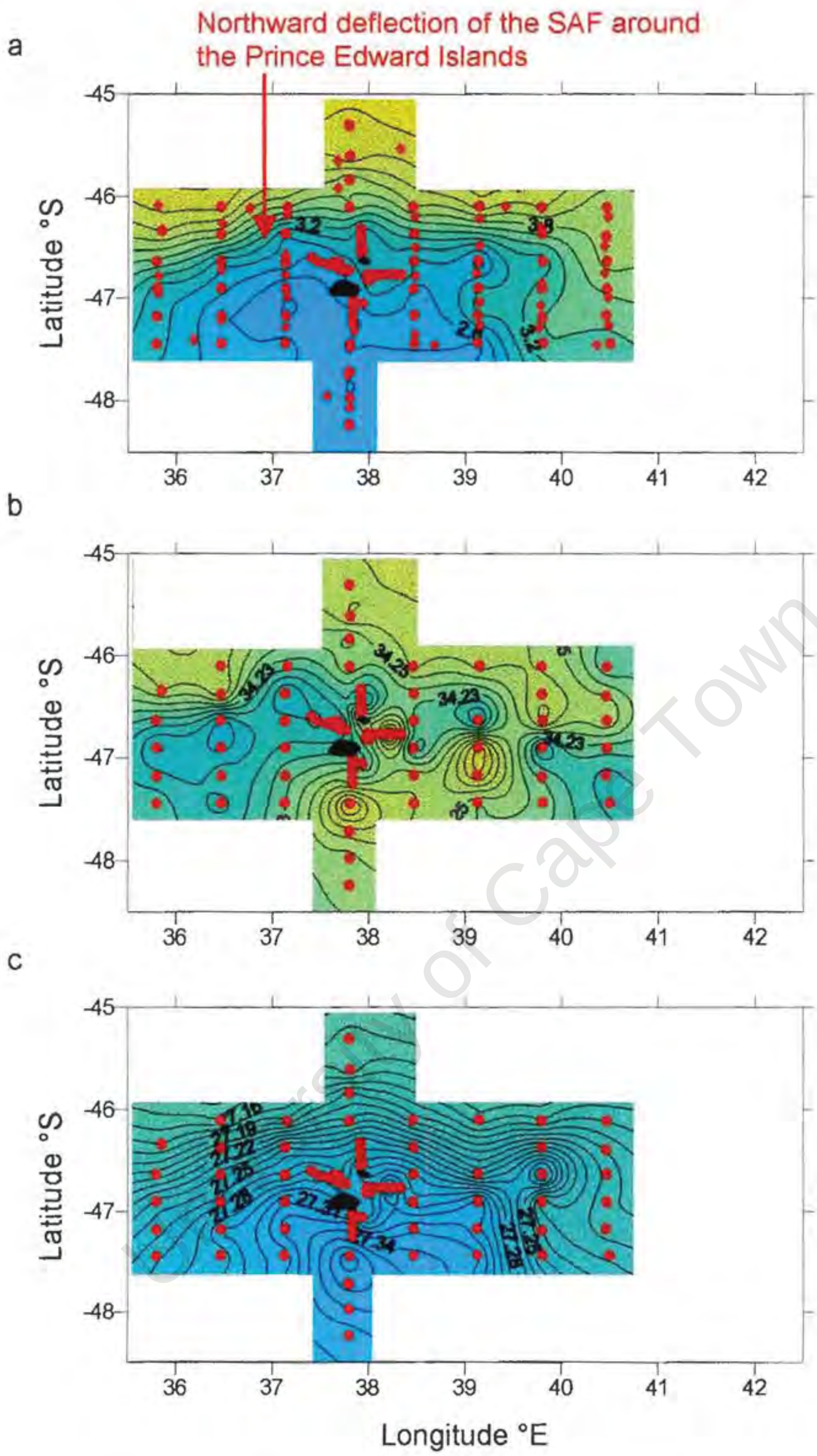


Figure 4.3: Horizontal distribution of (a) Temperature (°C), (b) Salinity (psu) and (c) Sigma-theta (kg m^3) at 500 m during MOES 2. The deflection of the SAF to the north of the Prince Edward Islands can be clearly observed in all 3 figures. Red dots represent the position of all CTD stations and red diamonds represent XBT stations (temperature only), which were deployed to a maximum depth of 750 m.

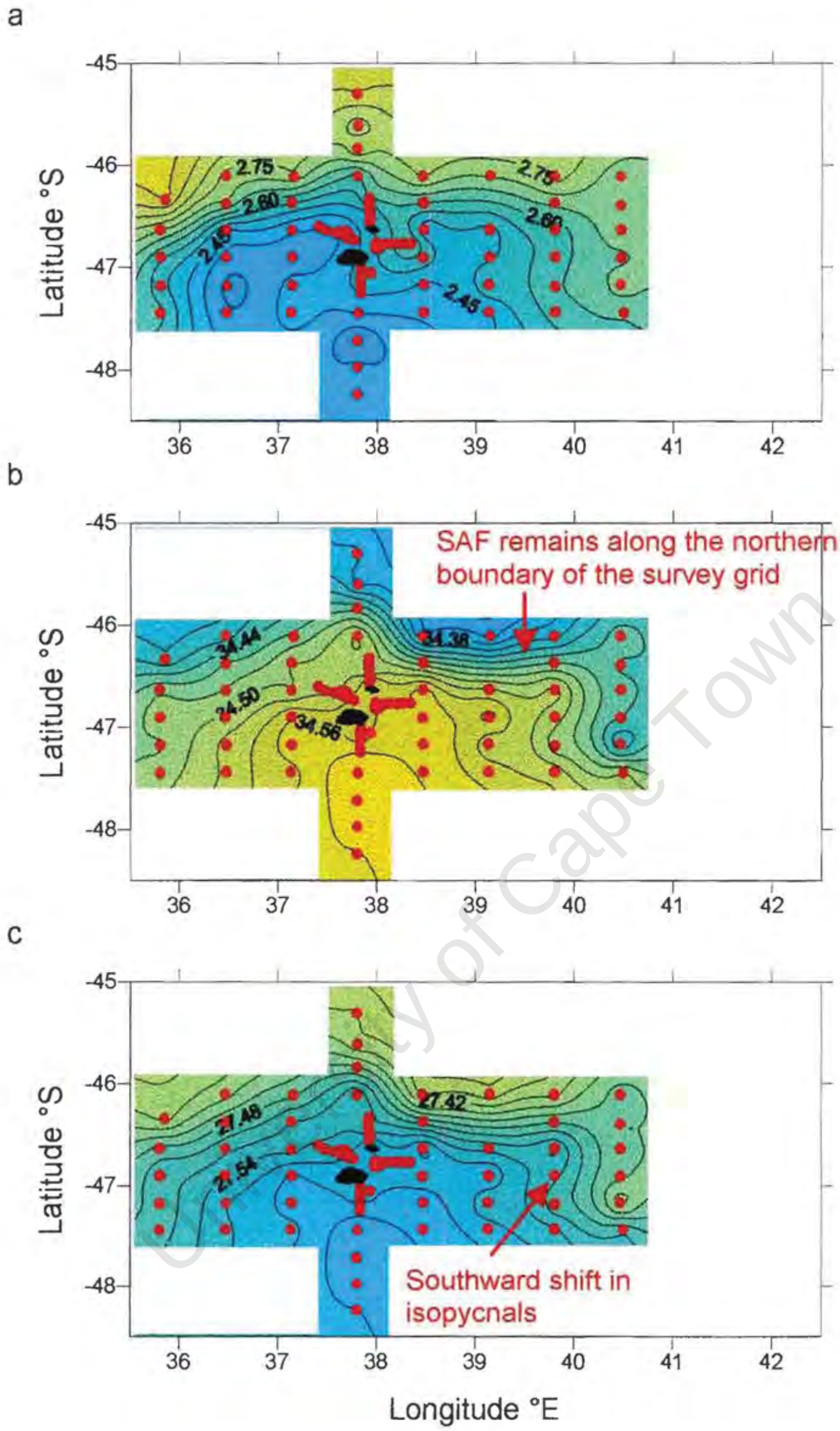


Figure 4.4: Horizontal distribution of (a) Temperature (°C), (b) Salinity (psu) and (c) Sigma-theta (kg m^3) at 1000 m during MOES 2. The meanders generated downstream of the Prince Edward Islands are still noticeable at this level. Red dots represent the position of all CTD stations.

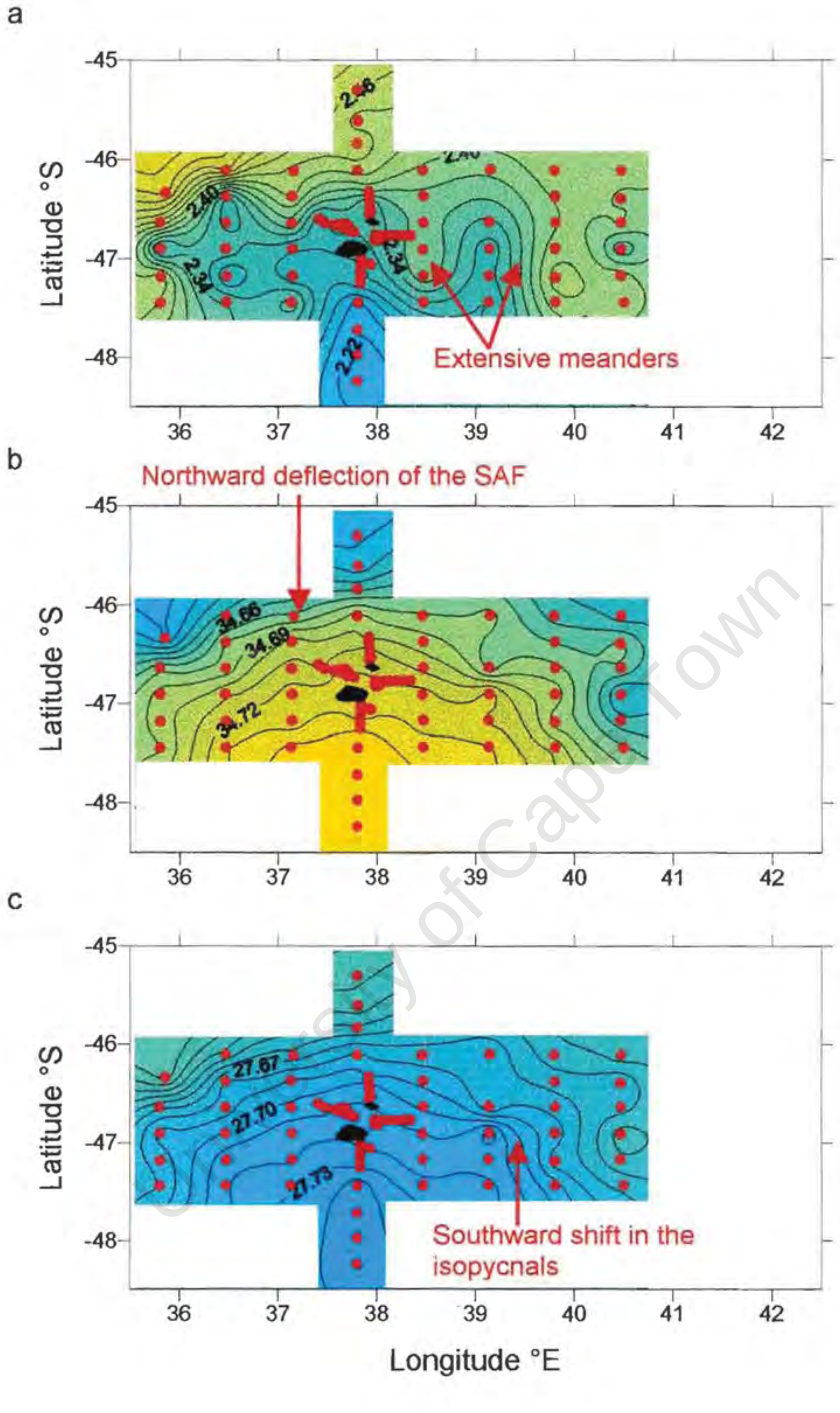


Figure 4.5: Horizontal distribution of (a) Temperature (°C), (b) Salinity (psu) and (c) Sigma-theta (kg m^3) at 1500 m during MOES 2. The deflection of the SAF to the north of the Prince Edward Islands can be clearly observed in all 3 figures. Isotherms clearly show a meandering wake downstream of the islands. Red dots represent the position of all CTD stations.

Oceanic environment during MIOS 2

The oceanic environment surrounding the Prince Edward Islands during the MIOS 2 proved to be very different. Upstream, the SAF was found to lie much farther south, at 47°20'S, where it formed an intensive surface frontal feature combined with the surface expression of the APF (Figure 4.6a). Surface temperatures and salinities across this front ranged from 5.8 - 8°C and 33.94 – 34 (Figures 4.6a and b). However, these salinity values do not fall with the band of values given in Table 1.1 page 6, this may be due to the warm overwash of SASW associated with the southern extent of the SAF. The frontal band may also possibly be intensified by the close proximity of cold AASW immediately to the south (surface values < 5.8°C, < 33.90 Figure 4.6a). These values fall within the APF surface criteria given by Holliday and Read (1998) and may suggest that a weak surface expression of the APF is combined with the SAF. Extensive observations by Lutjeharms and Valentine (1984) have shown that in the region south of Africa the surface and subsurface expressions of the APF rarely coincide. The temperature minimum of 2°C associated with the subsurface expression of the APF was not observed in the vertical section, shown in Figure 4.19, suggesting that the APF proper lay south of the survey grid. Closer to the islands the frontal feature separated resulting in a sharp northward deflection of the SAF, while the APF meandered southwards (Figures 4.6 – 4.10). Similar to MOES 2, the SAF continues its northward deflection, steered by the shallow topography, where it lies along the northern edge of the islands at 46°15'S.

Downstream of the islands, the subsurface isotherm (6°C) and isopycnal (26.90 kg m^3) representing the axis of the SAF (Figures 4.6 a and c) show that the front remained north of the survey grid. It may have been forced northwards by the existence of two counter-rotating eddies (Figures 4.6 – 4.10). A cold cyclonic (<6°C, 33.85) eddy was encountered to the north (Figure 4.6a). To the south and extending the entire length of the downstream survey, an anticyclonic circulation was found. Its surface chemical properties are characteristically those of SASW (>6.8°C, >33.95) suggesting that it may have been spawned from north of the SAF (Figures 4.6a and b). This eddy also appears to be wedged between the meandering bands of the APF. Sharp thermal gradients (7.4 - 4.8°C between 37° - 38°E and 6.6 - 4.8°C between 41° - 42°E: Figure 4.6a) are observed extending through the water column on both corners of the eddy where it borders onto the APF (Figures 4.6 – 4.10). Both eddies appear to be insular features extending through the water column to depths exceeding 1500 m (Figures 4.10a-c).

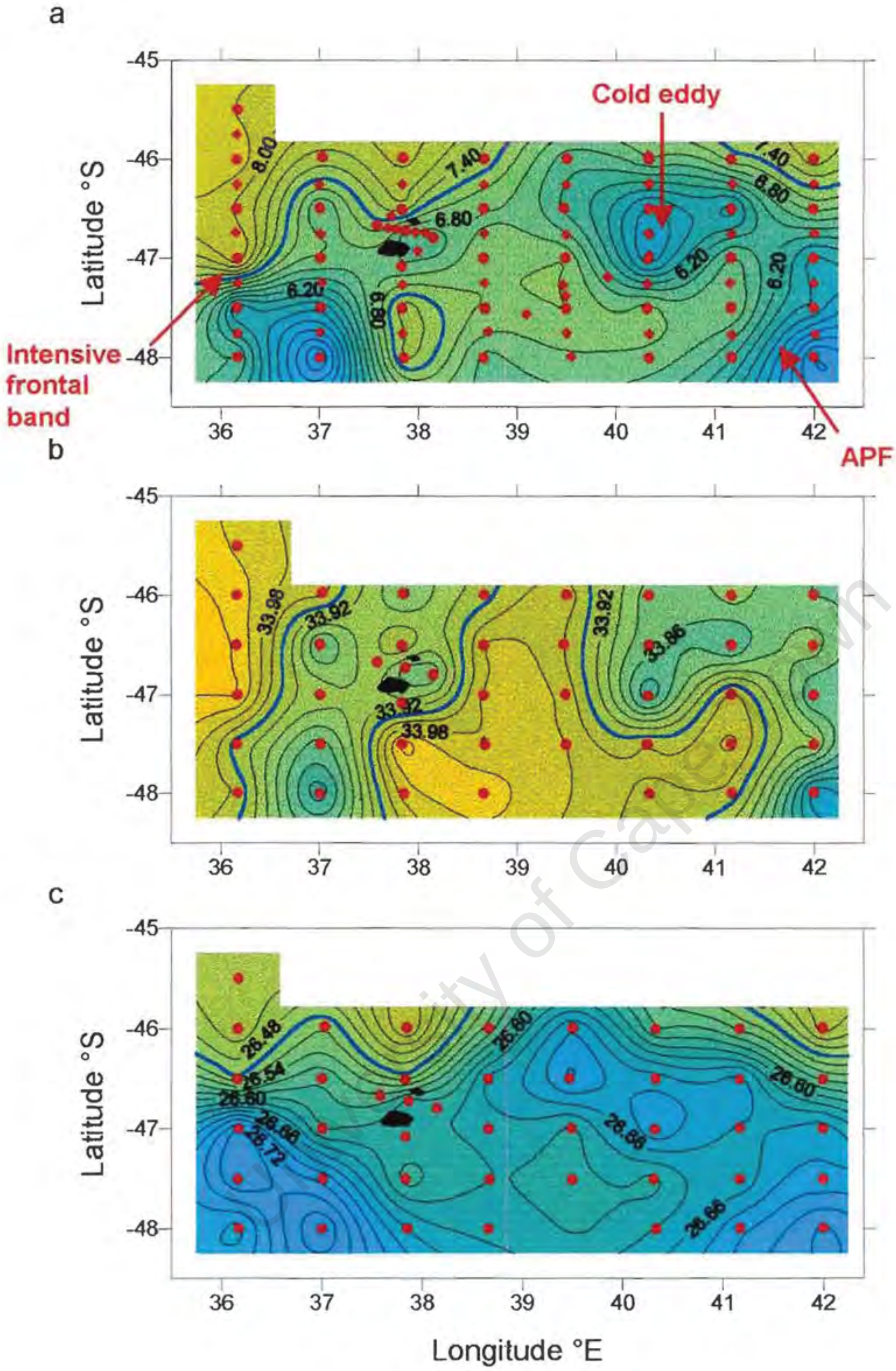


Figure 4.6: Surface horizontal distribution of (a) Temperature (°C), (b) Salinity (psu) and (c) Sigma-theta (kg m^3) during MIOS 2. A blue line marks the surface expression of the SAF axis. Two counter-rotating eddies are evident downstream. The APF lies in the southeastern corner of the survey grid. Red dots represent the position of all CTD stations and red diamonds represent XBT stations (temperature only), which were deployed to a maximum depth of 750.

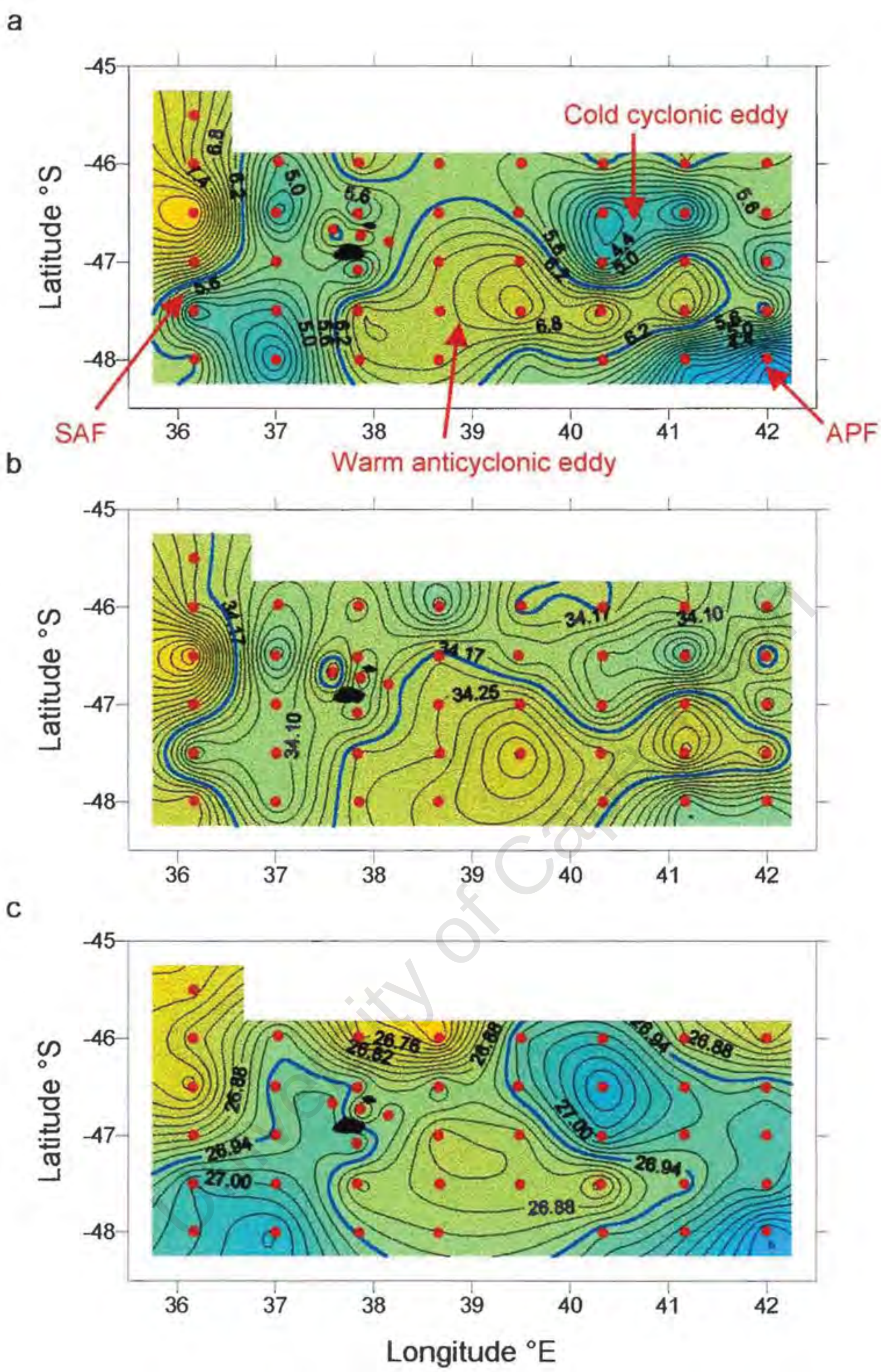


Figure 4.7: Horizontal distribution of (a) Temperature (°C), (b) Salinity (psu) and (c) Sigma-theta (kg m^3) at 200 m during MIOS 2. A blue line marks the sub-surface characteristic of the SAF. Two counter-rotating eddies are evident downstream. The APF lies in the southeastern corner of the survey grid. Red dots represent the position of all CTD stations and red diamonds represent XBT stations (temperature only), which were deployed to a maximum depth of 750.

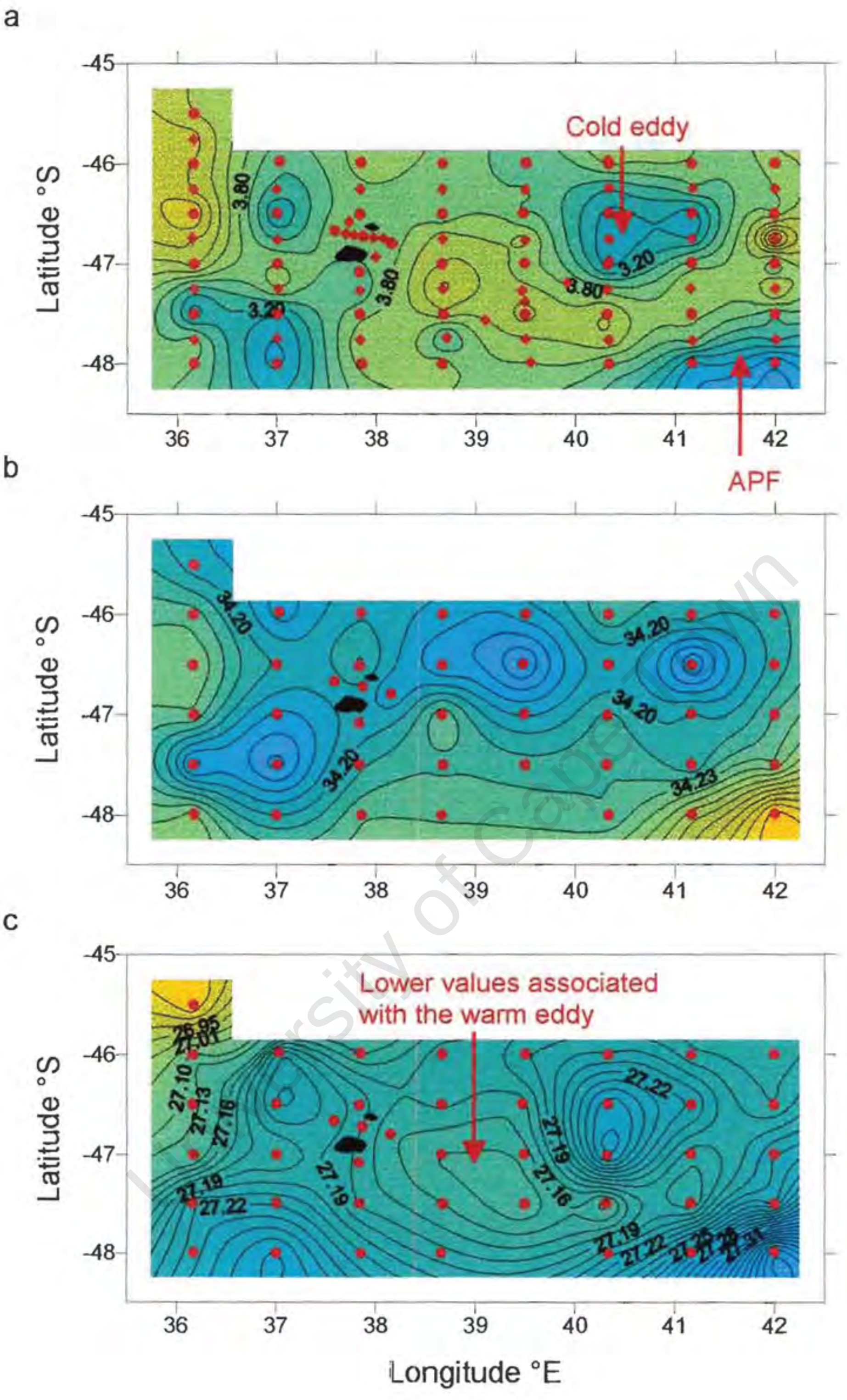


Figure 4.8: Horizontal distribution of (a) Temperature (°C), (b) Salinity (psu) and (c) Sigma-theta (kg m^3) at 500 m during MIOS 2. Two counter-rotating eddies are evident downstream. The APF lies in the southeastern corner of the survey grid. Red dots represent the position of all CTD stations and red diamonds represent XBT stations (temperature only), which were deployed to a maximum depth of 750.

Discussion – Water masses

Upstream region – MOES 2 and MIOS 2

The oceanic environment directly upstream of the Prince Edward Islands is characterised by the gradual widening of the PFZ as the SAF is topographically steered around the northern edge of the islands (Figures 4.1-4.10).

During MOES 2, water masses in the entire upstream region showed a gradual transition from Subantarctic Surface Water (SASW) to Antarctic Surface Water (AASW), typical of the PFZ. Surface temperatures steadily dropped from 6.98 – 5.13°C and salinities from 33.75 – 33.71 as the PFZ was crossed in a southward direction (Figure 4.11a). Upstream of the islands only a single station (CTD 2) lay north of the SAF and therefore out of the PFZ. Its θ/S properties were distinctly SASW, with a strong shallow salinity maximum (> 34.5) at the base of the surface mixed layer (Figure 4.11a).

SASW is strongly influenced by mixing with the adjacent subtropical gyres and air-sea interactions along its circumpolar path. Comparisons with hydrographic stations in the Drake Passage (Sievers and Nowlin, 1984) show that in the Indian sector of the Southern Ocean SASW is more saline (~ 0.02). The Agulhas Current system may also have a strong influence in this region by increasing surface temperatures and salinities (Lutjeharms and Ansorge, in review). This may partially explain the higher values observed during this survey. Antarctic Intermmediate Water (AAIW), formed by the subduction of AASW at the APF, crosses the frontal zone and strong mixing between cold fresh Subantarctic water and warm salty subtropical water takes place throughout the intermediate level. Interleaving occurs across the SAF as injections of AAIW cross the frontal band between sigma-theta surfaces 27.1 and 27.4 kg m^3 (Figure 4.11a - CTD 3). Park and Gamberoni (1997) have shown that the cross frontal exchanges of AAIW in the Crozet Basin are impulsive and influenced by strong frontal mesoscale activities. This may explain why the degree of interleaving, as AAIW is advected across the PFZ, varies considerably between upstream (Figure 4.11a) and downstream regions (Figure 4.15a and 4.16).

Although the APF was not crossed upstream of the islands during MOES 2, an eddy consisting of cold (< 5°C) fresh (< 33.80) water, indicative of AASW, was observed directly south of the islands (Figures 4.1-4.5 – CTD 20), suggesting that the APF may lie in close proximity south of the survey grid. This eddy may have been spawned from the APF. The meandering dynamics of the APF has been modelled using a Niiler and Robinson (1967) inertial jet model (Craneguy and Park 1999). It appears that under strong flow conditions, the APF meanders extensively across the Enderby Basin. These results are comparable to hydrographic observations in this sector of the Southern Ocean (Park et al. 1991, 1993, 1997) and perhaps explain the southward meandering nature of the APF observed in the vicinity of the islands during MIOS 2.

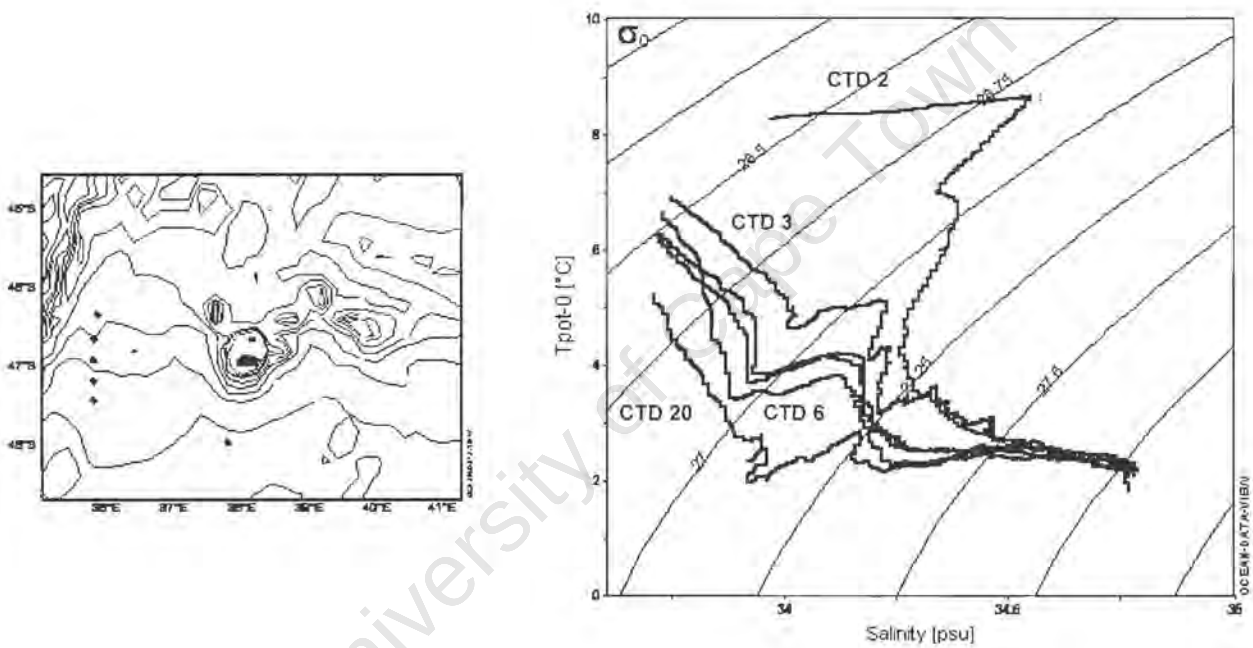


Figure 4.11a: θ/S profiles for CTD stations 2-6 in the upstream region during MOES 2. CTD 2 clearly shows a profile consistent with a station found north of the SAF in the Subantarctic zone (SAZ). The profile associated with CTD 20 has also been included as this station consists of Antarctic Surface Water (AASW) typical of the Antarctic Zone (AAZ). θ/S profiles show the gradual transition from SASW to AASW, which is characteristic of the PFZ. Isopycnals are marked every 0.25 kg m^{3}.

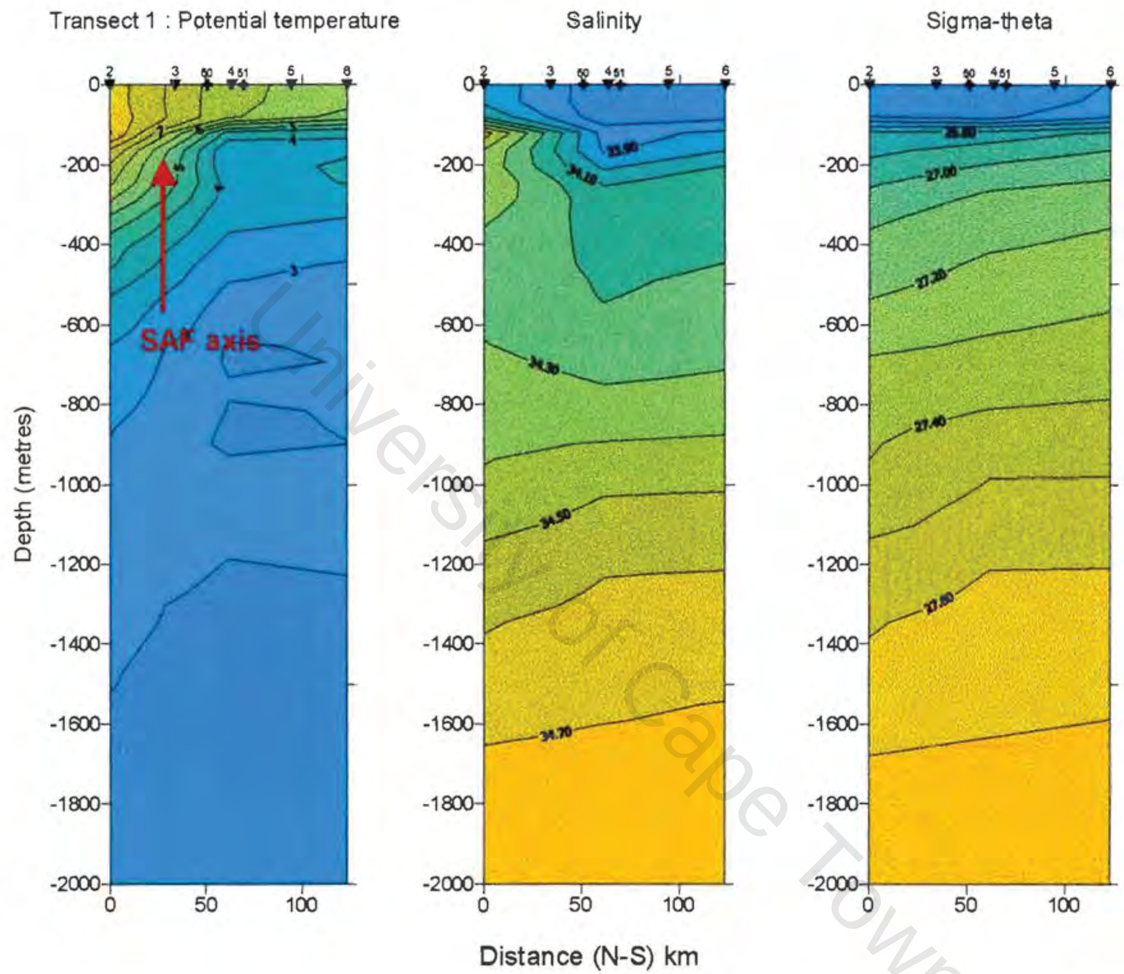


Figure 4.11b: Potential temperature, salinity and sigma-theta sections for stations 2-6 occupied in the upstream region during MOES 2. The sections clearly show the position of the SAF and the gradual transition of water masses across the PFZ. Crosses mark the position of XBT stations.

During the MIOS 2 survey the SAF lay farther south (47°20'S : Figure 4.6a) than during previous studies (Lutjeharms and Valentine 1984). An extremely intense temperature gradient of 0.05°C/km was observed for the first time in this region. Lutjeharms and Valentine (1984) have shown from a large number of crossings that the SAF exhibits surface temperature gradients between 0.015 - 0.019°C/km. In comparison to MOES 2, where only a single station (Figure 4.11a : CTD 2) lay to the north of the SAF, during MIOS 2 the southward shift of the SAF resulted in the majority of stations, occupied during the first transect (36°E) lying north of the SAF (Figure 4.12). Thus, the surface environment upstream of the Prince Edward Islands during MIOS 2 was warmer (> 1.5°C) and saltier (~ 0.4), with the majority of CTD stations displaying θ/S properties typical of SASW (Figure 4.13).

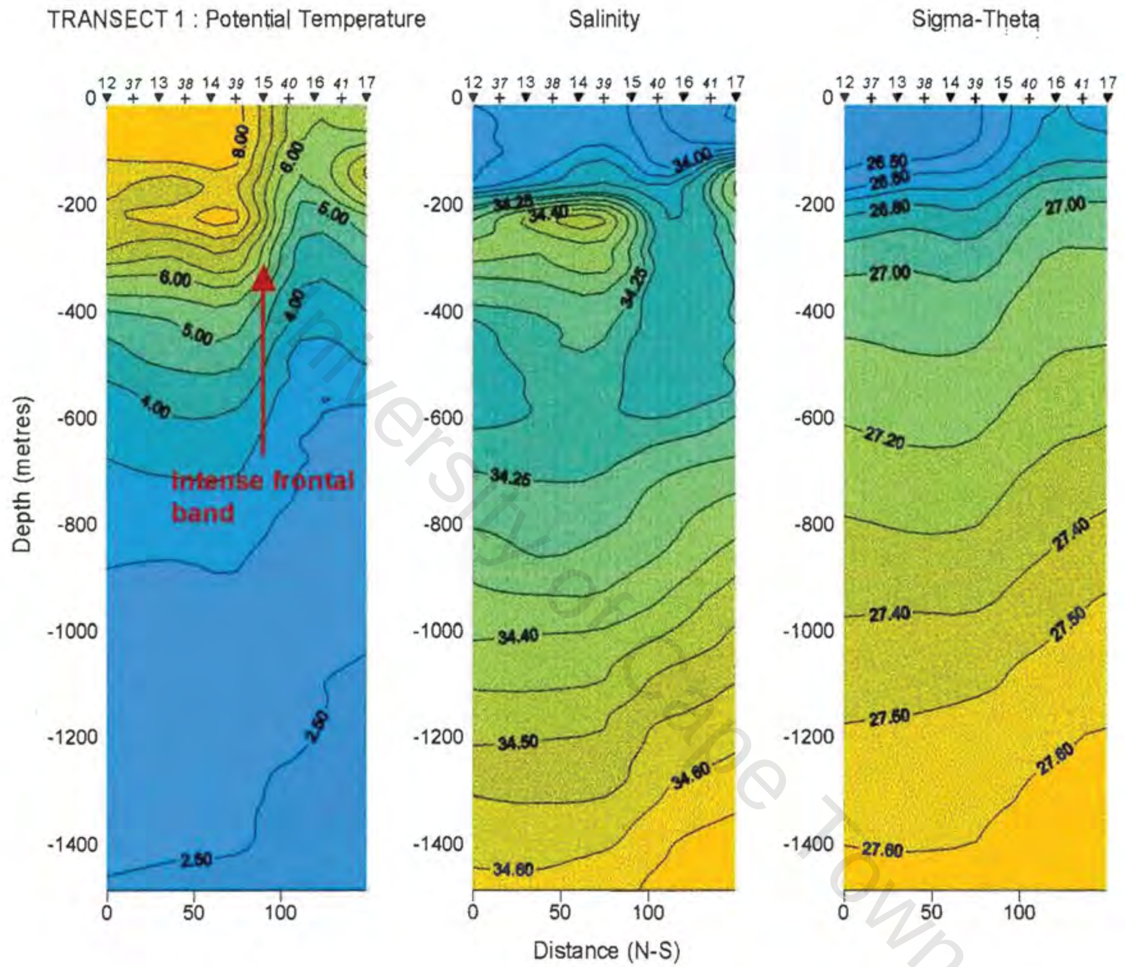


Figure 4.12: Potential temperature, salinity and sigma-theta sections for stations 12-17 occupied in the upstream region during MIOS 2. The sections clearly show the position of the intense frontal band associated with the SAF. Crosses mark the position of XBT stations.

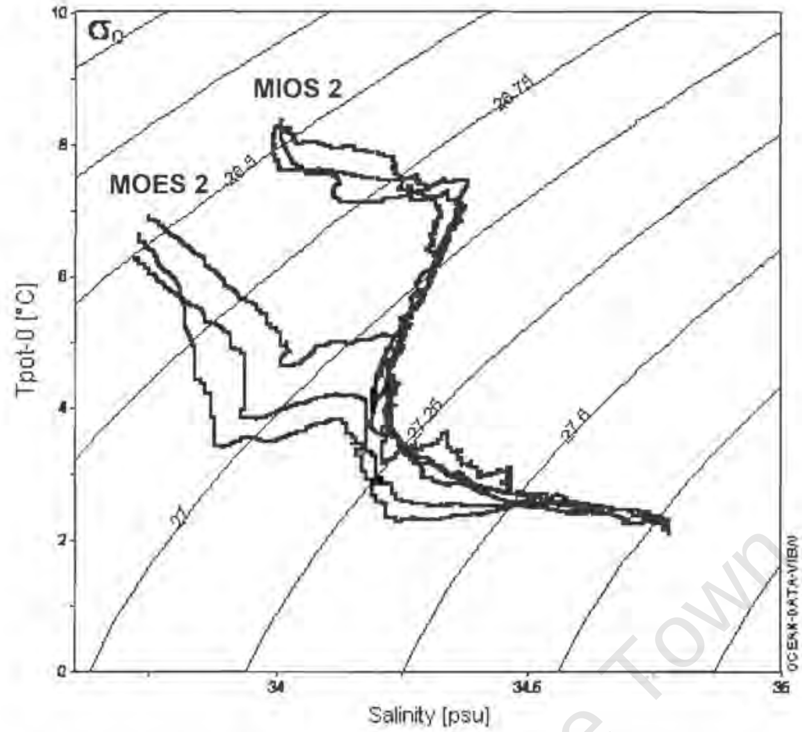


Figure 4.13: θ/S profiles for stations located in the first transect during both surveys in the upstream region of the islands. θ/S profiles clearly show the effect the latitudinal position of the SAF has on the local environment. Warm, salty θ/S profiles are associated with the MIOS 2 survey when the SAF was far to the south, while cooler, fresher profiles are associated with the MOES 2 survey when the SAF lay further north. Isopycnals are marked every 0.25 kg m^3.

Further downstream, the SAF is deflected northwards to lie on the northern edge of the Prince Edward Islands. The meandering nature observed in Figures 4.6-4.10 may be due to the presence of a cold core eddy, which is centred west of the islands at 46°30'S, 37°E. It is possible that this eddy may have been spawned from the APF, its subsurface properties < 5°C and < 34.10 suggest it may consist of AASW. Indeed, these properties are similar to those of the APF, which was again encountered downstream of the islands at 48°S, 42°E. The deflection of the SAF towards the northern side of the islands results in a widening of the PFZ and θ/S profiles typical of the transition between SASW and AASW (7.8 - 4.5°C and 34.0 - 33.80) are observed (Figure 4.14).

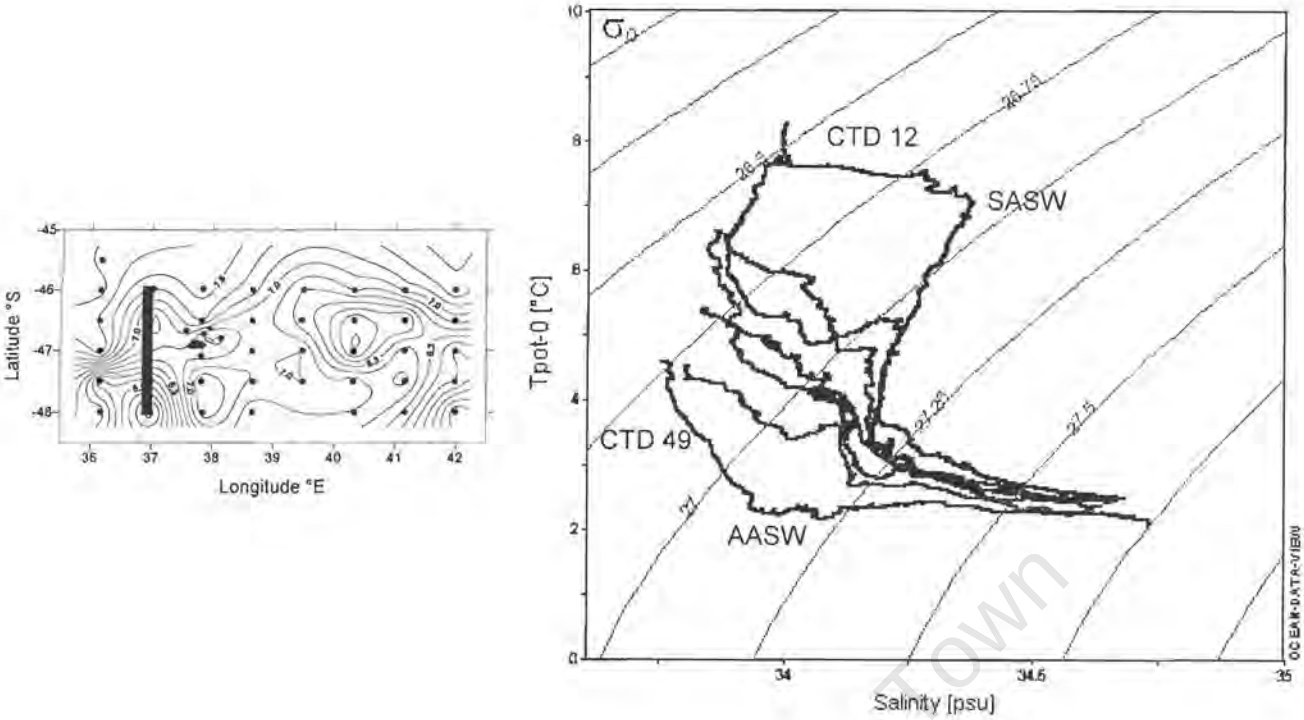


Figure 4.14: θ/S profiles for stations 18-22 located upstream of the islands during MIOS 2. The location of the transect can be seen in the insert, which also shows the distribution of horizontal. CTD 12 clearly shows a profile consistent with a station found north of the SAF in the Subantarctic zone (SAZ). The profile associated with CTD 49 has also been included as this station lies south of the APF and consists of Antarctic Surface Water (AASW) typical of the Antarctic Zone (AAZ). θ/S profiles show the gradual transition from SASW to AASW characteristic of the PFZ. Isopycnals are marked every 0.25 kg m^3.

Downstream Region – MOES 2

Downstream of the Prince Edward Islands the surface and subsurface properties of the SAF demonstrated a distinct wake between 38°30'E and 40°30'E. Deacon (1983) has postulated that the complexity of the current regime in the vicinity of the islands results in an increase in the interchange of Antarctic and Subantarctic surface water within the PFZ. In fact the surface waters associated with CTD 54 – 58, the western-most transect in the downstream region, do show the advection of distinctly warm (> 7°C) SASW across this region (Figure 4.15a). Although the gradual modification of this water mass with distance across the PFZ is still apparent, comparisons with θ/S properties observed upstream show this region to be warmer (~ 1°C) and more saline (+ 0.05).

Surface temperatures ranged from 7.8 – 6.2°C across the PFZ downstream of the islands compared to 6.98 – 5.13°C upstream. The increase in temperatures was a result of the meandering dynamics of the SAF, advecting SASW farther south across the PFZ. A distinct subsurface salinity maximum (34.38-34.20) between 27.10 -27.0 kg m^3 in each profile is characteristic of SASW (Figures 4.11a and b). AAIW is best characterised by the salinity minimum at 27.20 kg m^3. Interleaving between Sigma-theta levels 27.10 – 27.35 kg m^3 are associated with the northward descent of AAIW across the SAF (Figure 4.15a). Indeed, sections (Figure 4.15b) show the subduction of the salinity minimum associated with the AAIW (34.2-34.30 between 27.10 - 27.30 kg m^3) across the PFZ.

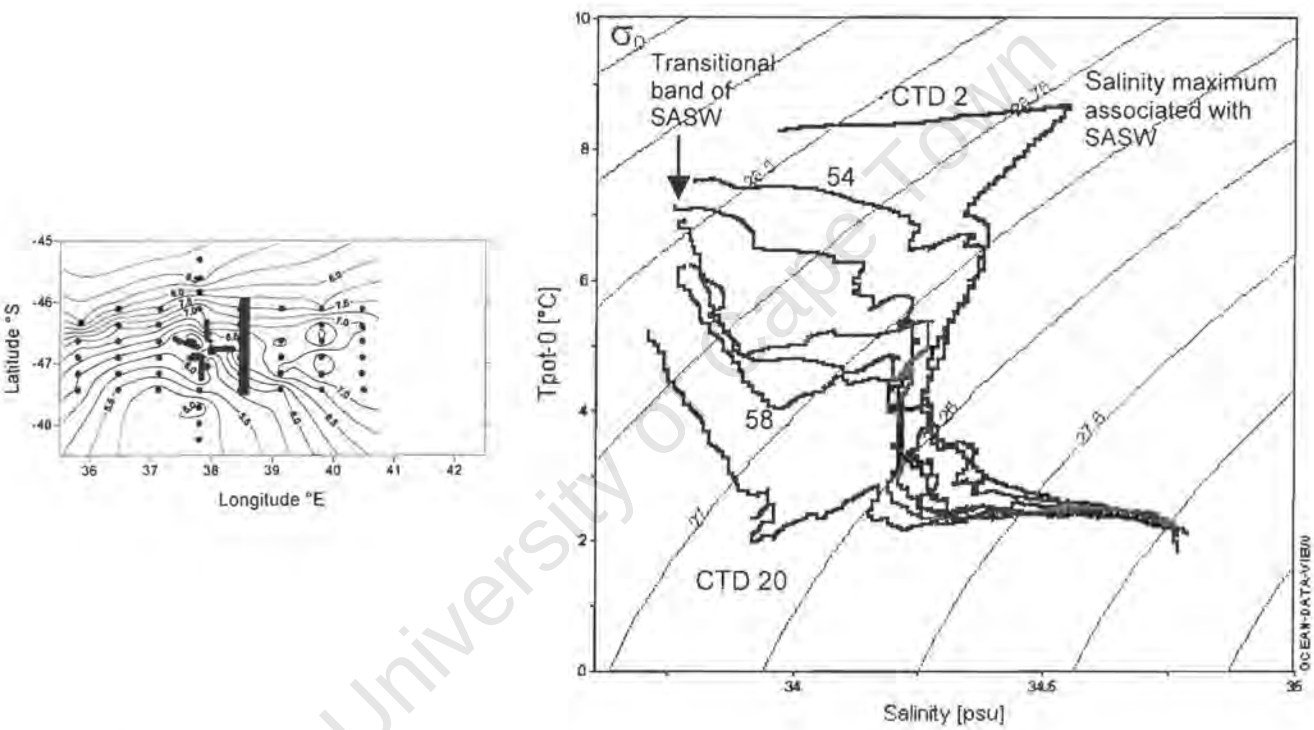


Figure 4.15a: θ/S profiles for CTD stations 54-58 during MOES 2. The location of this transect can be seen in the insert, which also shows the horizontal distribution of sea surface temperature. This transect was located within the poleward excursion of the wake. Profiles show the southward advection of warm SASW from north of the SAF. CTD 2 (SAZ) and CTD 20 (AFZ) represent stations located outside the Polar Frontal Zone (PFZ). Isopycnals are marked every 0.25 kg m^3.

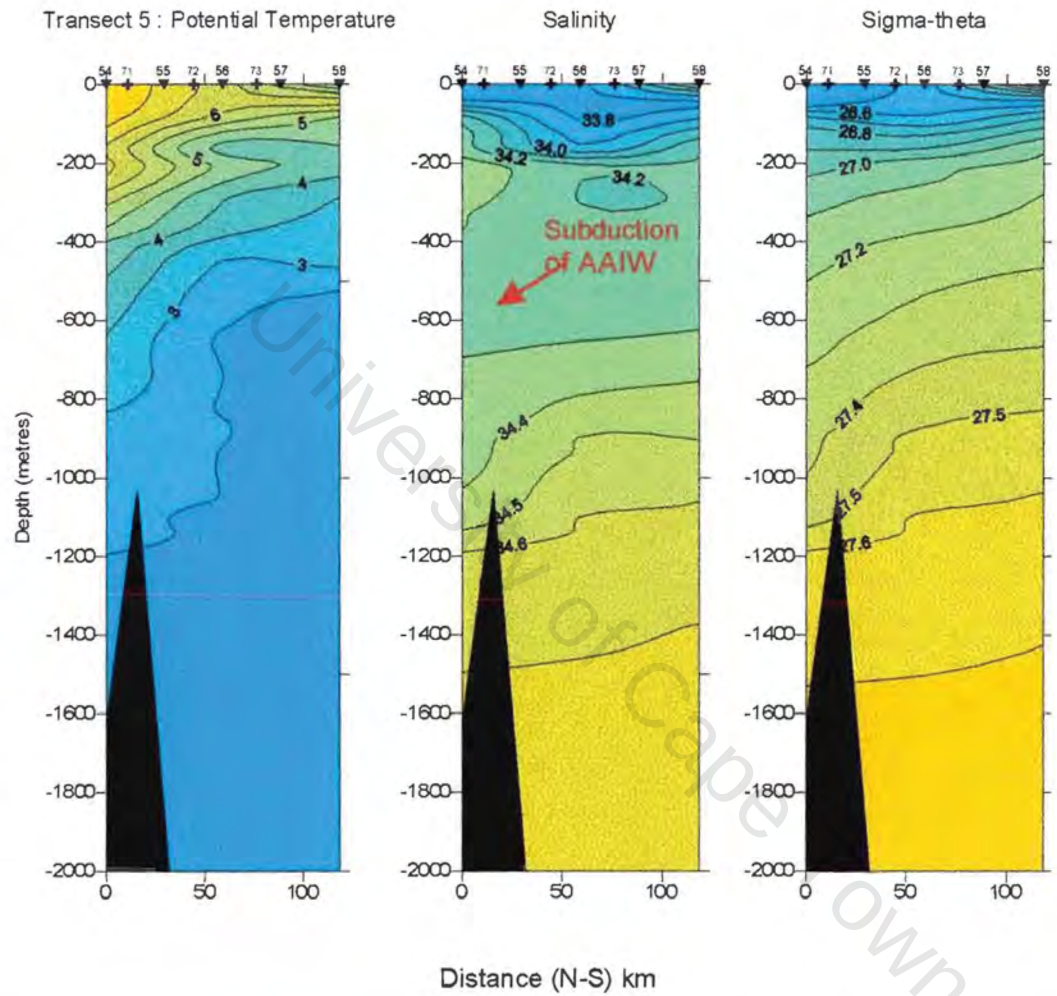


Figure 4.15b: Potential temperature, salinity and sigma-theta sections for stations 54-58 occupied in the downstream region during MOES 2. The subduction of AAIW at the SAF is shown. Crosses mark the position of XBT stations.

Downstream Region – MIOS 2

During MIOS 2 the subsurface expression of the SAF appeared to be steered by the regional bathymetry, lying between 45°30' and 46°15' S through the deep (> 2500 m) channel, which separates the Gallieni Knoll and the Del Cano Rise (Figure 4.7a - c). This is comparable with recent findings by Pollard and Read (1997), who were able to show from a series of current meters deployed during the research programme SWINDEX, that the major part of the transport of the ACC, 80 – 90 Sv, passes south of the Del Cano Rise. In contrast, south of the islands where the topography falls off rapidly to form the deep (> 4000 m) Enderby abyssal plain, the APF exists as a meandering flow seemingly unaffected by local bathymetry. Separating the two frontal bands downstream of the islands during MIOS 2 were two counter-rotating eddies within the PFZ.

Cold eddy

A likely possibility for the near zonal flow associated with the SAF is due to the presence of an extensive cold cyclonic eddy, in the downstream region of the Prince Edward Islands. θ/S profiles suggest that this cold eddy consisted of modified AASW (< 6°C, < 33.9), which had been advected northwards and trapped in the PFZ. The θ/S profile associated with CTD 45, located in the core of the eddy, is almost identical to that of CTD 48 which lay on the southern boundary of the PFZ in close proximity to the APF (Figure 4.18a). Koshlyakov et al. (1985) has shown that Subantarctic water masses may become entrained by the cyclonic rotation of cold eddies in the PFZ. Indeed, the θ/S profile of water in the eddy shows a slight increase in subsurface temperatures and salinities at 27.10 kg m^3, characteristic of SASW. This observation of entrainment of ambient waters by eddies is also consistent with hydrographic studies on cyclonic rings carried out in the Gulf Stream (e.g. Kamenkovich et al. 1982; Richardson, 1981) and in the Kuroshio Current (Kawai, 1972). Property sections (Figure 4.18b) confirm this feature to be a deep (extending to 1500 m), insular feature, separate from the surrounding warmer (> 6°C) and more saline (> 33.90) water masses (Figures 4.7 a-c). Its exact genesis is unknown, however a likely possibility is that it may have been shed from the APF. Previous studies conducted in the vicinity of the APF (Joyce & Patterson 1977, Sievers & Emery 1978, Koshlyakov et al. 1985) have shown single cold eddies of a synoptic scale forming in the PFZ as a result of the "cutting off" of northward extending meanders.

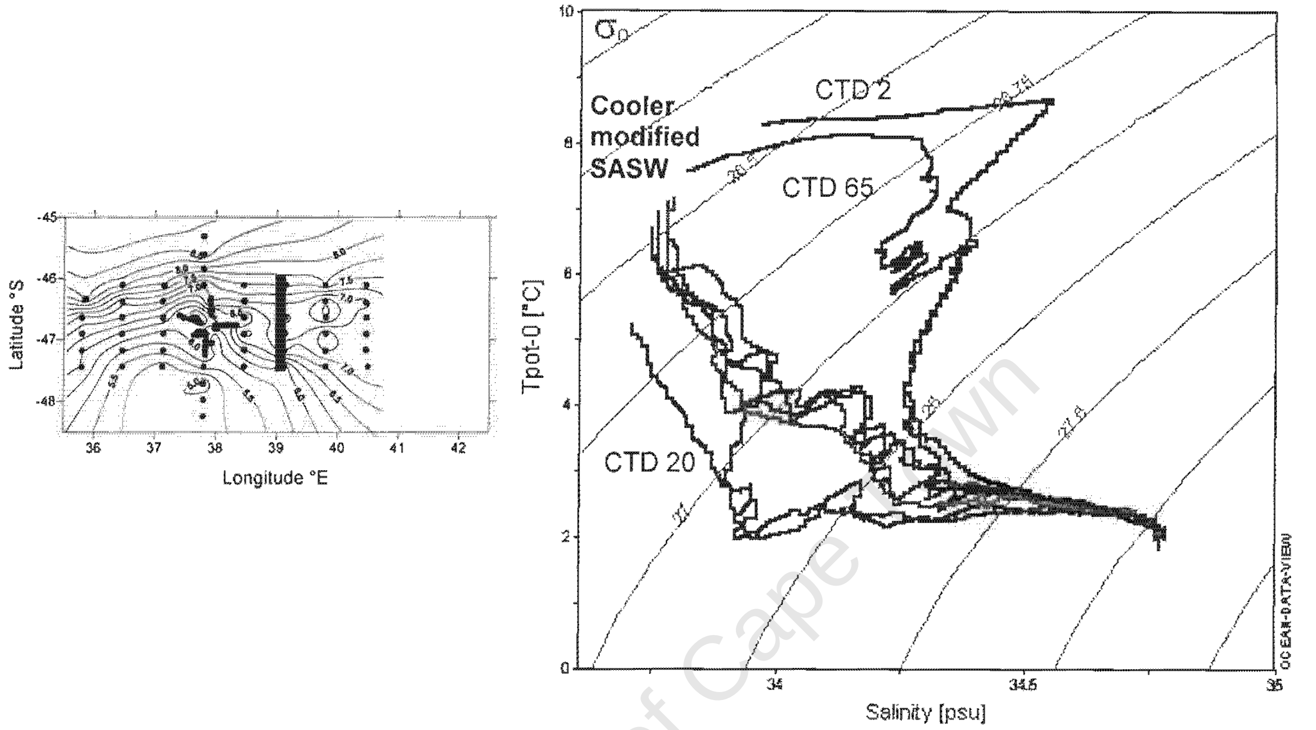


Figure 4.16: θ/S profiles for CTD stations 60 and 65 during MOES 2. The location of this transect can be seen in the insert, which also shows the horizontal distribution of sea surface temperature. This transect was located in the equatorward excursion of the downstream meander and therefore in the region where cooler modified SASW was advected northwards across the PFZ. CTD 2 (SAZ) and CTD 20 (AFZ) represent stations located outside the Polar Frontal Zone (PFZ) and are included for comparisons with stations located within the PFZ. Isopycnals are marked every 0.25 kg m^3.

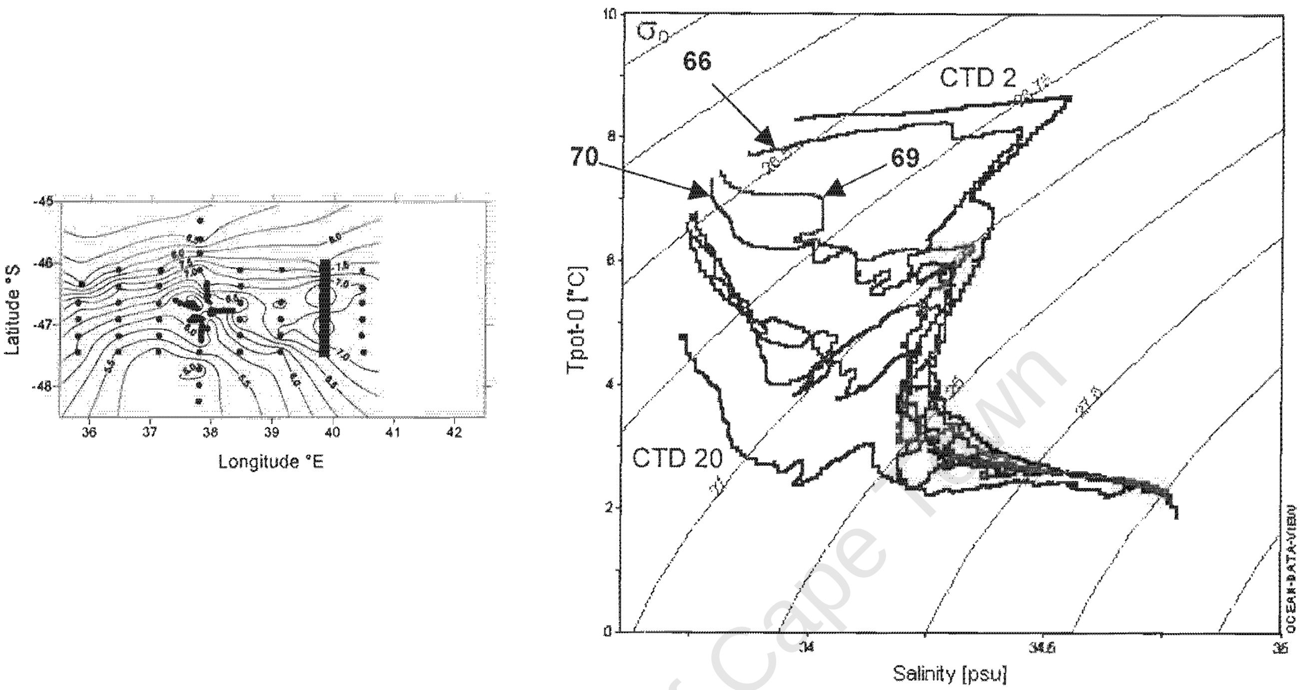


Figure 4.17a: θ/S profiles for CTD stations 66 and 71 during MOES 2. The location of this transect can be seen in the insert, which also shows the horizontal distribution of sea surface temperature. This transect passed through the warm anticyclonic eddy found in the downstream region of the islands. θ/S profiles (CTD 69 and 70) clearly show the eddy to consist of waters similar to SASW, which may have possibly been modified within the PFZ. In addition, CTD 66 lies along the northern edge of the SAF and displays physical characteristics similar to CTD 2. CTD 2 (SAZ) and CTD 20 (AFZ) represent stations located outside the Polar Frontal Zone (PFZ) and are included for comparisons with stations located within the PFZ. Isopycnals are marked every 0.25 kg m^3.

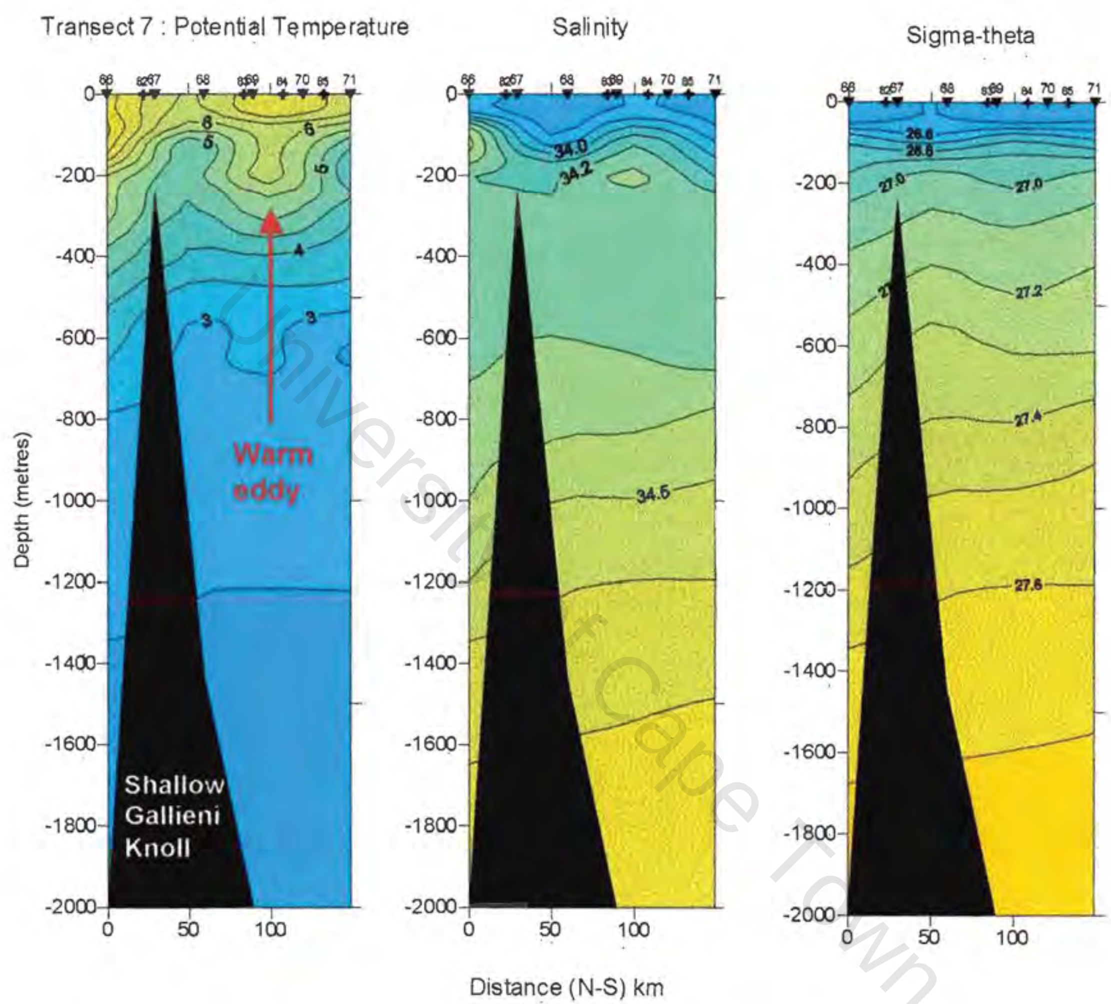


Figure 4.17b: Potential temperature, salinity and sigma-theta sections for stations 66-71 occupied in the downstream region during MOES 2. Crosses mark the position of XBT stations. The position of the eddy can be clearly seen between CTD 69 and 70. This eddy lies immediately south of the shallow Gallieni Knoll, its position possibly topographically controlled. The SAF can be found immediately to the north of the Gallieni Knoll at CTD 66.

Downstream Region – MIOS 2

During MIOS 2 the subsurface expression of the SAF appeared to be steered by the regional bathymetry, lying between 45°30' and 46°15' S through the deep (> 2500 m) channel, which separates the Gallieni Knoll and the Del Cano Rise (Figure 4.7a - c). This is comparable with recent findings by Pollard and Read (1997), who were able to show from a series of current meters deployed during the research programme SWINDEX, that the major part of the transport of the ACC, 80 – 90 Sv, passes south of the Del Cano Rise. In contrast, south of the islands where the topography falls off rapidly to form the deep (> 4000 m) Enderby abyssal plain, the APF exists as a meandering flow seemingly unaffected by local bathymetry. Separating the two frontal bands downstream of the islands during MIOS 2 were two counter-rotating eddies within the PFZ.

Cold eddy

A likely possibility for the near zonal flow associated with the SAF is due to the presence of an extensive cold cyclonic eddy, in the downstream region of the Prince Edward Islands. θ/S profiles suggest that this cold eddy consisted of modified AASW (< 6°C, < 33.9), which had been advected northwards and trapped in the PFZ. The θ/S profile associated with CTD 45, located in the core of the eddy, is almost identical to that of CTD 48 which lay on the southern boundary of the PFZ in close proximity to the APF (Figure 4.18a). Koshlyakov et al. (1985) has shown that Subantarctic water masses may become entrained by the cyclonic rotation of cold eddies in the PFZ. Indeed, the θ/S profile of water in the eddy shows a slight increase in subsurface temperatures and salinities at 27.10 kg m^3, characteristic of SASW. This observation of entrainment of ambient waters by eddies is also consistent with hydrographic studies on cyclonic rings carried out in the Gulf Stream (e.g. Kamenkovich et al. 1982; Richardson, 1981) and in the Kuroshio Current (Kawai, 1972). Property sections (Figure 4.18b) confirm this feature to be a deep (extending to 1500 m), insular feature, separate from the surrounding warmer (> 6°C) and more saline (> 33.90) water masses (Figures 4.7 a-c). Its exact genesis is unknown, however a likely possibility is that it may have been shed from the APF. Previous studies conducted in the vicinity of the APF (Joyce & Patterson 1977, Sievers & Emery 1978, Koshlyakov et al. 1985) have shown single cold eddies of a synoptic scale forming in the PFZ as a result of the "cutting off" of northward extending meanders.

The position of this eddy may have acted as a distinct hindrance to the baroclinic flow associated with the SAF, forcing it to remain north of the survey grid. This observation is consistent with that of Sievers and Emery (1978), who have shown that when a separate cold feature occupied the PFZ, the SAF intensified and moved northwards resulting in a widening of the PFZ. It is possible that this eddy may have been quasi-stationary, its position controlled by the shallow Africana Rise which lies immediately northeast (Figure 3.1 – page 36).). Indeed the eastern edge of the eddy, marked by 5.5°C and 26.98 kg m^3 (Figures 4.7a-c) appears to taper southeastwards around the southern edge of the Del Cano Rise. Observations south of Australia (Emery & Savchenko et al. 1978) and in the Drake Passage (Sievers & Emery 1978) have revealed that the northern edge of these cold eddies often combine with the front. This results in the cyclonic flow coupling with the SAF and increasing the associated zonal flow. Past hydrological investigations by Koshlyakov et al. (1985) and satellite observations by Gouretski and Danilov (1994) have indicated similar features in the same region on a number of occasions.

Hofmann and Whitworth (1985) have described a cold eddy that remained in the Drake Passage for over 20 weeks, suggesting that its eastward progress may have been hampered by the bathymetry. Although we do not have direct observations for the persistence of the cold eddy observed during MIOS 2, it is likely that the irregular topography associated with the Africana and Del Cano Rise could have affected its subsequent eastward passage.

In the southeastern corner of the survey grid the 2.5°C isotherm indicative of the close proximity of the sub-surface APF was encountered at 48°S, 42°E (Figure 4.19). In this region θ/S properties are typical of AASW with a near surface temperature minimum at 27.10 kg m^3 associated with the remnants of Winter Water.

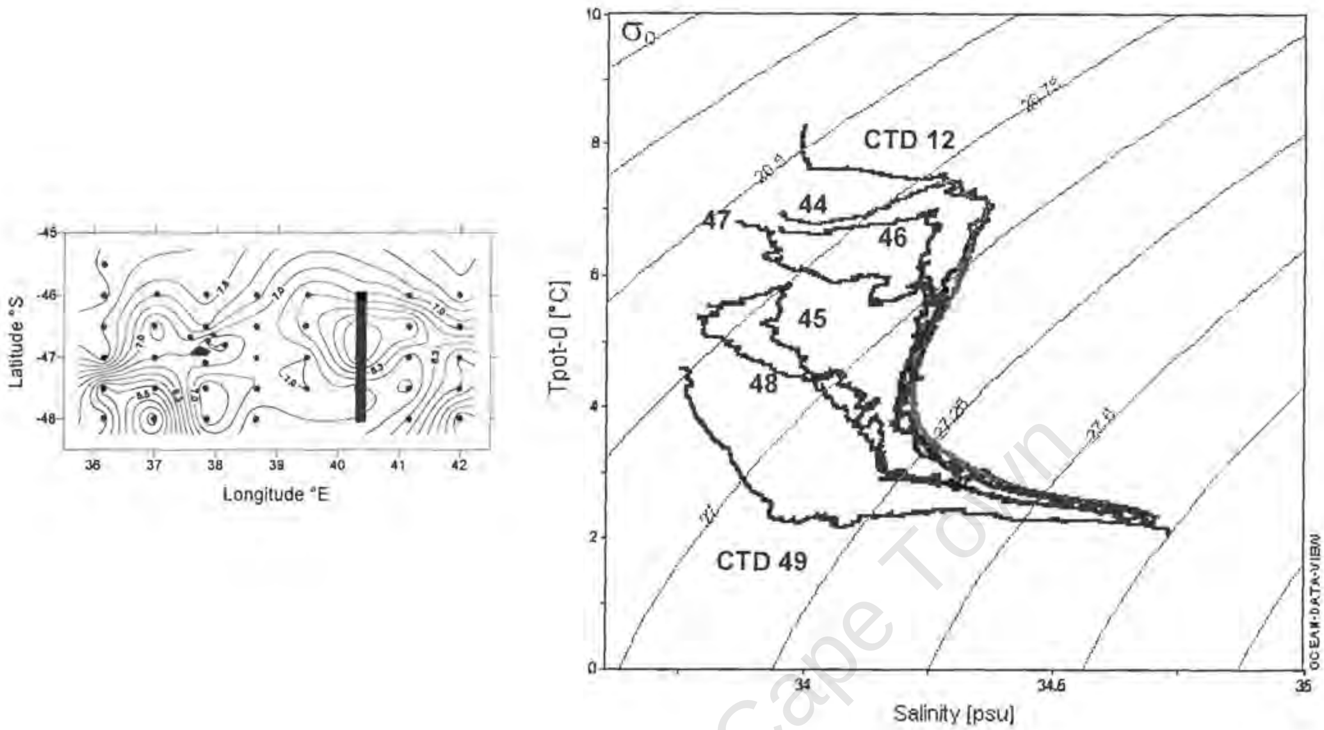


Figure 4.18a: θ/S profiles for CTD stations 44 to 48 that passed through the cold eddy to the north and the warm eddy to the south. The location of this transect can be seen in the insert, which also shows the horizontal distribution of sea surface temperature. θ/S plots show the similarity between CTD 45 located in the cold eddy with CTD 48 which is located on the northern edge of the APF. In addition, CTD 46 and CTD 47 are typical of SASW associated with the warm feature lying to the south of the cold eddy and are similar to CTD 44 which lies in close proximity to the SAF. CTD 12 (SAZ) and CTD 49 (AFZ) represent stations located outside the Polar Frontal Zone (PFZ) and are included for comparisons with stations located within the PFZ. Isopycnals are marked every 0.25 kg m^3.

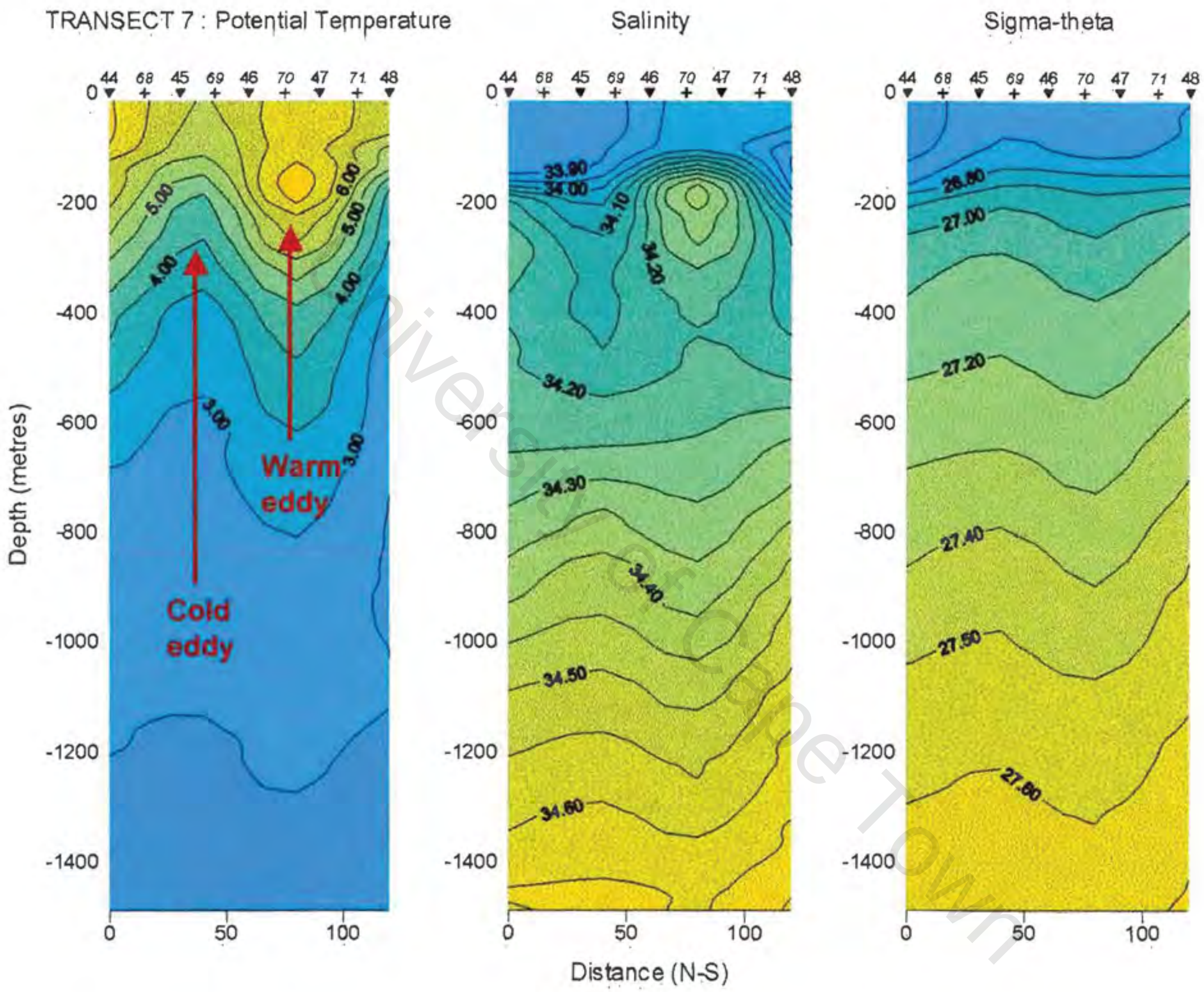


Figure 4.18b: Potential temperature, salinity and sigma-theta sections for stations 44-48 occupied in the downstream region during MIOS 2. The transect passes through both cold (CTD 45) and warm (CTD 47) eddies. Crosses mark the position of XBT stations.

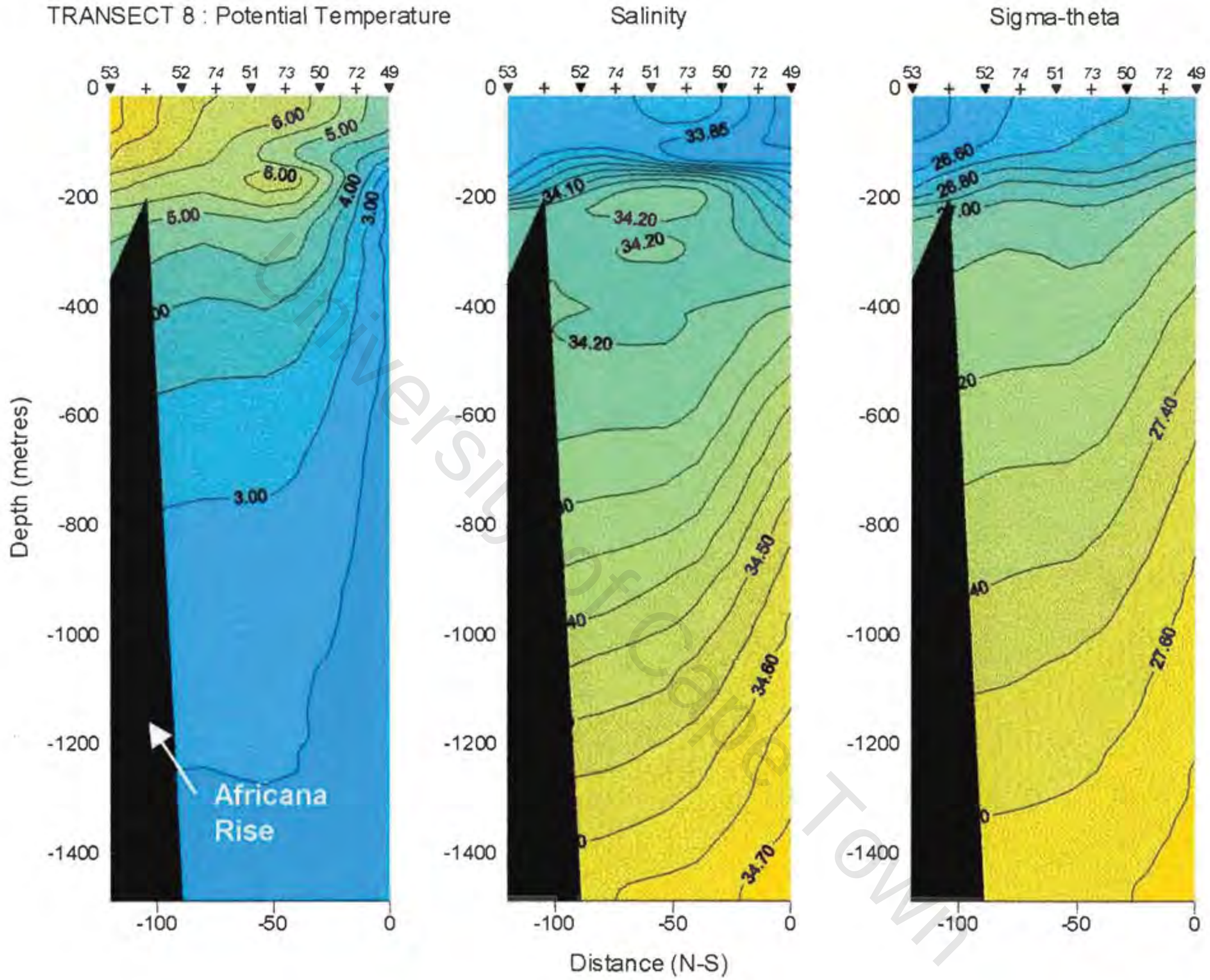


Figure 4.19: Potential temperature, salinity and sigma-theta sections for stations 49-53 occupied in the downstream region during MIOS 2. The subsurface temperature minimum (2.5°C) at CTD 49 indicates the close proximity of the subsurface APF. Crosses mark the position of XBT stations.

Anticyclonic eddy

A warm (> 6°C), elongated eddy was encountered south of the cold eddy. Horizontal distributions of temperature and sigma-theta (Figures 4.6-4.10 a-c) show this feature to extend the length of the survey grid. Subsurface temperature and sigma-theta distributions (Figures 4.7 a and c) show this feature to be deep, occupying the entire length of the survey grid from south of the islands to 42°E. Bryden and Heath (1985) have shown the existence of energetic eddies southeast of New Zealand, which are vertically coherent to 5000 m. θ/S profiles confirm the presence of SASW in this warm feature. Indeed, the warm, saline characteristics of this feature are similar to that of CTD 12, which lay far north of the SAF in the upstream region of the islands (Figure 4.20a). The eddy warmed the PFZ considerably, surface temperatures ranging from 7.4 – 6.8°C across the PFZ, compared to 7.6 – 4.8°C observed in the upstream region. Sections through the eddy (Figure 4.20b) indicate a deep mixed layer (150 – 200 m). Perissinotto et al. (2000) have shown that these mesoscale disturbances have a major impact on modifying the vertical stability of the water column and the depth of the mixed layer depth (MLD) in this region. The formation of this eddy may have resulted from the breakdown of a wake, similar to that observed during MOES 2. Observations in the Drake Passage by Joyce and Patterson (1977) have shown that instabilities generated in a meander at the border of the PFZ are primarily responsible for its final collapse, resulting in the formation of mesoscale eddies within the PFZ.

The formation of this eddy may have resulted from the breakdown of a wake, similar to that observed during MOES 2. The southward meanders associated with such a wake would certainly be responsible for the advection of warm water masses (SASW) from north of the SAF, across the PFZ (Ansorge et al. 1999). Klinck (1985) has suggested that an important factor leading to mesoscale variability within the PFZ is the regional bottom topography and the location of seamounts. Predicted topography charts drawn by Smith and Sandwell (1994), show that immediately east of the islands, the bathymetry is complex with several seamounts forming the northern edge of a deep basin at 39°E (Figure 3.1 – page 36). The position of this basin corresponds to the subsurface axial value of the SAF (6°C), the northern edge of the warm eddy as well as the contours of the basin. It is possible that the SAF may have been a meandering wake similar to the wake observed during MOES 2 before the MIOS 2 observations. Instabilities generated within this wake would been primarily responsible for its final collapse, resulting in mesoscale eddies within the PFZ and the SAF remaining north of the grid where it appears to closely follow the bathymetry as a near zonal flow.

Observations in the Drake Passage by Joyce and Patterson (1979) have shown the development over time of closed current rings from the breakdown of a meander. This finding is consistent with other observations in the Southern Ocean. In the PFZ, north of South Georgia (Trathan et al. 1997), an elongated anticyclonic warm eddy was surveyed south of the SAF at 37°30'W, 50°S centred over a deep basin between the Northeast Georgia Rise and its seamounts. Peterson and Whitworth (1989) have also shown a branch of SASW penetrating through the gap in the Falklands Ridge into the Georgia Basin. A further explanation for this warm eddy may be the entrainment of warm patches of SASW by the cyclonic circulation of a cold eddy centred within the PFZ and in close contact with the SAF.

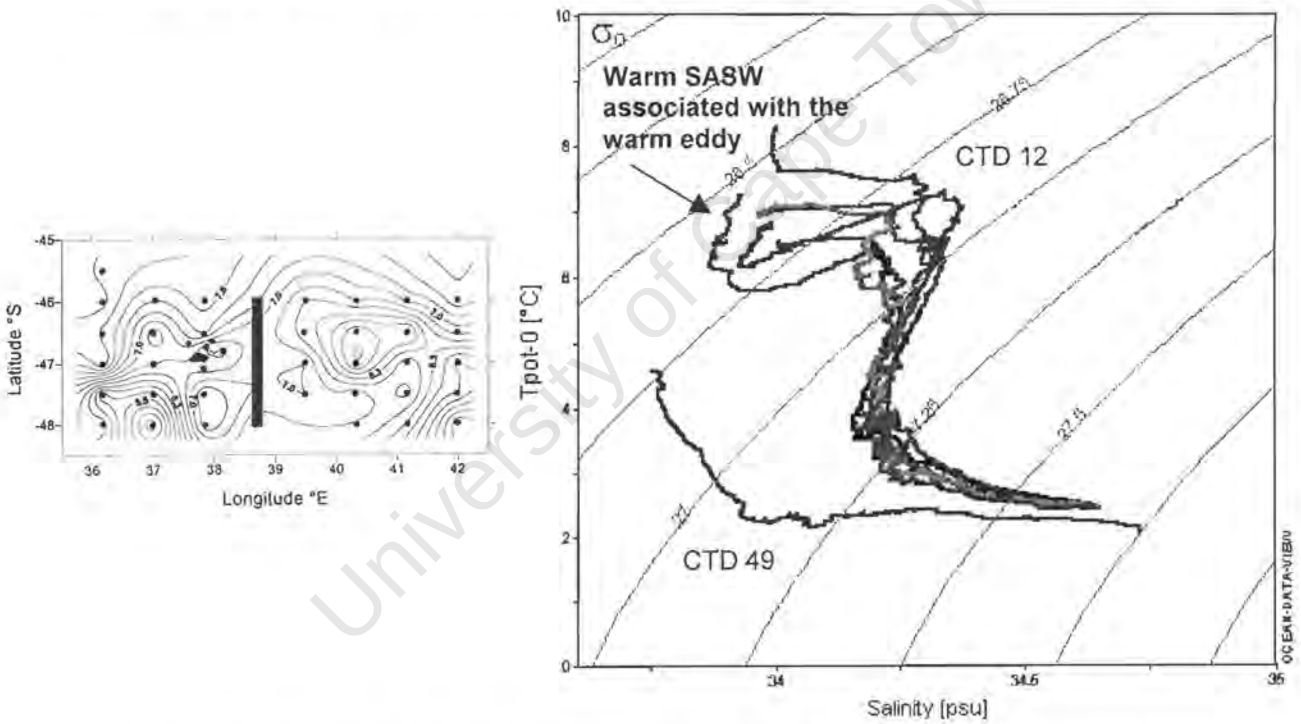


Figure 4.20a: θ/S profiles for CTD stations 30 to 33. The location of this transect can be seen in the insert, which also shows the horizontal distribution of sea surface temperature. This transect was located immediately downstream of the islands and passes through the warm eddy. θ/S plots are typical of warm SASW suggesting that the eddy may have been spawned from the SAF. CTD 12 (SAZ) and CTD 49 (AFZ) represent stations located outside the Polar Frontal Zone (PFZ) and are included for comparisons with stations located within the PFZ. Isopycnals are marked every 0.25 kg m^3.

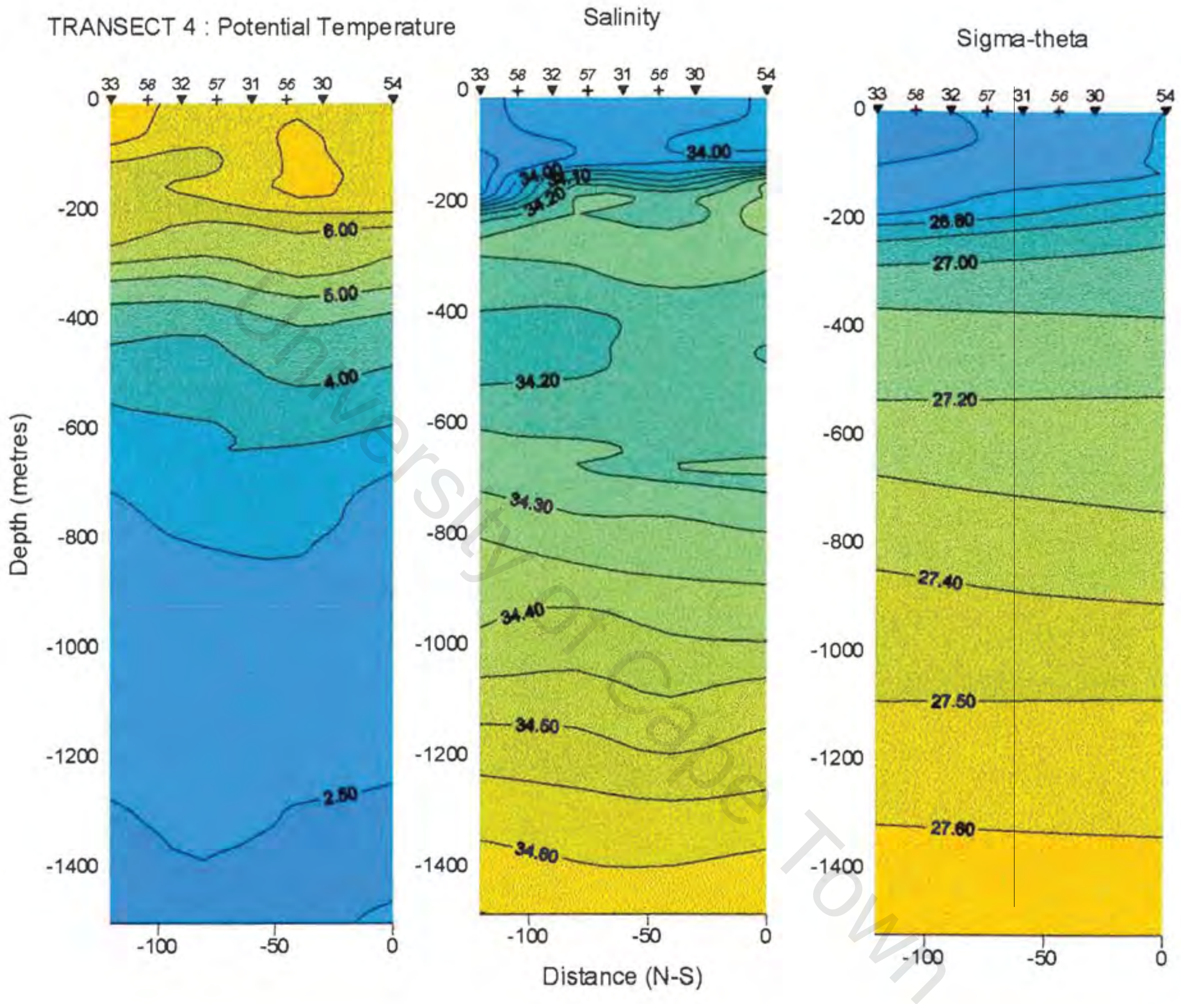


Figure 4.20b: Potential temperature, salinity and sigma-theta sections for stations 30-33+54 occupied in the downstream region during MIOS 2. This transect passes through the warm anticyclonic eddy. Crosses mark the position of XBT stations.

Comparisons between stations occupied in this region during the two surveys, shows significant difference in the θ/S profiles (Figure 4.21). During MOES 2 the existence of a cold eddy spawned from the APF resulted in cold, fresh θ/S profiles indicative of AASW, whereas during MIOS 2 the formation of a warm eddy resulted in the advection of warm SASW further south. Past investigations (Duncombe Rae 1989a) have shown that the oceanic environment immediately south of the islands is usually colder < 6°C and fresher < 33.85 than to the north, due to the deflection of the SAF around the islands and the close proximity of the APF. The substantial differences in the θ/S profiles between stations from MOES 2 and MIOS 2 certainly highlights the variability of the oceanic environment surrounding the Prince Edward Islands.

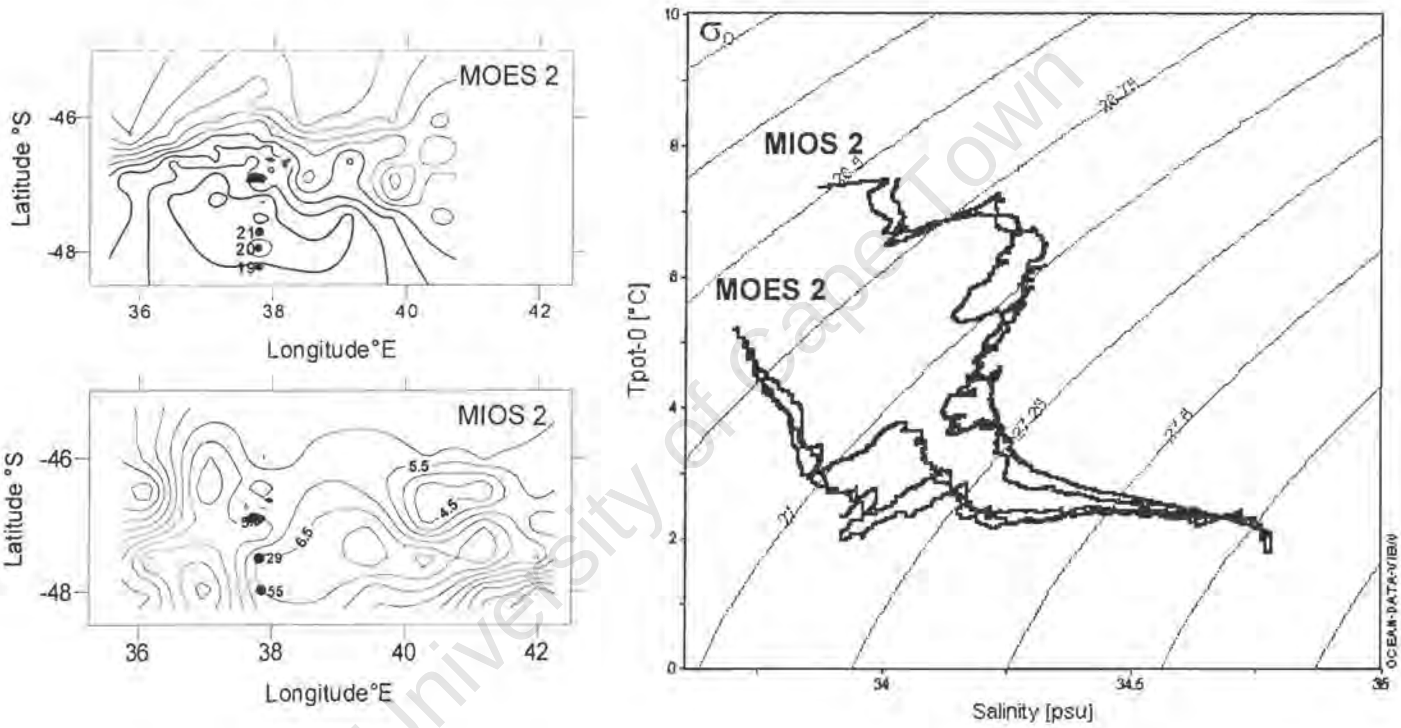


Figure 4.21: θ/S profiles of CTD stations occupied immediately south of the Prince Edward Islands during MOES 2 and MIOS 2. The location of each station can be seen in the insert, which also shows the horizontal distribution of sea surface temperature. By comparing the θ/S profiles, the impact flow that disturbances have on the oceanic environment can be clearly seen. During MOES 2, the environment associated with the meandering dynamics of the APF was considerably colder, while during MIOS 2 the warm eddy resulted in an increase in temperatures (+ 2°C). The horizontal distribution of subsurface temperatures shows the difference of the oceanic environment between the cruises.

Discussion - Geostrophic Velocities

Geostrophic flow and the geopotential anomaly has been calculated between station pairs to a maximum depth of 1500 db (using equations outlined in Chapter 3). Technical problems with the spooling of the hydrographic wire prevented the CTD instrument from being lowered more than 2000 m. Since the Antarctic Circumpolar Current is known to extend to depths exceeding this (Nowlin et al. 1977), the following speed calculations are likely to be underestimates.

MOES 2

Upstream of the islands the high-speed core of the SAF was found to lie along the northern edge of the survey, between 46° – 46°38' S, with geostrophic velocities between station pairs ranging from 20 – 28 cm s^{-1} (ref 1500 db). Geostrophic velocities dramatically decreased (< 5 cm s^{-1} - ref 1500 db) immediately south of the SAF. Relatively quiescent zones separate the SAF and APF and therefore velocities associated with the PFZ are usually minor (Nowlin et al. 1977).

Topographical steering by the Prince Edward Islands may have resulted in the SAF deflecting northeastwards to lie between CTD 50 and 52, with speeds exceeding 23 cm s^{-1} (ref 1500 db). There was a substantial reduction in speeds immediately north of CTD 52 (0.54 cm s^{-1} - ref 1500 db) and south of CTD 50 (7 cm s^{-1} - ref 1500 db) indicating that the SAF lay in a narrow concentrated band, only 55 km wide. Recent investigations by Pollard and Read (1997) during SWINDEX, have shown that between the gap west of Crozet and the Del Cano Rise, the ACC, influenced by the shallow and complex regional topography, narrows to between 40 and 70 km. Alternating eastward and westward flows south of the islands are associated with the cyclonic motion of the cold eddy spawned from the APF (Figure 4.22).

Downstream, geostrophic velocities show strong (> 16 cm s^{-1} - ref 1500 db) alternating westward and eastward flows around pools of weaker currents (5 cm s^{-1} - ref 1500 db) indicative of a meander within the PFZ. Comparing hydrographic data with vectors generated using the Fine Resolution Antarctic Model (FRAM) for the region north of South Georgia, Trathan et al. (1997) have shown that in the centre of a high speed meander lay relatively still waters (< 3 cm s^{-1} - ref 1500 db), that were stable and well mixed. Indeed, stations located in the warm eddy of the MIOS 2 have well-developed mixed layers with depths extending to > 60 m (Perissinotto et al. 2000).

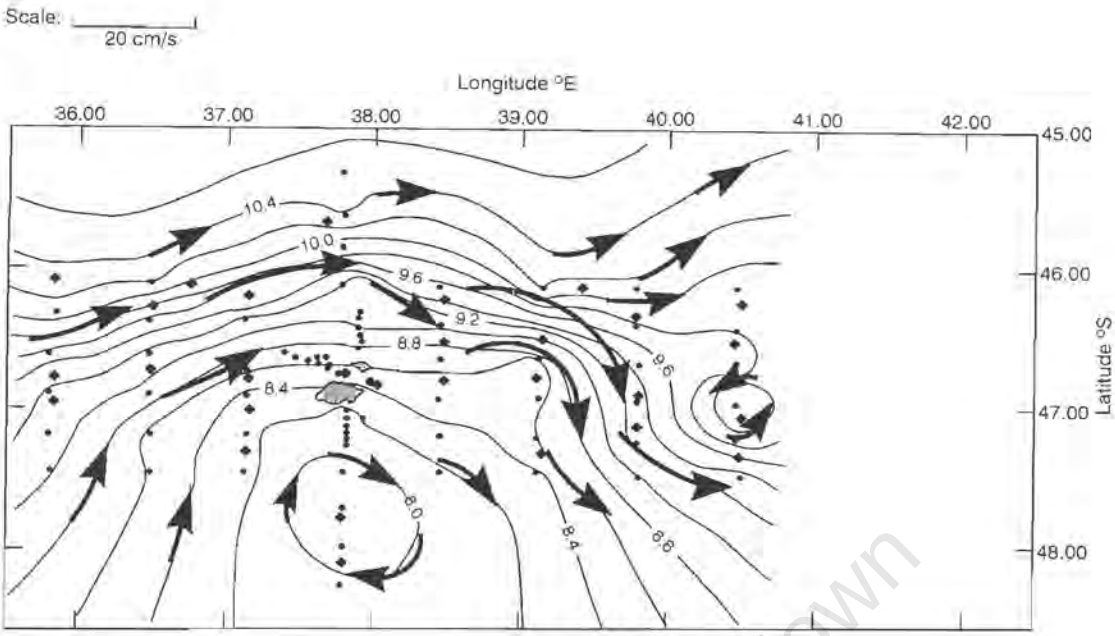
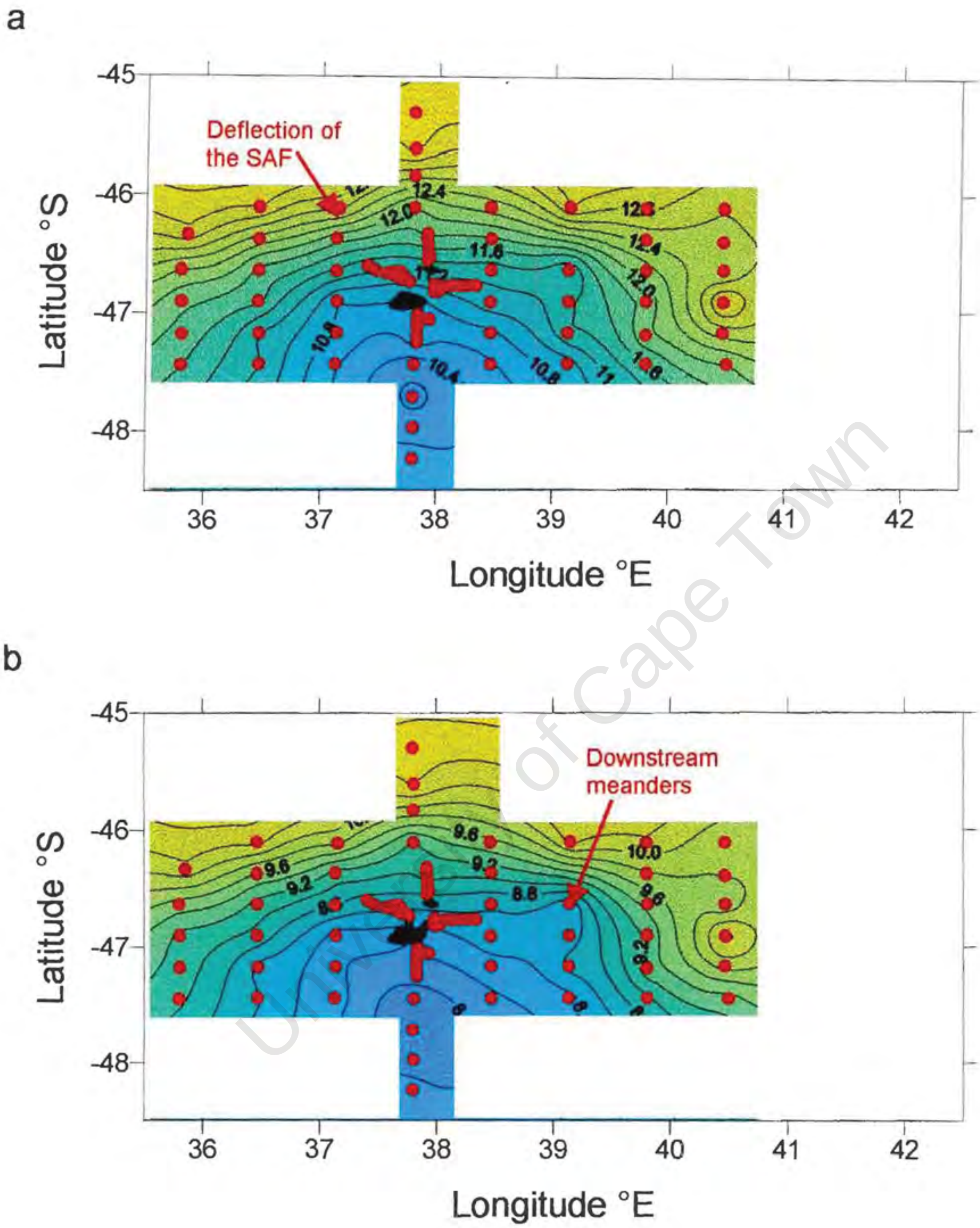


Figure 4.22: Geopotential anomalies in $m^2.s^{-2}$ at 200 db relative to 1500 db. Subsurface geostrophic velocities have been superimposed onto the geopotential lines. The meandering nature of the SAF can be clearly seen, as well as the position of a cold cyclonic eddy immediately south of the islands and a warm anticyclonic eddy downstream. The contour interval is 0.2 $m^2.s^{-2}$.

The highest velocities > 30 cm s^{-1} (ref 1500 db) observed during the entire survey were found along transect 6 (CTD 64 – 63), where the flow associated with the equatorward leading branch of the meander was coupled with the strong zonal flow associated with the SAF. Farther downstream a westward current (> 9 cm s^{-1} - ref 1500 db) was observed (Figure 4.22) that formed a part of the anticyclonic motion of the warm eddy between CTD 73 and 74.

Charts of geopotential anomaly isolines have been drawn for the surface, 200 m, 500 m and 1000 m relative to 1500 db (Figures 4.23 a-d). Reference to geopotential anomalies at these depths show the deflection of the SAF and the meanders downstream of the islands to extend through the measured water column.


a
Deflection of the SAF
Latitude °S
Longitude °E
-45
-46
-47
-48
36
37
38
39
40
41
42
12.4
12.0
11.6
10.4
10.8
b
Downstream meanders
Latitude °S
Longitude °E
-45
-46
-47
-48
36
37
38
39
40
41
42
9.6
9.2
10.0
8.8

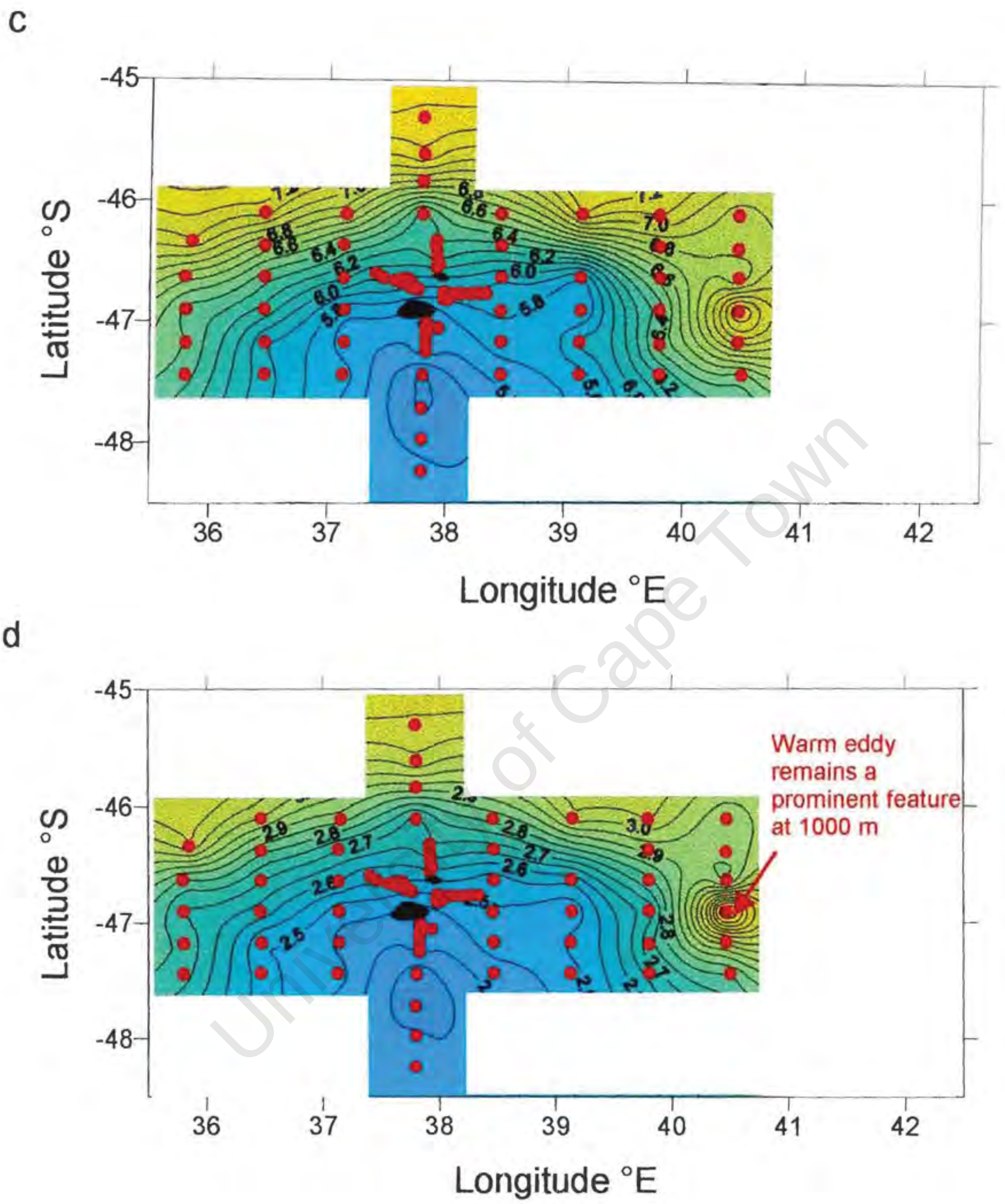


Figure 4.23: Charts of geopotential anomaly in $m^2.s^{-2}$ at (a) surface, (b) 200 m, (c) 500 m and (d) 1000 m relative to 1500 db during MOES 2. Disturbances generated downstream of the Prince Edward Islands are clearly evident. A deep eddy is apparent at the eastern extremity of the survey grid.

We are unable to determine the extent of the wake downstream of the survey grid. However, laboratory experiments in which the interaction of linear Rossby waves with non-zonal ridges was studied (Roden 1991) have shown that the amplitudes of such a wake decrease exponentially with distance from the ridge. This agrees with field studies around the island of Oahu, which have shown a Rossby wave breaking down 250 km downstream of a ridge (Mysak and Magaard 1983). The wake observed at the Prince Edward Islands during the MOES 2 - if indeed a true Rossby wave - could therefore have extended considerably farther than the station grid.

MIOS 2

In comparison to the MOES 2, where the SAF lay as a zonal band between 46°S and 46° 38' S, during the MIOS 2 the SAF appeared to meander extensively from where it initially lay far to the south at 47° 20' S (CTD 15 – 16). The two transects, occupied upstream of the islands (CTD 12 – 22) both show alternating eastward and westward flow indicative of a meandering front. The meandering nature of the SAF in this region may have been due to the presence of a cold eddy centred at 46° 30' S, 37° E, causing the SAF to deflect northwards.

Geostrophic velocities show this eddy to have been cyclonic with speeds ranging between 5 – 9 cm s^{-1} (ref 1500 db). Maximum speeds (> 25 cm s^{-1} - ref 1500 db) encountered during the upstream transects were associated with the combined SAF/APF surface front found between CTD 14 – 16. Closer to the islands the SAF and APF appeared to branch, reducing speeds substantially to 11 cm s^{-1} (CTD 19 – 20) and 12 cm s^{-1} (ref 1500 db) (CTD 18 – 19).

The general circulation downstream of the islands was dominated by two counter-rotating eddies (Figure 4.24). Geostrophic velocities along the northern edge of the grid (CTD 33 – 32) were low (3 cm s^{-1} - ref 1500 db), comparing better to flow expected within the PFZ than along a frontal band. This weak flow is in agreement with the hydrography that suggests that the SAF was not encountered during this transect, having been displaced northwards by the two eddies in the PFZ. Temperature and sigma-theta distributions (Figures 4.6 - 4.10) suggest that the SAF remained north of the survey grid up to 40° 25' E where it deflected southeastwards. Geostrophic velocities along the northern border of the survey grid (46°S) show a gradual increase with distance east (3 – 16 cm s^{-1} - ref 1500 db) confirming this southern shift.

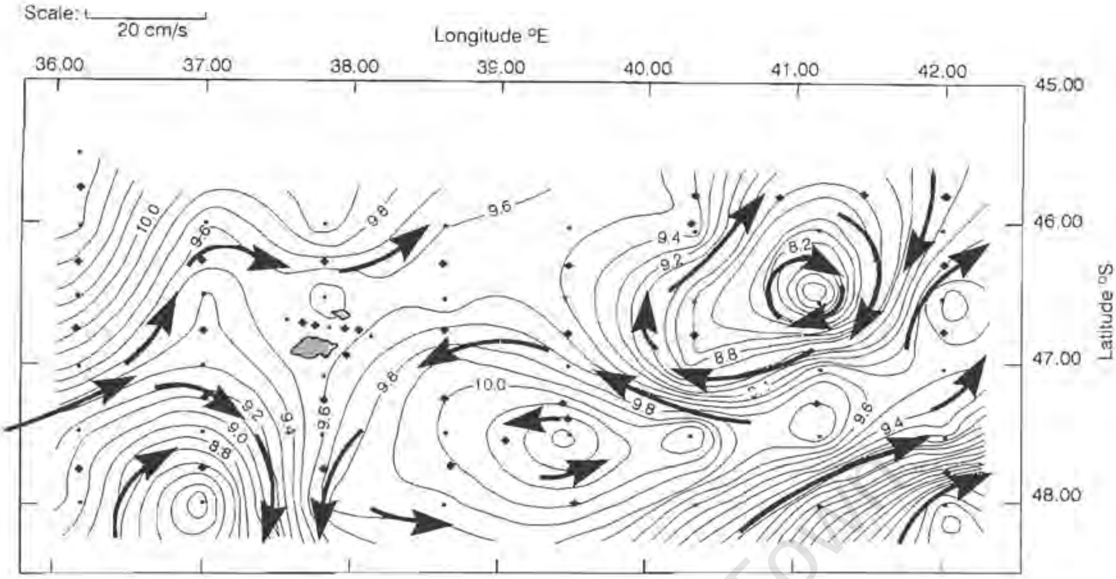


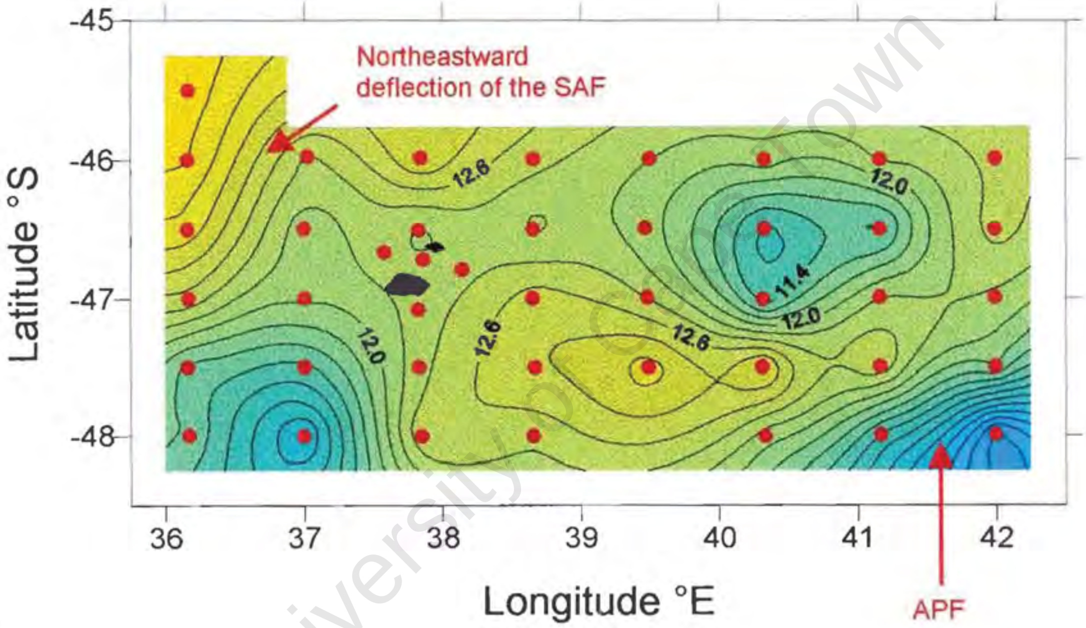
Figure 4.24: Geopotential anomalies $m^2.s^{-2}$ at 200 db relative to 1500 db. Subsurface geostrophic velocities have been superimposed onto the geopotential lines. The branching of the SAF/APF frontal band upstream of the islands can be clearly seen. Downstream of the islands the cyclonic flow associated with a cold eddy as well as the anticyclonic motion of a warm eddy is evident. The contour interval is 0.1 $m^2.s^{-2}$.

Immediately east of the islands and south of the SAF geostrophic velocities had both westward (9 cm s^{-1} - ref 1500 db) and eastward (6 cm s^{-1} - ref 1500 db) components associated with the anticyclonic motion of a warm eddy. In the centre of this eddy (CTD 30 – 31) flow was extremely weak > 1 cm s^{-1} (ref 1500 db) (Figure 4.24).

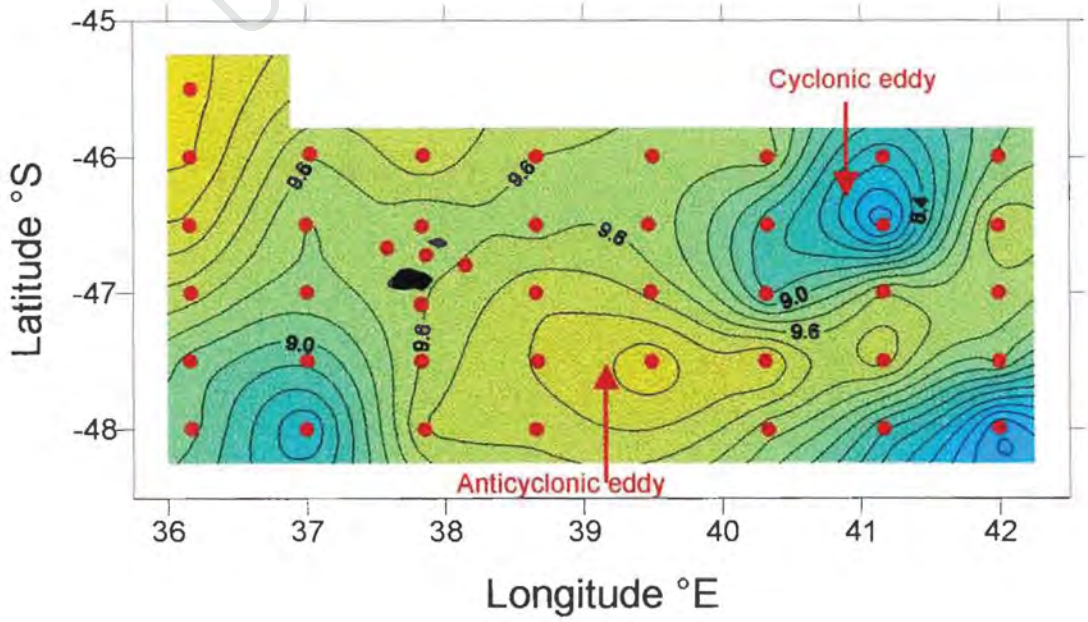
In the northeastern corner of the survey grid the general geostrophic flow associated with the cold eddy was cyclonic. Similar to MOES 2 there was an increase in flow to 16 cm s^{-1} (CTD 44 – 46), as the cyclonic flow appeared to couple with the SAF. The strongest surface flow > 30 cm s^{-1} (ref 1500 db) observed in the whole survey was found between CTD 40 – 41 and was associated with the coupling between the warm and cold eddy (Figure 4.24). Here a strong thermal gradient (0.03°C/km) extended through the water column. The APF was encountered in the southeastern corner of the survey exhibiting speeds of 24 cm s^{-1} (ref 1500 db). A possible explanation for the extremely high thermal gradient observed during MIOS 2 may be the close proximity of the APF to the southern edge of the warm eddy (CTD 49 – 50; Figures 4.6a (surface) and 4.7a (subsurface).

Charts of geopotential anomaly isolines have been drawn for the surface, 200 m, 500 m and 1000 m relative to 1500 db (Figures 4.25 a-d). Reference to geopotential anomalies at these depths show the deflection of the SAF and the counter-rotating eddies observed downstream of the islands to extend through the measured water column.

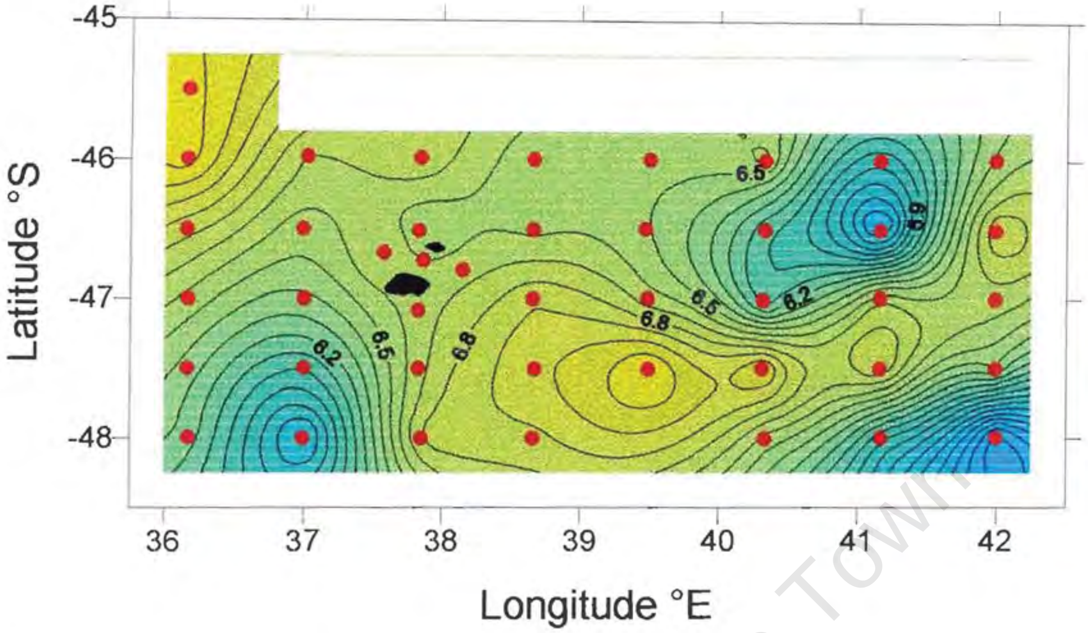
a



b



c



d

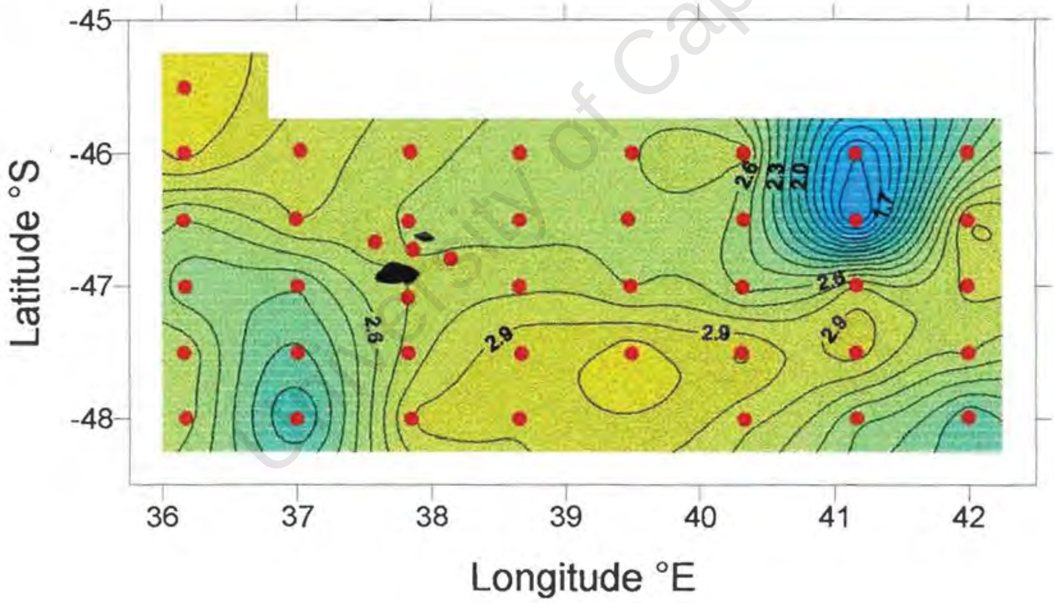


Figure 4.25: Charts of geopotential anomaly in $m^2.s^{-2}$ at (a) surface, (b) 200 m, (c) 500 m and (d) 1000 m relative to 1500 db during MIOS 2. The location of the two counter-rotating eddies in the downstream region are clearly evident. Both eddies are deep features extending beyond the measured water column.

Both surveys demonstrate that the flow regime downstream of the Prince Edward Islands is complex and dynamic. Investigations elsewhere (e.g. Barkley 1972; Heywood et al. 1990) have all shown that the size and form of flow disturbances, such as trapped eddies and meandering wakes, downstream of islands are directly related to the velocity at which the incident current reaches the islands. Observations during the MOES 2 and the MIOS 2 are consistent with this concept. At higher incident speeds of the ACC (MOES 2) a meandering wake was observed to extend the length of the survey grid downstream of the islands, while during a period of less intense flow as a result of the separation of the combined SAF/APF front during MIOS 2, two counter-rotating eddies with no identifiable wake were observed. Under both conditions, enhanced cross-frontal mixing was apparent (Ansorge et al. 1999, Froneman et al. 1999), resulting in the advection across and entrapment of water masses within the PFZ.

Conclusion

Past experiments using satellite observations (Cheney et al. 1983, Gamberoni and Park 1997), buoy trajectories (Hofmann 1985), inertial jet models (Craneguy and Park 1999) and hydrographic data (Gordon et al. 1977, Nowlin et al. 1977, Lutjeharms and Baker 1979, Park et al. 1993, Read and Pollard 1993, Trathan et al. 1997) have all revealed that high mesoscale variability is closely correlated to regions of prominent bottom relief.

The Prince Edward Islands lie in such a region, bordered to the west by the shallow Southwest Indian Ridge; while immediately east and north the Del Cano Rise and Gallieni Knoll can be found. Extensive surveys around islands throughout the Southern Ocean such as the Crozet and Kerguelan Island group (Park et al. 1991, 1993, 1997, 1998), South Georgia (Trathan et al. 1997, Atkinson and Peck 1990) and at Macquarie Island (Bryden and Heath 1985, Boyer and Guala 1972 and Gordon 1972) have all revealed extensive mesoscale disturbances within the PFZ. The MOES 2 and MIOS 2 surveys both show the deflection of the SAF around the northern edge of the islands, resulting in an increase in the width of the PFZ here. However, comparisons between the datasets show that the downstream region varies substantially more with a meandering wake observed during MOES 2 and two counter-rotating eddies during MIOS 2. The meandering dynamics of the SAF during MOES 2 resulted in the southward advection of warm water masses from north of the SAF, while the warm and cold core eddies featured in MIOS 2 may possibly trap

AASW and SASW within the PFZ. The formation of the wake is consistent with the model proposed by Perissinotto and Duncombe Rae (1990). The results clearly show that during both occasions the leeward side of the Prince Edward Islands represents an area of enhanced meridional exchange of physico-chemical properties, probably resulting from the interaction between the complex bottom topography and the eastwardly flowing ACC.

To summarise, extensive disturbances are generated in the downstream region of the Prince Edward islands. These disturbances vary considerably from one survey to another and are influenced by the oceanographic regime in the region upstream. It would therefore be of further interest to study the effect this spatio-temporal variability has on the distribution and community structure of the biological zooplankton and to see whether there is a strong physical-biological coupling in the waters surrounding the Prince Edward Islands.

Chapter 5

Physical-biological coupling in the waters surrounding the Prince Edward islands

Biological studies around the Prince Edward Islands have been largely concentrated in the waters in the immediate vicinity (Allanson et al. 1985, Boden and Parker 1986, Perissinotto 1989, Pakhomov and Froneman 1998). These studies have shown, that the zooplankton community are largely dominated by Antarctic and Subantarctic mesozooplankton (Boden and Parker 1986, Froneman and Pakhomov 1999, Froneman and Ansorge 1998). A key finding was the tremendous shifts in the community structure of taxonomic groups from year to year, suggesting that water masses of different origin were being sampled (Allanson et al. 1985, Boden and Parker 1986). Although flow disturbances of strong currents by oceanic islands and seamounts in the Southern Ocean have been described (Lanin 1985, Perissinotto and Duncombe Rae 1990, Pakhomov and Semelkina 1995), the biological consequences of such disturbances, particularly within the Subantarctic and Polar Frontal zones, are still poorly understood.

The last chapter has shown that the oceanographic regime surrounding the Prince Edward Islands is incredibly complex and dynamic, varying substantially from one survey to another. The meandering nature of the SAF identified during MOES 2 and the presence of two counter-rotating eddies during MIOS 2 certainly enhances cross-frontal mixing downstream of the islands and may also encourage the introduction of foreign species into the region. It is therefore possible that the zooplankton community structure near the islands may be strongly determined by the prevailing oceanographic regime and consequently reflects the variability between surveys. In this chapter the physical data to the biological species and abundance is compared and it will be possible to answer the following questions:

- *What impact does the physical environment have on the distribution and community structure of the biological zooplankton?*
- *Does the species distribution reflect the extreme variability of the oceanographic regime around the islands from one year to the next?*

Data and Methodology

The manner in which hydrographic data were collected during the MOES 2 and MIOS 2 surveys has already been discussed in detail in Chapter 3 Data and Methods. The collection and analysis of the zooplankton abundance and distribution were carried out by the Southern Ocean Group of Rhodes University (Ansorge et al. 1999, Froneman et al. 1999).

Results

As has been seen in the previous chapter, the oceanic environment surrounding the Prince Edward Islands is largely affected by the flow of the Antarctic Circumpolar Current. Past investigations have shown the position of this current and its associated circumpolar fronts, the SAF and APF, to display extreme latitudinal variability (Valentine and Lutjeharms 1984, Duncombe Rae 1989a, Lutjeharms 1990). Recent studies (Pakhomov and Froneman 1999) have shown that the position of the SAF in relation to the islands has important implications on the food availability of the top predators, influencing the hydrology and plankton communities of the intermediate waters. The results from both cruises show that extreme differences in the zooplankton community structure correlate with the oceanographic regime observed downstream of the islands. These oceanographic conditions and the degree of physical variability between MOES 2 and MIOS 2 have been discussed in detail in the previous chapters, however a brief description will be given again in order to refresh the reader.

Oceanographic conditions in both upstream and downstream regions, varied considerably between the two surveys (Figures 5.1a and b). During MOES 2, the SAF initially lay at 46° 38' S upstream of the islands (Figure 5.1a). In contrast, during MIOS 2 the SAF lay much further south at 47°20'S, where combined with the surface expression of the APF, it formed a sharp frontal band with surface temperatures ranging from 7.80°C to 5.20°C (Figure 5.1b). This had not been observed during any previous surveys (Duncombe Rae 1989a, Ansorge et al. 1999, Pakhomov and Froneman, 1998), and emphasises the extreme mesoscale variability of this region. Closer to the islands, probably as a result of the shallow topography associated with the Southwest Indian Ridge, the SAF showed a distinct northeastwards deflection around the islands at 46° 06' S. In the case of MIOS 2 this deflection resulted in a distinct separation of the two fronts (Figure 5.1b). The APF instead remained south of the islands as a meandering front. In contrast, during MOES 2 the APF was not encountered at all upstream of the islands. Instead, a cold eddy consisting of Antarctic Surface Water was found immediately south of the islands (Figure 5.1a).

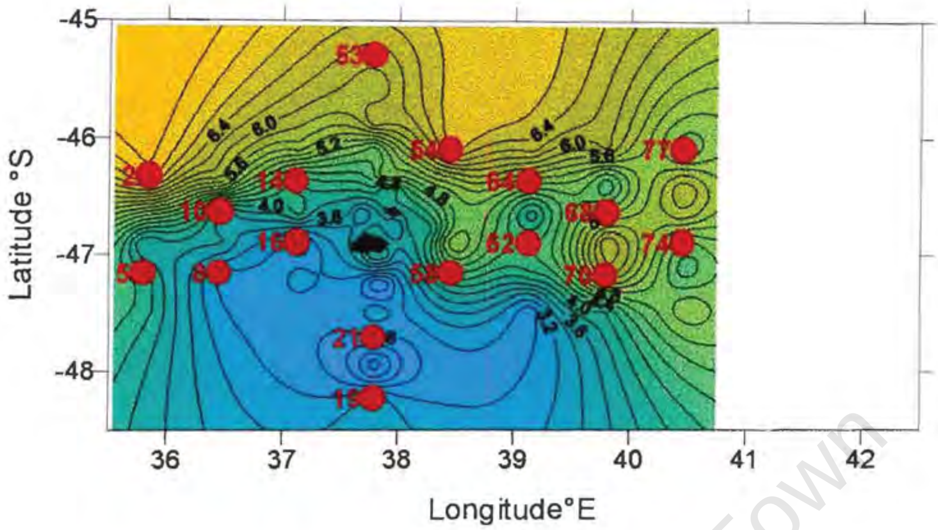


Figure 5.1a: Distribution of subsurface (200 m) temperatures in the vicinity of the Prince Edward Islands during MOES 2. The location and meandering of the SAF is clearly evident in the downstream region. Red dots represent the location of all zooplankton stations.

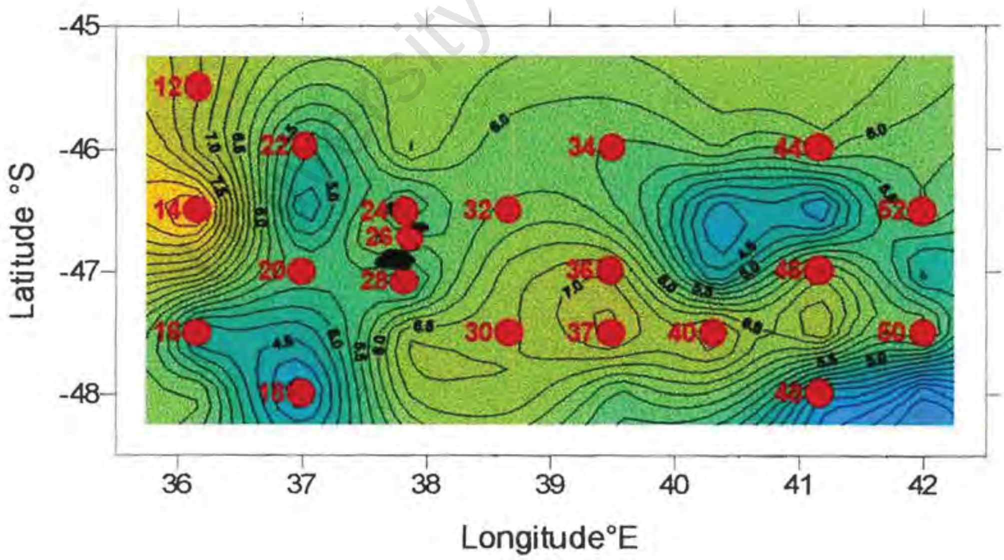


Figure 5.1b: Distribution of subsurface (200 m depth) temperatures in the vicinity of the Prince Edward Islands during MIOS 2. The location of the two counter-rotating eddies is clearly evident in the downstream region. Red dots represent the location of all zooplankton stations.

Disturbances generated downstream of the islands varied considerably. During MOES 2, the SAF exhibited a distinct broad wake in the upper layers extending between 46° 10' S and 47° 30' S. The dimensions of the wake increase with distance downstream, with a zonal wavelength estimated to be 150 km. In addition a deep (> 1500 m), warm eddy characteristic of Subantarctic Surface Water (> 7.5°C and > 33.8) was found (Figure 5.1a). In the downstream region of the Prince Edward Islands during MIOS 2 a cyclonic cold (< 6°C) eddy consisting of Antarctic Surface Water was observed. Its central position in the PFZ possibly acted as a barrier to the flow associated with the SAF causing the PFZ to bulge. South of this eddy and extending eastwards, an elongated warm > 6.6°C anticyclonic feature, indicative of SASW was also encountered (Figure 5.1b).

Numerical analysis and zooplankton species composition

For MOES 2 numerical analysis of the zooplankton data by the Southern Ocean Group (see Ansorge et al. 1999) has identified four major groupings of stations (Figure 5.2a). Since the groupings identified were associated with distinct oceanographic processes, the physical processes with which they were associated probably designated the groups.

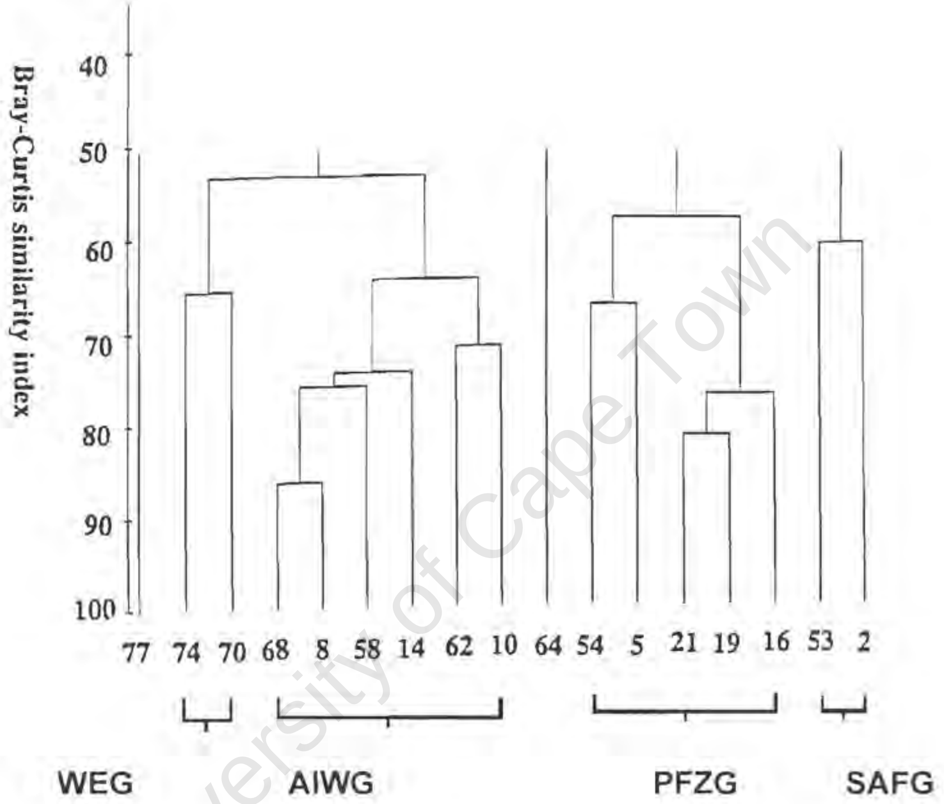


Figure 5.2a: Dendrogram drawn by the Southern Ocean Group showing the classification of zooplankton stations along the eight transects conducted in the upstream and downstream regions of the Prince Edward Islands during MOES 2 (see Ansorge et al. 1999). Abbreviations are as follows, WEG = Warm Eddy Group, PFZG = Polar Frontal Zone Group, SAFG = Subantarctic Front Group, AWIG = Antarctic Water Intrusion Group.

The four groupings of stations identified during MOES 2 were:

- Subantarctic Front Group (SAFG)
- Polar Front Zone Group (PFZG)
- Warm Eddy Group (WEG) and
- Antarctic Water Intrusion Group (AWIG).

The AWIG was associated with the meanders found in the upstream and downstream region of the islands (Figures 5.2a), whereas the SAFG and PFZG were associated with species found upstream of the islands. Stations 64 and 77 were identified by the numerical analysis as outliers, species that did not fit into any particular group.

The four groupings of zooplankton identified during MIOS 2 were:

- Subantarctic Surface Water Group (SASWG)
- Antarctic Surface Water Group (ASWG)
- Polar Front Zone Group (PFZG)
- The fourth grouping of stations identified with the numerical analyses comprised those stations where the lowest zooplankton abundances along the entire survey were recorded and thus, do not correspond to any distinct oceanographic feature. As a consequence, this group is designated the Outlier group (OG).

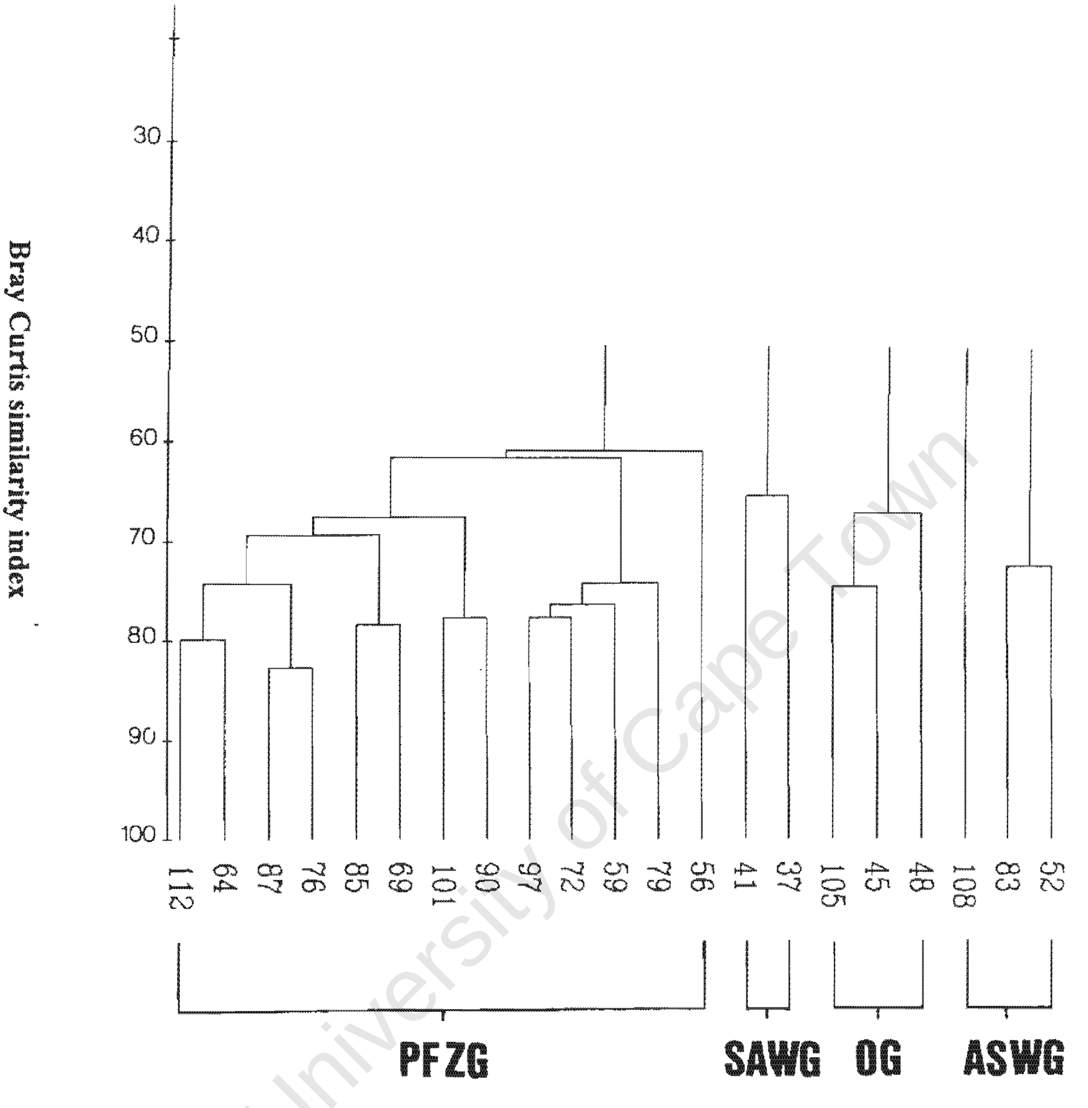


Figure 5.2b: Dendrogram drawn by the Southern Ocean Group (see Froneman et al. 1999) showing the classification of zooplankton stations along the eight transects conducted in the upstream and downstream regions of the Prince Edward Islands during MIOS 2. Abbreviations are as follows, ASWG = Antarctic Surface Waters Group, PFZG = Polar Frontal Zone Group, SASWG = Subantarctic Surface Water Group, OG = Outlier Group.

Discussion

Several studies have examined the interaction between the oceanographic and biological conditions in the waters surrounding the Prince Edward Islands (Ansorge et al. 1999, Pakhomov and Froneman 1999). These studies have, however, generally been restricted to the immediate waters surrounding the islands. The composition of the zooplankton community in the open waters near the islands has been well documented (Boden and Parker 1986, Pakhomov and Froneman submitted). These reveal the numerical dominance of copepods, ostracods and small euphausiids among the zooplankton assemblages during these investigations and agree well with previous studies conducted in the vicinity of the islands (Grindley and Lane 1979, Allanson et al. 1985, Perissinotto 1989, Perissinotto and Boden 1989). Estimates of zooplankton abundance and biomass during MIOS 2 and MOES 2 are, however, among the lowest recorded in the waters surrounding the islands (see review by Pakhomov and Froneman 1999). Although the dominant species during both surveys differ from previous studies, shifts in the dominants are a characteristic of the zooplankton assemblages in the water surrounding the islands, reflecting the extreme variability in the oceanographic regime around the islands (Perissinotto and Boden 1989).

The oceanographic and biological conditions surrounding the Prince Edward Islands during MOES 2 and MIOS 2 can be divided into distinct regions corresponding to the SAF and the regions upstream and downstream of the islands.

Frontal region

During MIOS 2, in contrast to previous studies conducted in the vicinity of the SAF and APF (Allanson et al. 1981, Lutjeharms et al. 1985, Boden. 1988, Pakhomov 1993, Froneman et al. 1995 a, b), no enhancement of zooplankton biomass was found in the vicinity of the fronts. Of particular interest is the virtual absence of larger macrozooplankton to total zooplankton biomass in the vicinity of the fronts. During this survey, total zooplankton biomass was almost entirely dominated by small mesozooplankton comprising mainly copepods (Froneman et al. 1999). This result is consistent with the findings of study conducted by Voronina (in press), which showed that copepods accounted for up to 98% of zooplankton biomass in the Southern Ocean.

Upstream region – MOES 2

Observations during MOES 2 show that in this region the SAF was deflected around the northern edge of the islands. A distinct grouping of stations (stations 2 and 53) was found in the vicinity of the SAF (see Figure 5.1a). Unfortunately, no stations were occupied farther north of the front and as a consequence unable to determine whether the grouping identified was specific to the front or consistent with SASW. The Similarity Program (SIMPER) employed during this study showed that with the exception of the grouping associated with the warm-eddy, average dissimilarity between stations north and south of the SAF was > 55%. This suggests that the SAF represents an important biogeographic boundary to the distribution of both Subantarctic zone (SAZ) microphytoplankton and zooplankton species (Froneman et al. 1995a,b, Pakhomov and McQuaid 1996). Enhanced zooplankton biomass has previously been recorded in the vicinity of the SAF (Pakhomov and McQuaid 1996). During this investigation, however, zooplankton biomass associated with the SAF was among the lowest recorded to date. Despite the low zooplankton biomass, the relative contribution of macrozooplankton to total zooplankton biomass was the highest at stations found in the vicinity of the front. It is probable therefore that when the SAF lies in close proximity to the islands, the macrozooplankton associated with the front may be available to the top predators e.g. penguins, seabirds and seals, found on the island.

A distinct grouping of stations designated the Polar Front Zone Group (PFZG) (stations 5-16, 19-21) were identified in the region south of the SAF (see Figure 5.1a). Within this grouping of stations, typical Subantarctic copepod species, numerically dominated accounting for > 90% of total zooplankton abundance suggesting that these stations were occupied within the PFZ water proper (stations 8, 10 and 14). Water masses upstream of the islands demonstrate a gradual transition in θ/S properties, as Subantarctic Surface Water (SASW) is modified becoming cooler (~6°C) and fresher (33.70), typical of the PFZ.

Unfortunately, there is no evidence for the gradual shift in zooplankton associated with the transition of water across the PFZ. Indeed, the numerical analyses group all the stations south of the SAF into a single grouping (see Figure 5.1a). However, the absence of different groupings south of the SAF is probably the result of a poorer plankton sampling resolution employed.

- MIOS 2

During MIOS 2, upstream of the Prince Edward Islands between 36° and 37°E, the SAF lay further south (47°20'S) than during previous studies (Valentine and Lutjeharms 1984, Lutjeharms 1990) and formed a very tight confluence possible due to its interaction with a weak surface APF (see Figure 5.1b). This merging of the two fronts was not seen during MOES 2 (Ansorge et al. 1999). However, this finding is comparable to observations made further upstream at 30°E (Read and Pollard 1993, Park and Charriaud 1997) and 34°20'E (Holliday and Read 1997), which show the SAF and APF to be merged. Although several studies conducted in different sectors of the Southern Ocean have highlighted the importance of oceanic fronts as biogeographic boundaries to the distribution of planktonic species (Froneman et al. 1995a, b, Pakhomov and McQuaid 1996, Pakhomov et al. 1997), no shift in the phytoplankton species composition was observed across the SAF/APF. This is in contrast to the zooplankton distribution, which showed a distinct shift in community structure in Antarctic (Antarctic Surface Water Group), and Subantarctic surface waters (Subantarctic Surface Water Group). The lack of a distinct microphytoplankton grouping associated with the different water masses in the region can also probably be explained by cross frontal mixing. Indeed evidence of cross frontal exchange of water masses has been observed by Park and Gamberoni (1997) to be impulsive and influenced by strong frontal mesoscale activities.

Downstream Region – MOES 2

During MOES 2 a distinct wake was observed resulting in the advection of water masses from outside the PFZ. Within these upper layers, zooplankton species composition was comprised of typical Subantarctic and Antarctic species. The presence of species from the two distinct regions suggests that Subantarctic and Antarctic waters were being meridionally exchanged within the meander. Indeed, θ/S properties differed considerably (see chapter 4) between transects as a result of SASW water being advected either polewards from the SAZ or AASW, that has been modified in the transitional band of the PFZ, being advected equatorwards. In comparing the four transects it can be seen that the surface waters associated with stations 54-58 show the advection of distinctly warm > 7°C SASW into the region (Figure 5.1a).

By contrast, stations 60-65, lying on the equatorward edge of the wake (Figure 5.1a), show the advection of cooler, modified AASW northwards. Surface temperatures and salinities between stations 60 and 64 were < 7°C and < 33.8, with only the northernmost station CTD 65 showing water masses characteristic of SASW and typical of a station to the north of the SAF.

- MIOS 2

During MIOS 2 a cyclonic eddy consisting of Antarctic Surface water masses (< 6°C, < 33.9) appeared trapped in the PFZ (Figure 5.1b). Its exact genesis is unknown, however a likely possibility is that it had been shed from the APF as the result of the breakdown of a northward meander. The absence of a distinct zooplankton grouping associated with the cold-eddy is surprising as it is well documented that eddies, in particular south of Africa, have specific planktonic communities associated with them (Froneman and Pakhomov 1998). Analysis of the zooplankton community (Polar Front Zone Group PFZG) within the region of the eddy, however, showed the presence of both Antarctic as well as Subantarctic zooplankton species (Grindley and Lane 1979). These data suggest that the warmer Subantarctic species were rapidly entrained into the cold eddy. It is not unreasonable to suggest that the close proximity of the eddy to the southern boundary of the SAF may have facilitated the transfer of zooplankton species between the two features. Observations south of Australia (Savchenko et al. 1978), have shown that the northern edge of such cold eddies often combine with the front resulting in the cyclonic flow coupling with the SAF and increasing the associated zonal flow.

In addition, both surveys show the presence of a warm eddy (> 7°C, > 33.80), corresponding to SASW (see Figures 5.1a and b). The eddy observed during MOES 2 showed (stations 70-74) the presence of typical Subantarctic zooplankton and species typically associated with the Temperate Zone. These data suggest that the warm eddy may have developed as a result of baroclinic instabilities within the flow pattern of the SAF (Lutjeharms and Baker 1980). Indeed, the numerical analysis employed by the Southern Ocean Group (see Ansorge et al. 1999, Froneman et al. 1999) shows that the zooplankton community associated with this eddy was not significantly different from stations found within the SAFG. Also, the physical properties of the eddy were consistent with SASW water.

Eddies such as these, therefore, appear to represent a mechanism capable of transporting biological communities across the biogeographical boundary represented by the SAF (see Froneman et al. 1995a,b, Pakhomov and McQuaid

1996). Also, the insular nature of eddies and increased water column stability within these features may also locally provide a more stable environment for phytoplankton growth (Perissinotto and Duncombe Rae 1990). Studies carried out by Williams (1988) have shown that air-sea interactions modify the structure and life cycle of ocean eddies in the seasonal boundary layer, through the exchange of heat, moisture and momentum. Although the life expectancy of the warm eddy discussed here is unknown, it is unlikely that its effect on the biological communities would persist for a long period. This is partially supported by the analysis of the zooplankton community structure within the eddy, which showed the presence of PFZ species, suggesting that these species are being entrained within this feature (Froneman et al. 1999).

The warm eddy observed during MIOS 2 was found directly south of the cold eddy (see Figure 5.1b). The formation of this particular feature may have resulted from a breakdown of a southward penetrating meander within the SAF, which would advect warm SASW (> 6.6°C, > 33.90) across the PFZ. A further, although less likely possibility suggested by Sievers and Emery (1978), is the entrainment of warm patches of SASW from north of the SAF by the cyclonic circulation of the cold eddy to the north. Numerical analysis did not identify a distinct zooplankton community associated with this feature. In contrast to MOES 2 Antarctic zooplankton from a colder environment were identified. These species may have been entrained into the eddy from the APF. Indeed, directly south of the islands a strong thermal front exists between the APF and the western edge of the warm eddy (Figure 5.1b).

The results of the two oceanographic surveys, MOES 2 and MIOS 2, clearly show that the leeward side of Prince Edward Islands represents an area of enhanced meridional exchange of physico-chemical properties with the formation of an extensive wake during MOES 2 and a pattern of eddies during MIOS 2. These features, which appear to have been generated by the meandering frontal systems to the north and south of the islands, facilitate the transfer of water and zooplankton assemblages between the various water masses downstream of the islands. Although the oceanographic regime differed between the two surveys, the effect on the zooplankton community appeared to be similar. Generally, zooplankton assemblages within the PFZ were characterised by species of both Subantarctic and Antarctic origin, which reflect the meridional exchanges of water within the region. The zooplankton community structure during this investigation was therefore consistent with the prevailing oceanographic regime.

The previous chapters have shown that the geographic location of the SAF in relation to the islands substantially influences the oceanological and biological conditions within and around the island group. The data collected during MOES 2 and MIOS 2 surveys, as well as historical data (Lutjeharms and Valentine 1984, Duncombe Rae 1989b, Lutjeharms 1990), have indeed shown the SAF to fluctuate considerably. However, little is known of the variability of the flow passing through the inter-island region. Investigations have certainly indicated that biological productivity varies considerably from year to year in this region suggesting that the flow-through may be irregular (Pakhomov et al. 1998). Pakhomov et al. (submitted) have in fact shown that the distribution of biota between the islands varies considerably from year to year. Whether continuous advection of large plankton and nekton species occurs over the island's saddle has not been resolved, although it has been hypothesised that pulses of water may occasionally pass between the islands (Miller 1982, Pakhomov and Froneman submitted). It is therefore of great interest to study the synoptic dynamics controlling the oceanographic and biological parameters over the inter-island region in order to see whether there is any evidence of synoptic pulsing through the island region.

Chapter 6

Prince Edward Islands inter-island environment: evidence for synoptic pulses

Typical of many Subantarctic oceanic islands, the Prince Edward Islands accommodate large populations of predatory birds and mammals seasonally, suggesting an adequate supply of food (Williams et al. 1979, Condy 1981, Perissinotto and McQuaid 1992). The mechanism, which sustains numerous communities of marine life, has been termed a 'life-support system' (Perissinotto and McQuaid 1992). It is now recognised that the 'life-support system' of the islands includes two important components, an inshore and offshore component (Pakhomov and Froneman 1999). The inshore component represents the trophic links between the selected top predators and rich benthic and demersal fish communities, while the offshore component establishes links between numerous penguins, birds, seals and open ocean allochthonous macroplankton and nekton (Perissinotto and McQuaid 1992, Pakhomov and Froneman 1998).

It has been suggested that the geographic location of the SAF in relation to the islands may substantially influence the oceanological conditions within and around the island group (Perissinotto and Duncombe Rae 1990, Ansorge et al. 1999, Perissinotto et al. in press, Froneman et al. 1999, Pakhomov and Froneman 1999). When the SAF lies far to the north of the island plateau, the PFZ broadens and advective forces associated with this zone are weak. As a consequence, eddies generally coupled with an extensive phytoplankton blooms, resulting in the little exchange of inshore/offshore waters, have been observed over the inter-island region of the Prince Edward Islands (Perissinotto and Duncombe Rae 1990). In contrast, when the SAF lies in close proximity to the islands, advective forces associated with the strong frontal flow prevail, and a flow-through system is established between the islands (Pakhomov and Froneman 1999). Consequently eddies are no longer present in the inter-island region and may be observed farther downstream (Perissinotto et al. 2000).

Most recently the trophic importance of open ocean macroplankton and micronekton stocks around the Prince Edward Island has been studied in detail using large nets and acoustics (Pakhomov and Froneman 1999). The possible importance of large plankton and nekton within the inter-island area is, however, still poorly understood. The previously proposed replenishing hypothesis suggested that micronekton which were consumed by the top predators during the day would be replenished during night time (Perissinotto and McQuaid 1992). This hypothesis has, however, not received support during recent investigations (Pakhomov and Froneman in review). The continuous advection of the large plankton and nekton over the island's saddle has not been confirmed, although it was hypothesised that pulses of water may occasionally occur between the islands (Miller 1982, Pakhomov and Froneman submitted). It is possible that the presence of the SAF close to the island shelf (resulting in a flow-through regime) may result in the stocks of large plankton and nekton associated with this front to become directly accessible to the top predators on the islands (Pakhomov and Froneman submitted).

The Prince Edward and Marion Islands, lying 19 nautical miles apart, are separated by a shallow saddle with a depth range between 40 and 200 m. In the centre of this saddle, a deep (> 200 m) and narrow (> 5 nautical miles) channel runs southeastwards, cutting the plateau into northern and southern regions (Figure 6.1). This channel may act as a funnel to the flow associated with the SAF, possibly resulting in its acceleration between the islands. It may also act as a "catchment area" retaining water flowing through the inter-island region.

Despite numerous studies conducted between the islands over the last 20 years, the macroplankton composition has only been investigated on 2 occasions (Miller 1982, Pakhomov and Froneman in review). The main aim of this investigation described in this chapter is therefore:

- *To understand the synoptic dynamics of oceanographic and biological parameters in the inter-island region of the Prince Edward Islands in order to test the pulsing hypothesis.*

Materials and methods

All measurements and samples were collected during voyage 87 on board the SA Agulhas between 7 and 24 April 1998 in the inter-island region of the Prince Edward

Islands (Figure 6.1). Biological samples were analysed and are described throughout this chapter by the Southern Ocean Group at Rhodes University (see Pakhomov et al. 2000). This formed part of the third cruise of the Marion Island Oceanographic Study (MIOS III). The exploratory shelf survey (TR_0) was conducted during evening hours (17:00 to 20:00 local time) on 7 April. The first trench survey (TR_1) was carried out between 13 and 14 April. The second trench survey (TR_2) was undertaken during 20 April, while the fourth survey (TR_3) was conducted between 23 and 24 April (Figure 6.1). For comparison, a single station was occupied (2 May) in the downstream region of the islands at approximately 46 ° 42.07' S, 38 ° 13.35' E. Except for the TR_0 survey, at each station a CTD (conductivity-temperature-depth) cast was undertaken. A Neil Brown Instrument system Mark IIIC underwater unit was attached to a rosette and the cast lowered to within 10 m off the bottom. Although the average depth of the cast was 210 m, actual station depths ranged from 80 m on the shelf to ~500 m in the western sector of the survey.

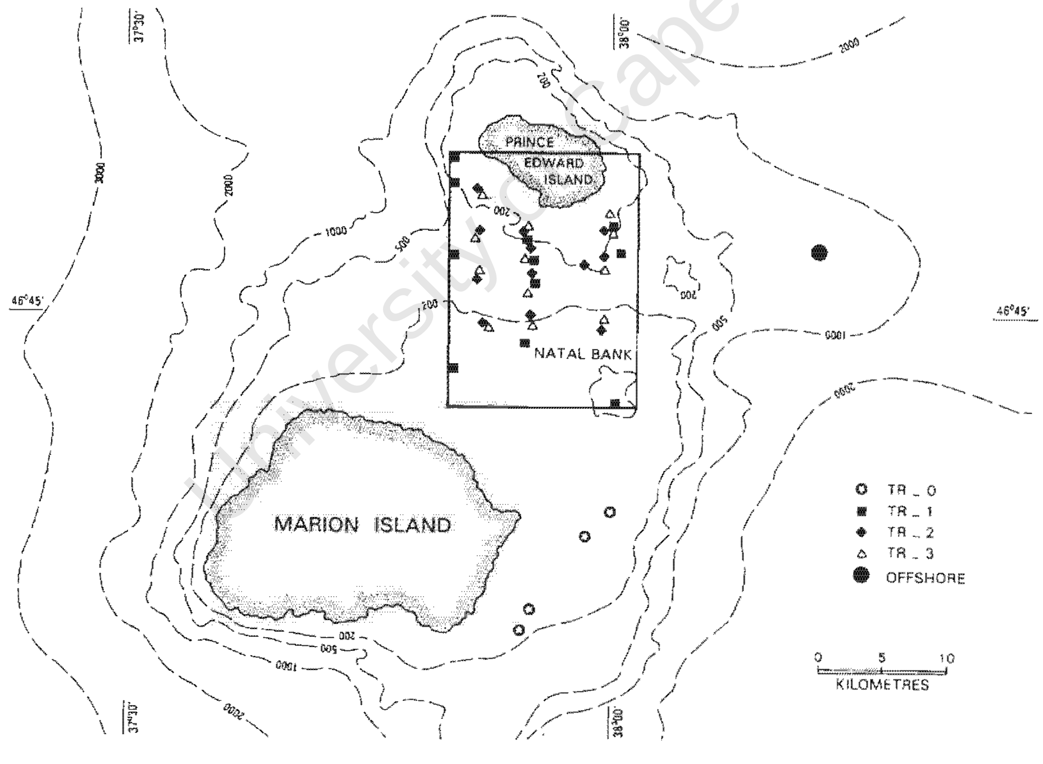


Figure 6.1. Oceanographic/biological stations (CTD + RMT-8) occupied during the three trench surveys in April 1998. TR_0: exploratory shelf survey (7 April), TR_1: first trench survey (13-14 April), TR_2: second trench survey (20 April), TR_3: third trench survey (23-24 April), Offshore: downstream offshore station (2 May).

To locate and monitor the position of the SAF in relation to the Prince Edward Islands, several transects upstream of the islands along 37°E were carried out during a period of 4 weeks. These lines were occupied enroute to the islands (4-5 April), during a northern transect (15-16 April) and during the return voyage to Cape Town (8-9 May). The front was identified by the subsurface expression (T_{200}=6°C) after the definition proposed by Park et al. (1993). During these transects Sippican T7-XBT probes were deployed at 15' intervals to a maximum depth of 760 m. Prior to deployment the XBTs were placed in a water bath for 5 minutes in order to minimise the difference between the probe's own temperature (~22ºC) and that of the sea surface (~7-5ºC).

Macroplankton/micronekton samples were collected by the Southern Ocean Group at Rhodes University (see Pakhomov et al. 2000) using a Rectangular Midwater Trawl (RMT-8) with a nominal mouth area of 8 m^2 and a mesh size of 5 mm. The trawl was towed obliquely from the bottom to the surface or between 300 and 0m. Towing speed and duration varied between 1.5 and 3.3 knots and between 5 and 20 minutes, respectively. The trawl was equipped with a Universal Underwater Unit (U^3, Robertson et al. 1981) that continuously monitored depth and temperature as well as registering the opening and closing times of the trawl. Samples were preserved in 6% buffered formalin and examined in the laboratory within three months of collection. No adjustments were made to correct for tissue loss due to formalin preservation. Entire catches were sorted and analysed for taxonomic identification, numerical abundance and wet weight biomass. The dry weight of the main macrozooplanktonic and micronektonic groups was obtained by oven-drying fixed specimens for 36 hours at 60°C.

To compare plankton communities, non-metric cluster analysis and multidimensional scaling were used in conjunction with the Bray-Curtis similarity index after log-transforming [$\log_{10}(x+1)$] species abundance data. Significance levels and sources of difference between zooplankton assemblages associated with the different group of stations were tested using the similarity analysis programs ANOSIM and SIMPER of the Plymouth Routines In Multivariate Ecological Research (PRIMER, Clarke and Warwick 1994) computer package, according to the procedure described by Field et al. (1982).

Results

During the course of the voyage the geographic position of the SAF, north of the islands, was shown to have shifted considerably. During the first transect, carried out enroute to the islands, the subsurface expression lay at 45° 45'S. Following TR_1, the SAF appeared to have shifted northwards to 45° 15'S. Although the final northern transect was occupied approximately 2 weeks after TR_3, the position of the SAF at 45° 50'S, emphasises the extent of latitudinal variability of this front (Figure 6.2).

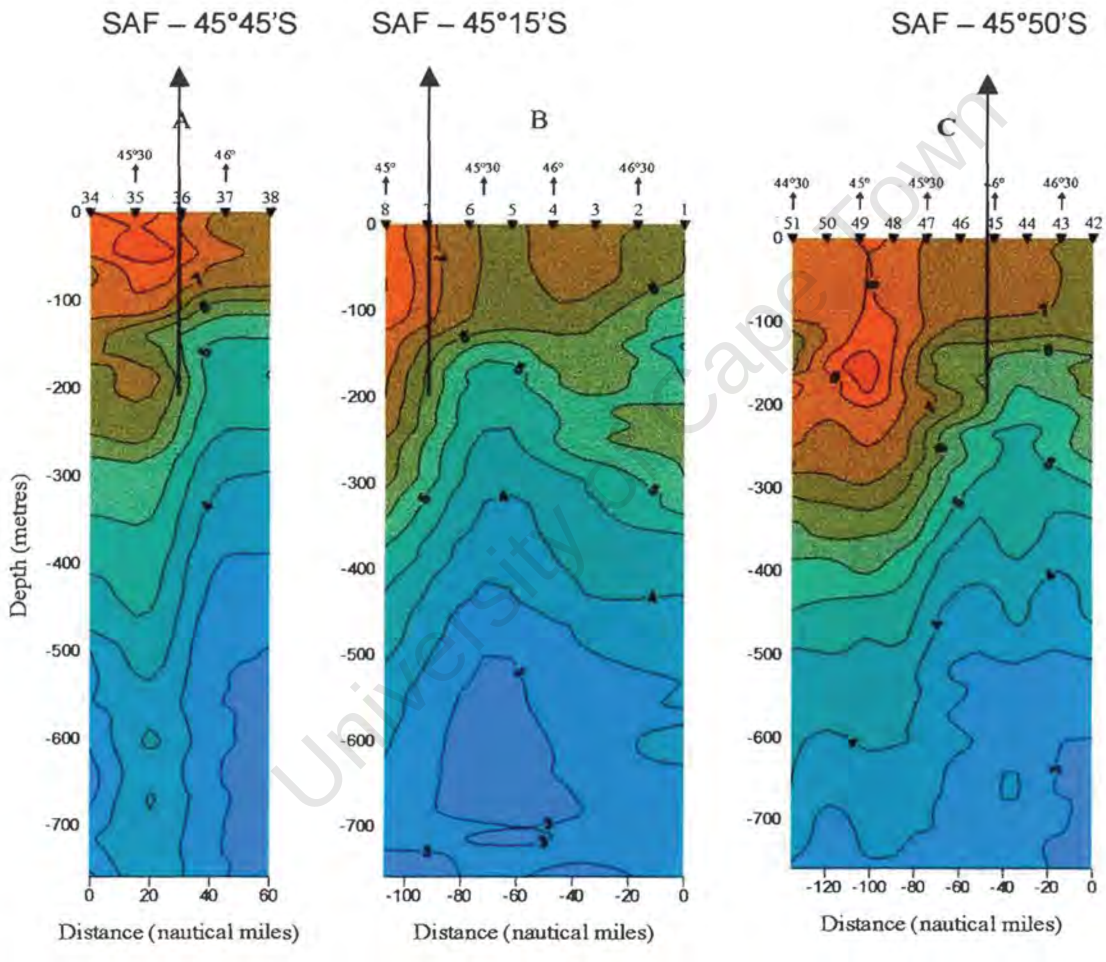


Figure 6.2. Underway XBT temperature sections occupied along 37° E to and from the Prince Edward Islands. The position of the SAF is determined by the intersection of the 6ºC isotherm and the 200 m depth line (marked as a bold line). (A) 4-5 April, (B) 15-16 April, (C) 8-9 May 1998.

The oceanic environment in the inter-island region during the surveys clearly shows an extreme variability in the flow of water between the islands. During the TR_1 survey, an eddy-type feature, centring within the inter-island channel, was evident (Figure 6.3).

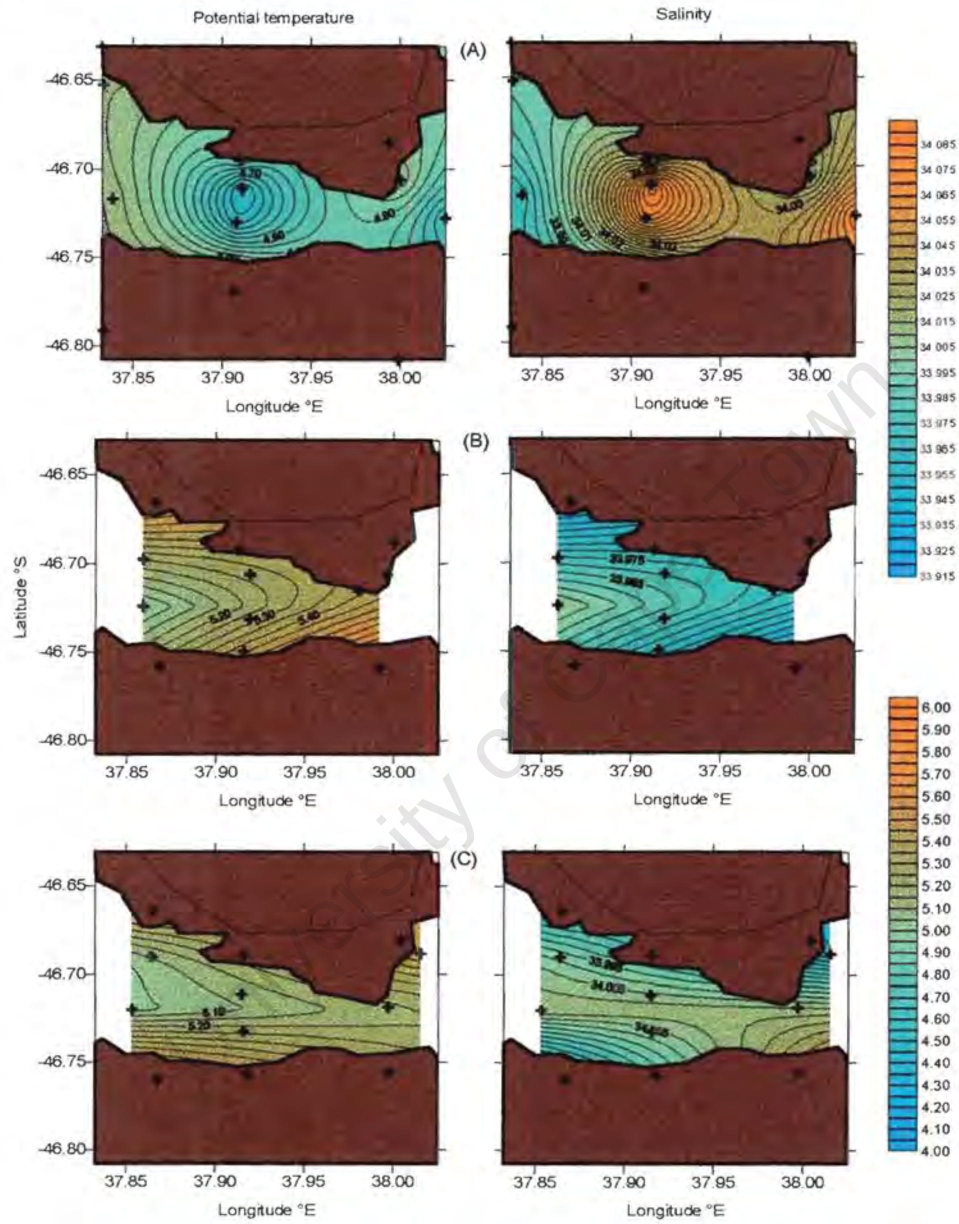


Figure 6.3. Subsurface (150 m) potential temperature and salinity distributions for each trench survey (A to C: TR_1 to TR_3), conducted over the shelf region between Prince Edward and Marion Island. The 200 m isobath is outlined, while symbols indicate the position of each hydrographic station.

Its position appears to be guided by the bathymetry, which narrows with distance east. Subsurface (150 m) physical properties of this feature are colder (4.6°C) than in the surrounding environment suggesting that this water body, indicative of modified Antarctic Surface Waters, may originate from the southern region of the Polar Frontal Zone. In the eastern corner of the trench the tail end of a similar feature can be observed. In contrast, water properties appear to become warmer (> 5ºC) and fresher (< 33.90) west of the central feature suggesting that the flow-through the shallow trench may occur in a series of pulses.

Physical properties obtained during TR_2 and 3 showed very different distribution in the inter-island region (Figure 6.3). The eddy type feature observed during TR_1 was no longer present. Instead the properties appeared to correspond to those associated with northern PFZ waters. Temperatures are higher >5°C and salinities higher 33.97 - 34.01, both increasing eastwards, in the form of a tongue, along the trench (Figure 6.3). However, along the northern and southern edges water appears to freshen < 33.96. This is also clearly evident in the surface property distributions (not shown) and may possibly be due to the runoff of freshwater from the islands.

Plankton distribution

The spatial distribution of macroplankton/micronekton densities showed different patterns during TR_1 to TR_3 surveys (Figure 6.4). During the TR_1, the highest plankton densities (both abundance and biomass) lay in close proximity to the cold eddy-type oceanographic feature. The plankton distribution patterns during the TR_2 and TR_3 showed high degree of similarity with the lowest zooplankton densities coinciding with the warm water intrusion observed between the islands (Figures. 6.3 and 6.4). Overall, the spatial distribution of zooplankton densities are not inconsistent with the mesoscale oceanographic features recorded between the islands (Figures 6.3 and 6.4).

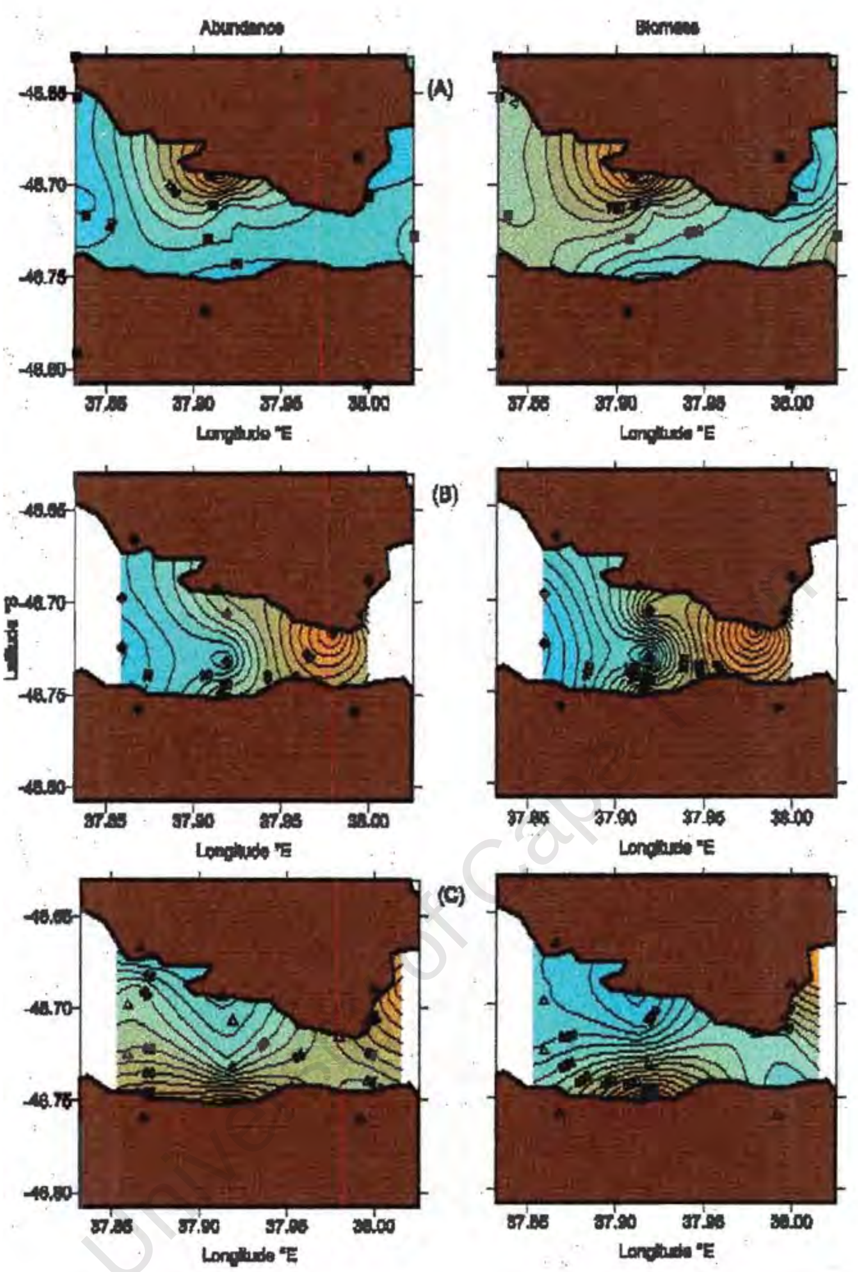


Figure 6.4: Abundance and biomass distributions during each trench survey (A to C: TR_1 to TR_3) conducted in April 1998 between the Prince Edward Islands (Pakhomov et al. 2000).

Discussion

Previous oceanographic studies, conducted in the vicinity of shallow open-ocean seamounts, have suggested that episodic events enhance biological productivity (Boehlert and Genin 1987, Genin et al. 1988, 1994, Pakhomov and Semelkina 1995, Dower and Mackas 1996). Such events would likely affect the downstream region of seamounts rather then local tertiary production (Darnitski 1984, Genin and Boehlert 1985). Allochthonous energy input from the surrounding open waters rather than localised events has been suggested as a sustaining mechanism for the rich populations of fish inhabiting seamounts (Tseitlin 1985, Pakhomov 1993). It has been hypothesised that the shallow waters above the seamount would prevent the diurnal downward migration of zooplankton (Isaac and Schwartzlose 1965). Trapped zooplankton would, therefore, become vulnerable to predation by visual predators (Kashkin 1984, Genin et al. 1988). As a development of this hypothesis, a combination of synoptically trapped eddies with a mechanical accumulation and retention of allochthonous plankton within these eddies has been demonstrated over some tropical and Antarctic seamounts (Pakhomov 1993, Pakhomov and Semelkina 1995, Mullineaux and Mills 1997). This process may be responsible for an energy input equivalent to up to ten times the regional primary production (Isaac and Schwartzlose 1965). A similar mechanism has also been hypothesised for the Prince Edward Islands ecosystem (Perissinotto and McQuaid 1992).

However, an assessment of the amount of food (mainly mesopelagic fish, shrimps and squid), which could be potentially transported through the island saddle, is substantially lower than daily food requirements of the main land-based top predators (Perissinotto and McQuaid 1992). As a consequence, the deficit has to be derived from offshore. The most recent studies have indicated that only mesozooplankton may mechanically be transported with the surface waters over the saddle between the islands (Pakhomov and Froneman in review). Large zooplankton and micronekton, through interactions between bottom topography and vertical migrations, were largely deflected around the island shelf and accumulated in the leeward side of the island group (Pakhomov and Froneman in review).

In the past, investigations have confirmed that the SAF position changes considerably in relation to the Prince Edward Islands plateau (Nagata et al. 1988, Duncombe Rae 1989a, Lutjeharms 1990). It has been suggested that the actual location of the front in the vicinity of the islands may have a profound influence on the associated biological productivity between the islands (Perissinotto and Duncombe Rae 1990, Ansorge et al. 1999, Froneman et al. 1999, Pakhomov and Froneman in review). However, it is still unclear what affect the position of the SAF would have on the flow regime and biological productivity of the environment surrounding the islands.

Temperature sections obtained during this study using XBT probes clearly demonstrated the short-term variability in the SAF position (Figure 6.2).

During a period of two weeks, the front, initially recorded at ~ 45°15' S, had shifted by a total of 35 minutes of latitude to the south. Such fluctuations are consistent with previous observations, when over a similar time scale, the SAF was shown to move southwards by up to one degree of latitude (Duncombe Rae 1989a). Based on the analogy of processes identified during previous studies (Perissinotto and Duncombe Rae 1990), the SAF location far north of the island plateau during the TR_1 could possibly result in weaker advective forces associated with the current flow in the vicinity of the islands. As a consequence, the reduced flow would most likely be conducive to the trapping of water in the inter-island region. Such trapping was deduced in several occasions during earlier studies (Perissinotto and Duncombe Rae 1990). The "funnel"-like shape of the trench marked by the 200 m isobath (Figure 6.1) may further facilitate slow moving water bodies to become trapped in the narrow constriction at the eastern end or "exit point" of the channel. Duncombe Rae (1989b) has suggested that an eddy-like feature could be "constrained to the inter-island channel". However, unlike the present study, during his survey only a single transect was conducted and consequently it was impossible to determine the spatio-temporal variability of this event.

During the TR_1 survey, the spatial patterns of oceanographic variables and plankton densities indicated that a closed circulation might have occurred between the islands. There is, however, no conclusive evidence for the long-term water trapping between the islands, which would result in the primary production build-up. Indeed, no enhancement in primary production was evident during the entire study (M. Balarin unpublished MSc thesis). It is most likely, therefore, that a parcel of cold and saline water was moving through the inter-island region during the period investigated. In contrast to TR_1 survey, during TR_2 and TR_3 surveys, the SAF had shifted southwards considerably. According to the above mentioned hypothesis (Perissinotto and Duncombe Rae 1990), in such situation advective forces would dominate between the islands, thus preventing the retention of water in the inter-island region. Distribution patterns of both the physical and biological parameters during TR_2 and TR_3 surveys demonstrated consistency with the above mentioned hypothesis.

While the exact origin of water parcels sampled during different trench surveys is unclear, their physico-chemical properties are characteristic of PFZ waters. It is not unreasonable to suggest that the position of the SAF could also have a direct influence on the modification of these waters. During occasions when the SAF is situated far to the north, the PFZ broadens considerably because the location of its southern boundary, the APF, is spatially more stable than the SAF position (Sievers and Emery 1978, Nagata et al. 1988, Belkin and Gordon 1996). Duncombe Rae (1989a) has shown that the formation of the Antarctic Intermediate Water, originating from the APF advects northwards across the PFZ. Waters in the southern part of the PFZ are therefore more characteristic of Antarctic waters (Ansorge et al. 1999). As a consequence, during the TR_1 survey, waters encountered between the islands could be advected from the PFZ proper, most likely from its southern part. Findings of 'signal' Antarctic and some subtropical species along with many typical PFZ species would further support this suggestion. By contrast, during the TR_2 and TR_3 surveys waters encountered across the trench were more influenced by the Subantarctic Surface Waters, which may be linked to the presence of the SAF close to the island plateau. No Antarctic species were found during these surveys, while Subantarctic and some subtropical species were well represented.

It is evident that during this investigation both oceanographic and biological data indicated that episodic events on a synoptic scale occur between the islands. Water parcels with the different physical characteristics coupled with different zooplankton communities most likely pulsed through the inter-island region. A good consistency between proposed pulses of water and the latitude of the SAF should also be noted. Similar short-term dynamics in a water pulsing has also been demonstrated at the Antarctic Ob and Lena seamounts (Lanin 1985, Pakhomov and Semelkina 1995). Here, Taylor columns ('hydrodynamic traps' after Lanin 1985) were established and removed from the seamount summit on the synoptic scale, which was closely correlated to the wind stress and current speeds in the vicinity of the seamounts (Lanin 1985).

As a result of the similarity in the processes operating around oceanic islands and seamounts, it is important to understand the biological consequences of such events for the Prince Edward Archipelago inter-island ecosystem. Recent studies conducted around the islands (Pakhomov and Froneman in review) have demonstrated that in contrast with the seamount scenario (Isaac and Schwartzlose 1965, Kashkin 1984, Genin et al. 1988), macrozooplankton and micronekton stocks are not transported over the inter-island region, as suggested by Perissinotto and McQuaid (1992). Indeed, during the present study the macrozooplankton community identified within the inter-island region was significantly different from the offshore community. Also, while there was little evidence for quantitative differences in macroplankton densities between the inshore surveys, zooplankton biomass at the offshore station was at least three to eight times higher than these found during the trench surveys. The biological consequences of water pulses, in regard to the amount of large plankton transported over the inter-island saddle, were, therefore during this set of surveys, negligible despite the fact that different water masses were sampled.

A few important findings of the present study should be mentioned. Firstly, numerous juveniles of the bottom dwelling shrimp Nauticaris marionis were sampled by the Southern Ocean Group (see Pakhomov et al. 1999) for the first time at the offshore region. Although it hardly surprising, this finding provides evidence that waters from the inter-island region seeded with the bottom-dwelling fauna, are swept downstream. Secondly, contributions of the two major groups of zooplankton, e.g. euphausiids (mostly Euphausia vallentini) and chaetognaths, were substantially higher between the islands compared to the offshore region (Pakhomov and Froneman in review). It is possible, therefore, that some degree of water retention, even when a flow-through regime has been established between the islands, may occur over the island's shelf. This could be possible either through the limited water trapping or through the combination of high allochthonous mesozooplankton stock input with low predation by selected birds, local benthic and fish communities within the inter-island region (Pakhomov and Froneman 1999).

It was particularly evident during the TR_1 survey because biomass of E. vallentini was 3 to 5 folds of that found during other surveys. A similar mechanism could also be demonstrated for N. marionis and hyperiid Themisto gaudichaudi (Pakhomov et al. 1999). These facts provide partial evidence for the retention mechanism similar to that observed around South Georgia and Kerguelan Archipelago (Atkinson and Peck 1990, Pakhomov 1995). Here, the front-like feature associated with the upwelling along the island slope is established at the shelf break, which minimises water exchange between shelf and oceanic regions. Thirdly, the increased contribution of gelatinous zooplankton (siphonophores, ctenophores and jellyfish) and chaetognaths to the total plankton stock above the island shelf, may indicate the close link between these water masses and mesopelagic waters of the PFZ (Pakhomov and Froneman, in review). The latest may originate from the upstream upwelling of deep-sea waters along the abruptly rising slope of the island plateau (Perissinotto et al. 2000). Finally, the shelf front-like feature mentioned above may provide an explanation for the predominance of mesoplanktonic crustaceans, chaetognaths and gelatinous groups in the inter-island zooplankton community (Pakhomov et al. 2000).

If the deep-waters are assumed to be the major source of water supply for the saddle region of the Prince Edward Islands, it would certainly favour the higher contribution of the last two groups (Pakhomov and Froneman in review). The processes at the very surface layers could only explain the enhanced contribution of small crustaceans, such as E. vallentini, N. megalops, and T. gaudichaudi. All of the above species are known to undertake marked diel vertical migrations to the top 10-20 m layers (Pakhomov and Froneman in review). Here, they would be exposed to the wind induced Ekman Drift and, as a consequence, swept over the island shelf (Perissinotto and McQuaid 1992), while the bulk of waters in the depth range of 50-200 m would most likely have to be directed around the islands. This hypothesis requires verification for future studies.

Conclusion

Results of the current study demonstrated that synoptic pulses of water may be advected through the inter-island region of the Prince Edward Islands. The location of the SAF to the north of the island plateau appeared to determine whether water trapping/retention would occur between the islands on the different time scales.

In the present study, only a short-term water trapping has been observed. However, even during the flow-through scenario, some degree of water retention over the island's shelf probably occurs. Biological consequences of such water pulses, regarding food supply to the top predators, are not yet clear but seemed to be minimal, at least during the time when the present investigation took place. Intensity of the water pulses and their importance as possible carriers of macroplankton and nekton stocks over the inter-island saddle should be further investigated, particularly including a seasonal aspect of these events. Furthermore, the position of the SAF and its effect of the inter-island environment should also be studied, especially at different temporal scales.

In order to understand fully the dynamics of the ocean circulation in the vicinity of the Prince Edward Islands and the impact this may have on the island's ecosystem, it is essential to monitor the flow of water passing the islands. The deployment of an array of current meters in the inter-island region would provide for the first time a long term, high-resolution, time series of oceanographic data necessary to study the variability of flow in this region. A proposal has been laid out for a series of current meters to be left for a period of 10 to 12 months. Hourly readings of temperature, current velocity and direction will be recorded and the data downloaded the following year after retrieval of the meters. Such an enormous high quality data set will provide for the first time vital information in studying the variability of water passing the islands on a day to day basis, as well as the impact of seasonal changes.

The last three chapters have highlighted the extreme variability of the oceanic environment in which the Prince Edward Islands lie. The SAF is shown to fluctuate considerably from week to week as well as over an annual basis. These temporal meridional shifts of the position of the SAF play a large role in the physical environment and consequently may be responsible for the extreme variability in the plankton species composition and biomass observed in the island's ecosystem. However, while the dataset presented from both mesoscale surveys (MOES 2 and MIOS 2) and the inter-island survey (MIOS 3) are of high quality, each one presents only a synoptic picture of the quasi-instantaneous circulation around the Prince Edward Islands. The extent and occurrence of these meridional shifts as well as the gradual development or decay of mesoscale eddies downstream of the islands can only be speculated. Comparative studies between altimetric and in situ data have previously been performed with GEOSAT measurements (Hallock et al. 1989, Willebrand et al. 1990). These studies have shown that satellite observation forms an accurate representation of the regional circulation, thereby enabling mesoscale features to be monitored, for the first time, over longer time periods of time.

Chapter 7

Is altimetry a good representation of the flow dynamics found at the Prince Edward Islands?

Our knowledge of ocean mesoscale dynamics has been greatly improved by the advent of satellite altimetry. In the past 5 years a new era of space oceanography has started with the launching of the European Space Agency (ESA) satellite ERS –1 in 1991 and ERS-2 in 1995 and the TOPEX/POSEIDON (T/P) mission on the 10^{th} August 1992. These two missions, flying concurrently after mid 1992, provide complementary datasets. T/P is a highly precise altimetric mission dedicated to large scale sea level monitoring (Fu et al. 1994), while ERS –1 and –2 is less precise than T/P, but its dense spatial coverage allows us to survey the mesoscale circulation of the ocean (Wakker et al. 1993). The combination of TOPEX and ERS data will allow a mapping of the surface ocean variability with a high accuracy and an improved spatial and temporal coverage (Le Traon et al. 1995).

The T/P derived dynamic topography seen in Figure 7.1 reveals the large-scale circulation of the global oceans. The sea level variability as defined here, can be considered as a statistical measure of temporal variations in major current systems, caused by either mesoscale eddy activities such as meandering, eddy shedding; displacement of current axes or fronts or changing speed and direction of currents (Park and Gamberoni 1995). Regions of high mesoscale variability were found closely correlating to either the terminal region of a major western boundary current such as the Agulhas Current, Kuroshio and Falklands Currents, Gulf Stream and the Antarctic Circumpolar Current or where the current crossed prominent bottom topography. Such areas have been identified as the Drake Passage and the Scotia Ridge in the South Atlantic, the Southwest Indian Ridge and Crozet-Kerguelan Plateaux in the South Indian ocean and the Macquarie Ridge in the Pacific (Lutjeharms and Baker 1980).

(a)

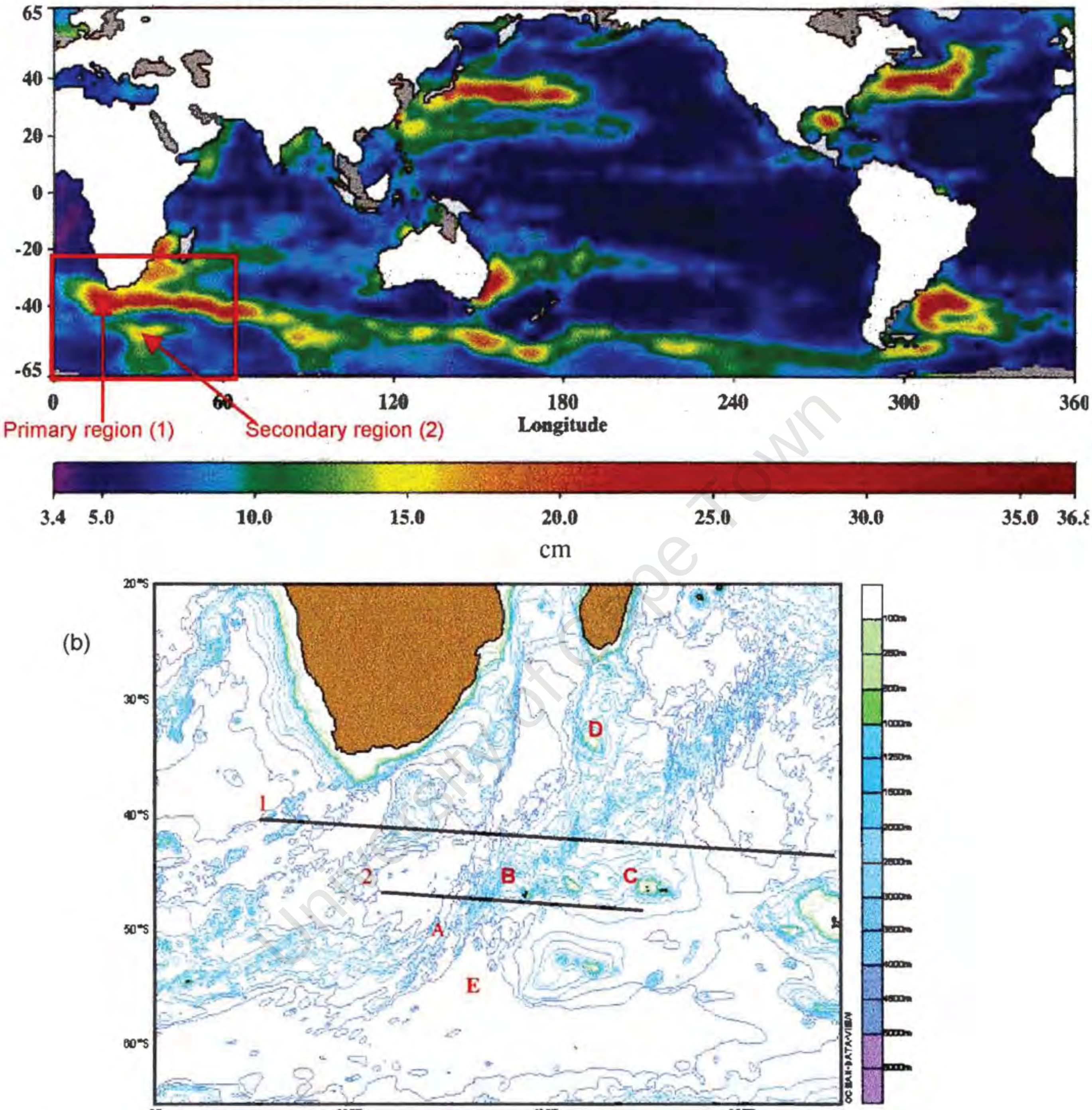


Figure 7.1: (a) RMS of sea level variability (SSHA) from TOPEX/POSEIDON cycles 2 to 51, (b) Map showing the complex bathymetry of the Southwest Indian sector of the Southern Ocean, an area outlined in Figure 7.1a. Abbreviations denote the following: A = Southwest Indian Ridge, B = Prince Edward Islands, C = Crozet Island Group, D = Madagascar Ridge, E = Enderby Basin. Boundaries marking regions of high variability (1 = Primary) and secondary variability (2 = Secondary) are marked.

An area of high eddy variability can be found in the Southwest Indian sector of the Southern Ocean (area outlined in Figures 7.1a and b). This zone (region 1) corresponds to the area of strongest currents in the Southern Ocean. It is associated with the confluence of the warm Agulhas Return Current, Subtropical Convergence and the Subantarctic Front to form one of the strongest and most intense fronts in the world - the Crozet Front (Belkin and Gordon 1996). The Agulhas Return Current formed by the retroflection of the western boundary Agulhas Current (Lutjeharms and Ansorge in review) marks the initiation of this major zone of intense baroclinicity. Here variability values reach 20-30 cm and are confined to a narrow latitudinal band 300 km in width extending 39°S to 43°S and from 20°E to 65°E (Figure 7.1a).

South of this band an area of secondary variability can also be observed at approx. 45°S (region 2) (Figure 7.1a) (Gouretski and Danilov 1994). This area again appears to correspond to regions of prominent topography associated with the Southwest Indian Ridge and Enderby Basin (Figure 7.1b) and form a triangular shape narrowing considerably to the south. The Southwest Indian sector of the Southern Ocean is characterised by numerous fracture zones, extensive ridge systems, seamounts and large shallow rises such as the Del Cano and Conrad rises; while immediately south of 48°S the topography plummets into the deep Enderby Basin (Figure 7.1b).

The Southwest Indian Ridge as seen in Figure 7.1b, lies approximately 600 km to the west of the Prince Edward Islands. Hydrographic surveys upstream of 35°E (Read and Pollard 1993, Park and Gamberoni 1997) have shown region 2 to be highly variable with the main frontal systems (SAF and APF) temporarily merging and separating in a concertina type fashion. Further studies using a Niiler Robinson model (Park and Craneguy 1999) have indicated that the position of the APF may be dependent on the velocity at which it approaches the shallow Southwest Indian Ridge. Thus during periods of high speeds the APF overshoots the ridge turning northwards while during slower periods the APF deflects southwards on encountering the deep Enderby basin lying in the lee of the ridge. In addition, Gordon et al. (1978) has shown from hydrographic measurements that the ACC fragments into a northerly and southerly branch east of the Southwest Indian ridge. The southerly branch has been observed as far south as 60°S between 30 - 50°E (Khimitsa 1976). Both these branches are represented by regions of high sea surface height variability and indicate continued eddy activity after crossing the Southwest Indian Ridge (Snaith and Robinson 1996). The easterly extension of this zone of secondary variability (region 2) appears to be restricted by the deep water channel between the Conrad

Rise and the Crozet Ridge (Figure 7.2).

The Prince Edward Islands lie immediately downstream of the Southwest Indian Ridge (Figure 7.1b) and as can be seen from Figure 7.2 are situated directly on the northern boundary of region 2. The results presented in Chapters 4 and 5 have shown the existence of mesoscale disturbances in the form of either a meandering wake or counter-rotating eddies downstream of the islands. It has been presumed that the islands themselves, which act as an obstacle to the ACC, generate these disturbances. However, it is also highly likely, as these islands lie on the northern edge of a zone of high variability, that mesoscale disturbances generated further upstream may in fact be washed into the islands region.

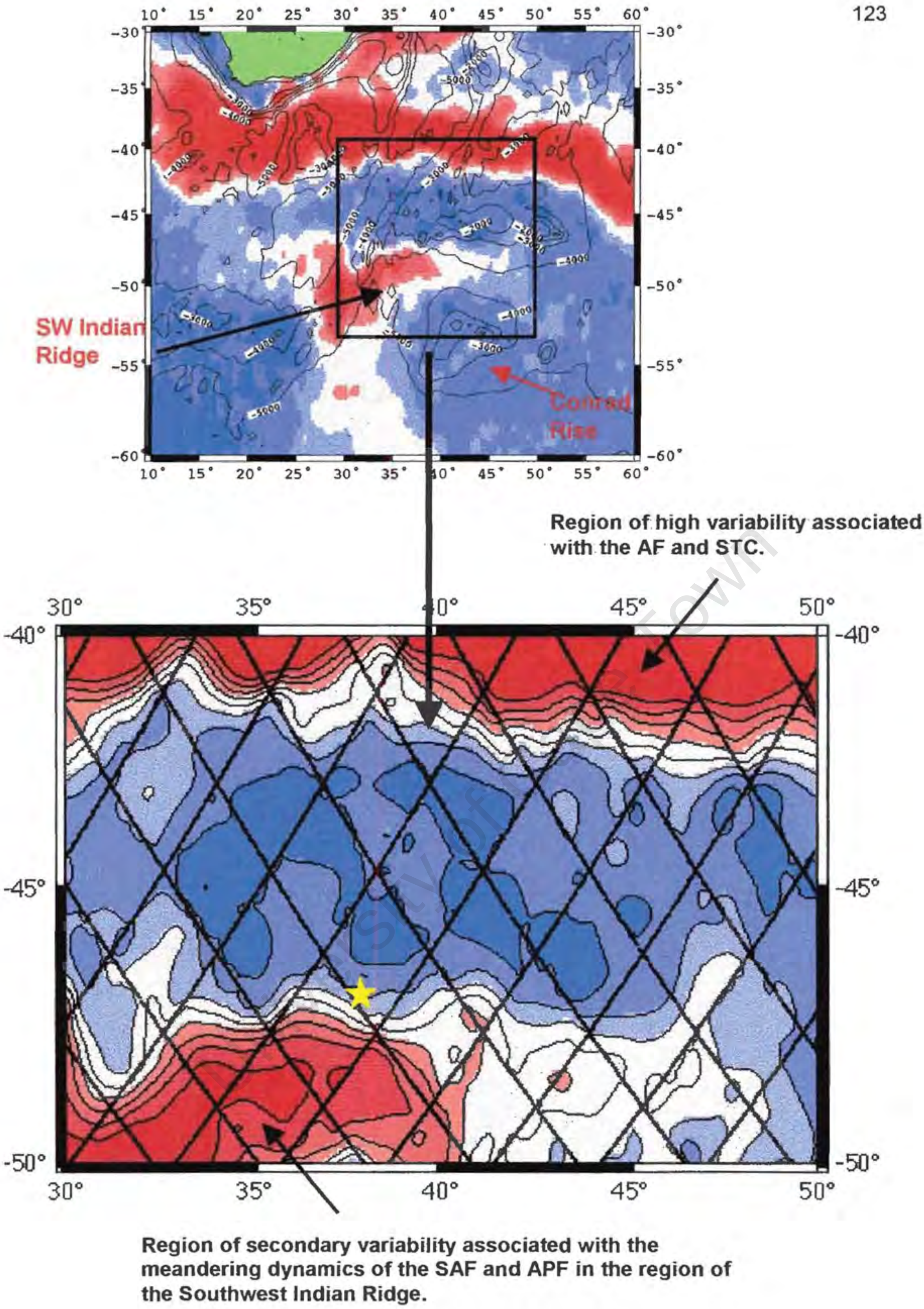


Figure 7.2: RMS Sea Surface Height Anomaly (SSHA) from blended TOPEX and ERS data (reproduced with kind permission from M. Schouten – Utrecht University, Netherlands). The yellow star denotes the geographic location of the Prince Edward Islands. TOPEX ground tracks are shown in black. Isobaths at 1000 m intervals are shown.

Our knowledge of the mesoscale circulation around the Prince Edward Islands has until now relied entirely on in situ hydrographic and biological measurements made during the MOES 2 and MIOS 2 surveys (Chapters 4 - 5). Both surveys have provided a snapshot of the flow disturbances downstream of the islands. As expected by the position of the islands in relation to the zone of variability (Figure 7.2) these disturbances vary considerably between surveys; an extensive wake observed during MOES 2 and two counter-rotating eddies during MIOS 2. Unfortunately these two datasets present only a synoptic picture of the circulation at the islands at the time of each survey and consequently the development, advection or dissipation of these features can only be speculated.

Comparative studies between altimetric and in situ data have previously been performed with GEOSAT measurements (Hallock et al. 1989, Willebrand et al. 1990). These studies have shown that satellite observations form an accurate representation of the regional circulation and it may be possible to follow the development of mesoscale features. In this chapter blended TOPEX and ERS 2 altimetry data will be evaluated with hydrographic measurements collected during the MIOS 2 survey. In doing so it will be possible to answer the following questions:

- *Is TOPEX/ERS 2 a good representation of the flow dynamics found at the Prince Edward Islands?*
- *Is it possible to track the development and/or decay of mesoscale features for an extended period of time?*
- *Are the eddies formed in the lee of the Prince Edward Islands or are they generated at the Southwest Indian Ridge and washed downstream?*

Hydrographic observations versus altimetry

Unfortunately, T/P was only launched in 1992 and therefore there is no data available to compare the MOES 2 survey. As a result, only data collected during MIOS 2 survey will be used. The ocean circulation observed during the MIOS 2 survey in April-May 1997 has been discussed in detail in Chapter 4. As seen from Figure 7.3a, the hydrographic data have shown the existence of two counter-rotating eddies downstream of the islands; a warm anticyclonic feature indicative of SASW to the south and a cold cyclonic eddy consisting of AASW to the north. SSHA obtained from TOPEX/ERS are gratifyingly well-correlated with these observations. The position of positive and negative SSHA downstream of the Prince Edward Islands forms an almost identical fit with that of the eddies (Figure 7.3b).

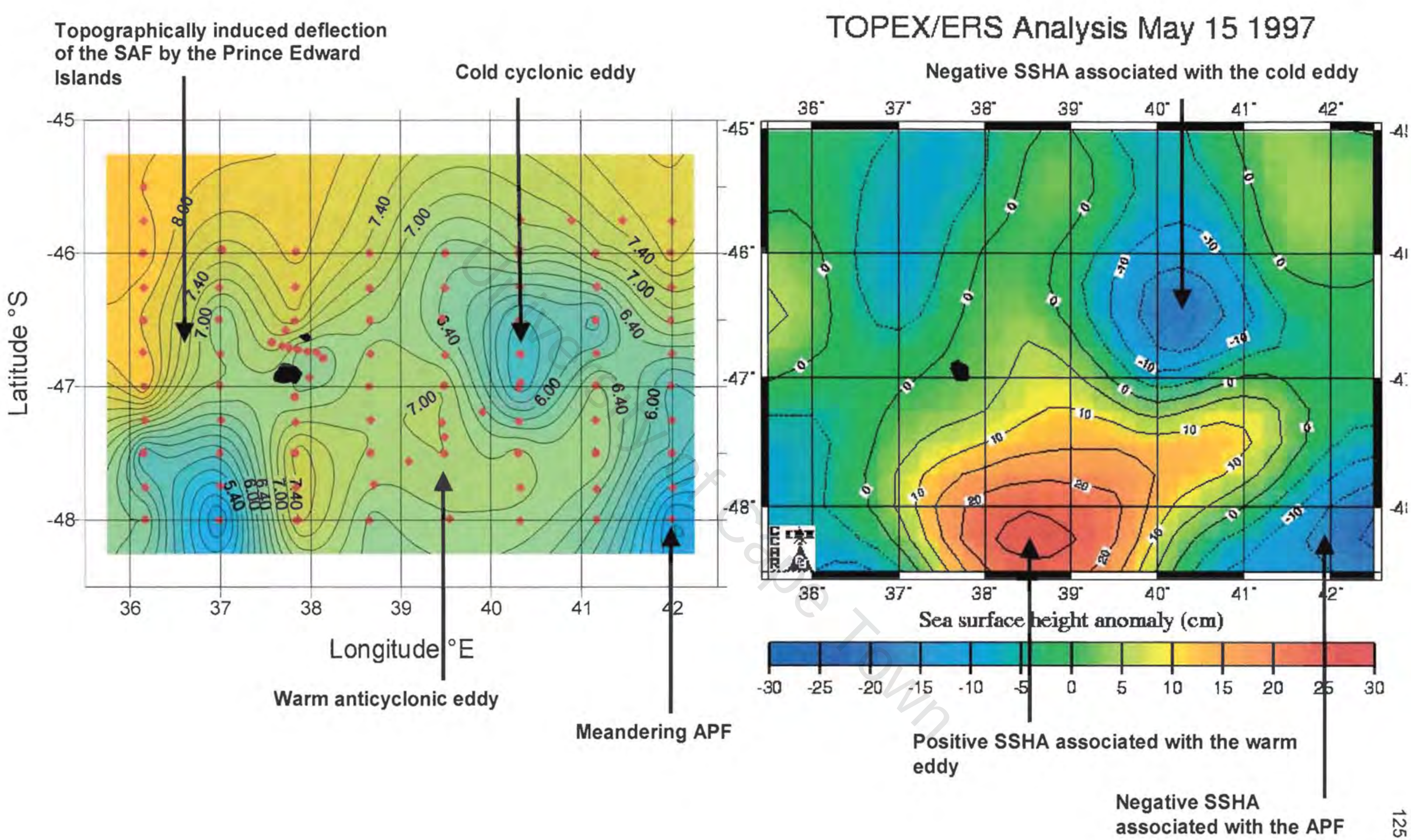


Figure 7.3: (a) Sea surface temperature distribution and (b) Blended TOPEX/ERS SSHA in cm. Disturbances generated downstream of the Prince Edward Islands in the form of a cold cyclonic and warm anticyclonic eddies are clearly visible in the altimetry, which shows a positive and negative SSHA associated with each feature.

Downstream region - Warm eddy

In order to compare both (hydrographic and altimetric) datasets it is necessary to compare sea surface temperature and sigma-theta derived from in-situ measurements with SSHA derived from the TOPEX/ERS altimetry. Temperature distributions (Figure 7.4a) have shown that the eddy appears to be wedged between the meandering surface expressions of the APF. Sea surface temperatures across this feature (from 36°E to 42°E) (Figure 7.4b) rapidly increase from 5.8 - 7.5°C as the eddy is crossed before falling again to 5.5°C as the APF is again encountered. The rapid change in temperatures in both regions is a result of the strong thermal gradient between the meandering APF and both western/eastern boundaries of the warm eddy (Figure 7.4a). The position of the warm eddy is also reflected in the sigma-theta, which decreases from 26.72 - 26.62 kg m^3 as SASW is crossed, increasing once again to 26.71 kg m^3 as cold dense AASW is once again encountered in the southeastern corner of the grid (Figure 7.4c).

SSHA show a gradual increase from west to east as the warm eddy is encountered. Negative anomalies (-5 cm) are found between 36°E and 37°E and are associated with the cold dense AASW, which has been advected northwards by the meandering dynamics of the APF (Figures 7.3 and 7.4 a - d). Further east, as the warm eddy is encountered SSHA become positive (+14 cm) as a result of the warm SASW. Horizontal distributions of surface temperatures (Figure 7.3) show that the position of this feature may be governed by the APF, which lie on either side. SSHA once again become negative (-5 cm) at the eastern extremity of the survey grid, as cold AASW associated with the meandering APF is once again encountered. This is clearly evident in the TOPEX/ERS altimetry data, which show negative anomalies immediately east and west of the warm eddy (Figure 7.3).

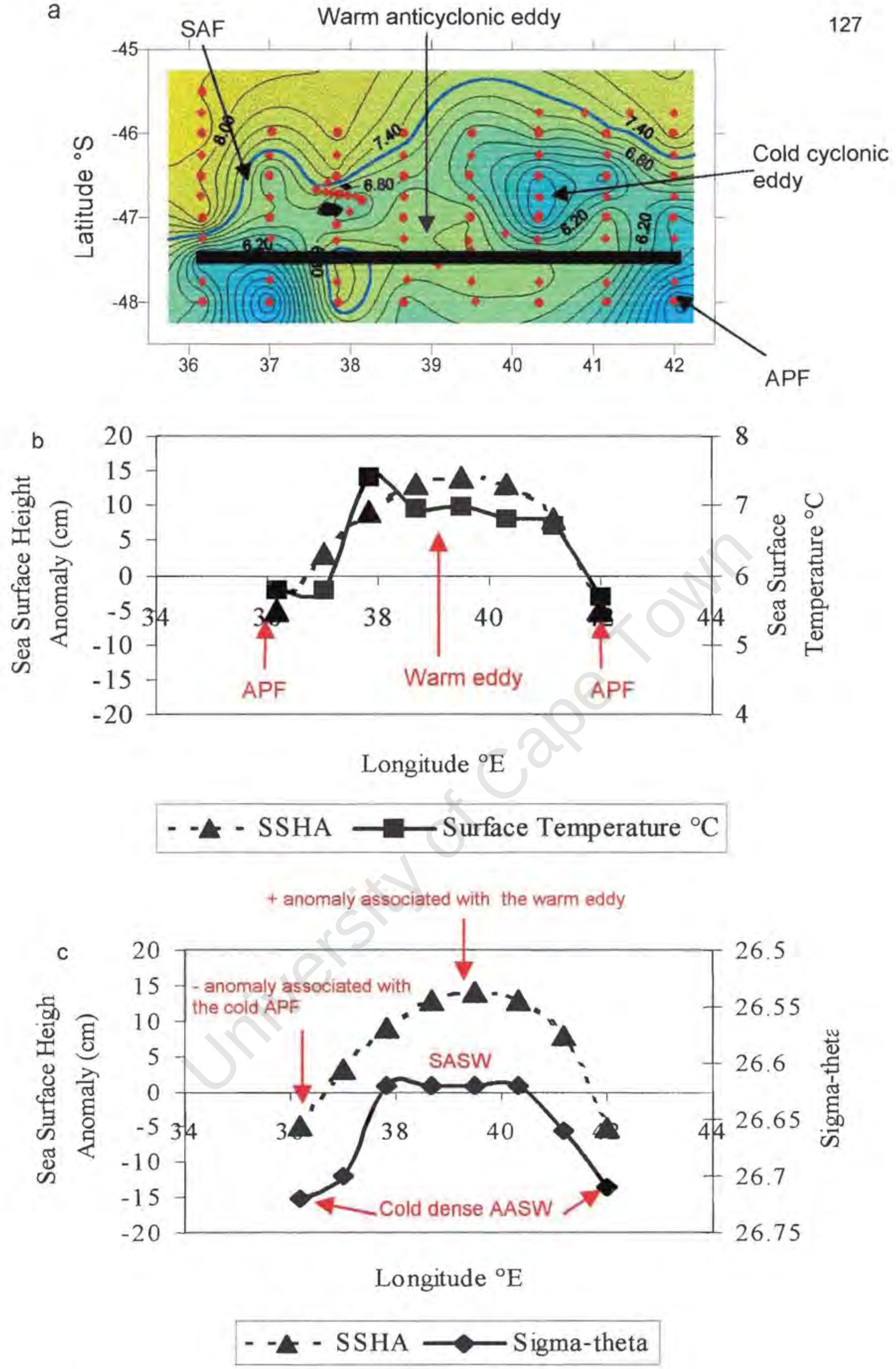


Figure 7.4: (a) Surface temperature distribution for MIOS 2, (b) Sea surface temperature and SSHA through the warm eddy, (c) Sigma-theta and SSHA through the warm eddy.

Downstream region – cold eddy

A second transect through the cold eddy has also been taken in order to further validate the TOPEX/ERS altimetry data. This transect passes from north to south through the cold cyclonic eddy centred at 46°30'S and 40°20'E and through the eastern boundary of the warm eddy (Figure 7.5a). Surface temperatures show a gradual change from 5.5°C to 7°C as both features are crossed. It is believed that the eddy has been spawned at the APF, which lies in the southeastern corner of the survey grid. Immediately north of the cold eddy, warm > 7°C temperature and low sigma-theta 26.56 kg m^3 are associated with the SAF, which lies along the northern edge of the survey grid (Figure 7.5a). As the cold eddy is crossed sigma-theta increases to 26.68 kg m^3 as colder denser AASW associated with this feature is encountered. Further south, surface temperatures increase to 6.8°C and sigma-theta decreases to 26.62 kg m^3 as warmer less dense SASW associated with the warm eddy is crossed (Figure 7.5b).

Altimetry data presents a good comparison with in situ hydrographic data. As both eddies are crossed the SSHA fluctuates from a negative anomaly (-20 cm) associated with the AASW cold eddy to a positive anomaly (+15 cm) as SASW associated with the warm eddy is encountered (Figure 7.5c).

Surprisingly the region upstream of the Prince Edward Islands exhibits low variability. Past investigations have shown that in the region upstream of the islands the latitudinal position of the SAF is highly variable. Indeed, observations discussed in the previous chapter have shown that during a period of 4 weeks the SAF meandered by up to 35' of latitude. The low SSHA values observed in Figure 7.3b may indicate that during MIOS 2 the SAF lay at its average location. In addition, these values also suggest that the northeast deflection of the SAF around the islands is in fact a permanent feature. This certainly agrees with both MIOS 2 and MOES 2 observations.

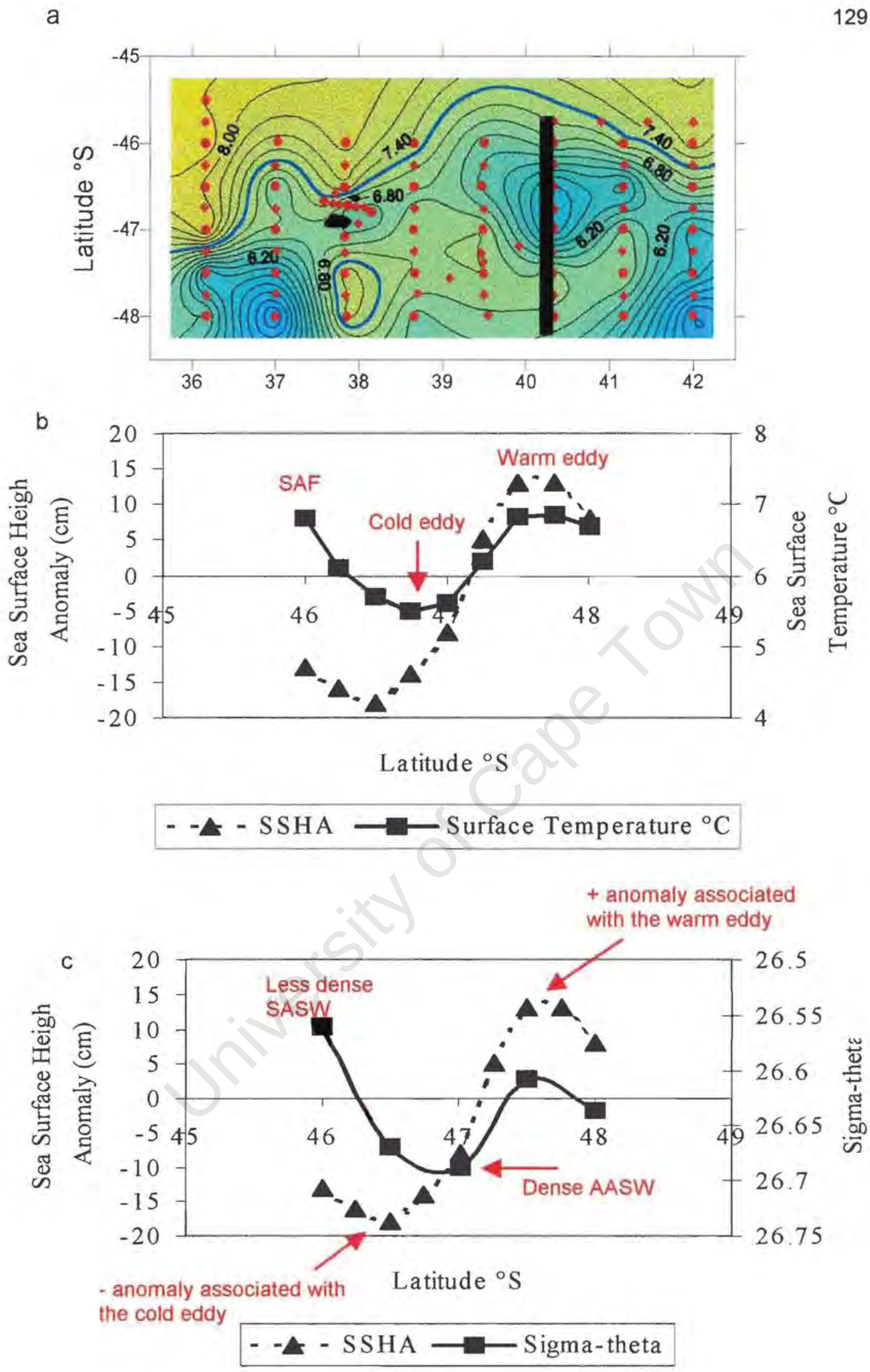


Figure 7.5: (a) Surface temperature distribution during MIOS 2, (b) sea surface temperature and SSHA through both eddies, (c) sigma-theta and SSHA through both eddies. The blue line in (a) represents the axial value of the SAF.

Since the hydrographic data therefore strongly validates the altimetric portrayal, we have confidence in using the altimetric information to study the development or advection of these eddies prior to and after the cruise. This could lead to the first clear understanding of the origin of these eddies and of the enhanced variability at the Prince Edward Islands. However the hydrographic data presents only a snapshot of the circulation at the time of the survey. Understanding the dynamics of these features is limited by the difficulty of sampling eddy properties using conventional ship-borne instruments (Snaith and Robinson 1996). It is difficult to collect high quality year round data. Measurements in the Southern Ocean are further restricted by costliness of ships time, persistently high sea states and harsh environmental conditions (Snaith and Robinson 1996). The advent of remote satellite is an important aid in the study of the Southern Ocean, allowing mesoscale features identified in hydrographic surveys to be followed over a longer period of time.

Altimetry Data

Real time ERS –2 Geophysical Data Records (RGDR), in conjunction with the higher precision TOPEX/Poseidon data, were selected for a period of 5 months between March and August 1997. These images focus on the region 45 - 49°S and 35 - 43°E in the vicinity of the Prince Edward Islands. The data was freely downloaded from the Colorado Centre for Astrodynamics Research.

http://www-ccar.colorado.edu/~realtime/global-hist-topex_ssh/

The following geophysical corrections were applied for: solid and ocean tides; wet and dry troposphere corrections based on the NOAA operational weather model; measurements from NASA's Microwave Radiometer provided estimates of the total water-vapour content in the atmosphere and an ionosphere correction from IRI90 model (Bilitza 1990). Previously ocean tides have been corrected using the Cartwright and Ray (1990) and Schwiderski (1980) models. While Gründlingh (1995) has found both models to be comparable, Park and Gamberoni (1995) instead found the two models to be contaminated by GEOSAT orbit errors due to their use of GEOSAT data (Molines et al. 1994). RGDR used in this study has been corrected using the University of Texas CSR 3.0 tide model (Ma et al. 1994). Dynamic height associated with geostrophic currents was computed using fully corrected sea surface heights referenced to the Ohio State University geoid (Rapp et al. 1991, Yi 1995). In addition, along-track "loess" filtering was used to remove orbit and environmental correction errors. A fast multigrid preconditioned Cressman analysis was used to interpolate the data to a 0.25° of longitude along-track grid (Hendricks et al. 1996).

Global sea surface height variability from the ERS-2 altimeter collinear differences have shown a large decrease in orbit and media errors following improvements in the ERS-2 processing in late 1998 (Lillibridge et al. 1997). Sea height variability associated with actual variations in currents and the effect of seasonality yield rms values of 15 – 20 cm, while values associated with ERS-2, (since improvements in 1998) are now only 5 – 10 cm higher. These combined measurements allow scientists to chart the height of the sea surface with an accuracy of less than 13 cm.

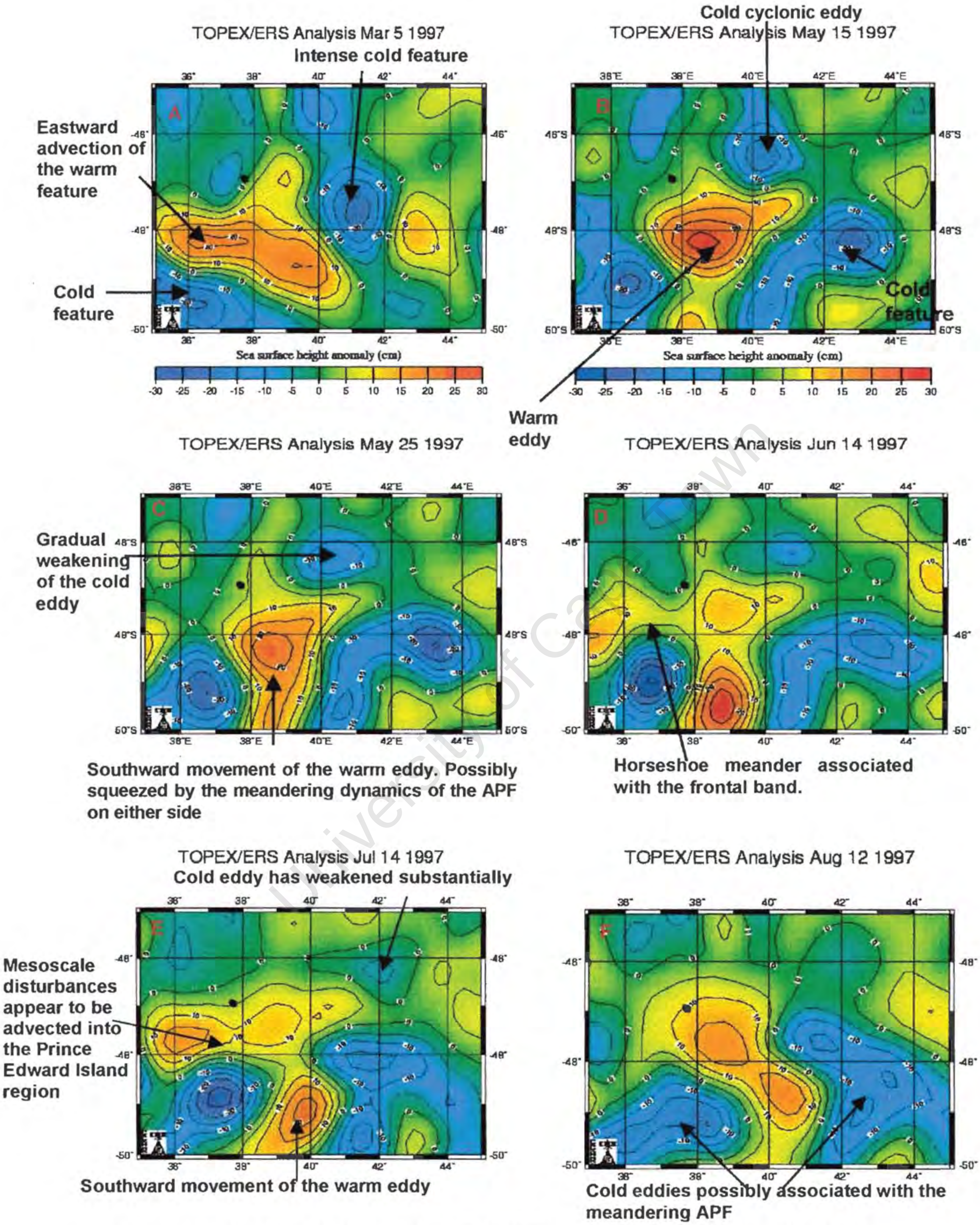
In addition, 3 independent techniques determine the satellite altitude within 10cm (Lillibridge et al. 1997):

- NASA's Laser Retroreflector Array is used with a network of 10 to 15 satellite laser ranging stations to provide the baseline tracking data for precision orbit determination and calibration of the radar altimeter bias.
- The DORIS system provides an alternate set of tracking data using microwave Doppler techniques. The system is composed of an onboard receiver and a network of 40 to 50 ground transmitting stations, providing all-weather, global tracking of the satellite.
- NASA's Global Positioning System (GPS) Demonstration Receiver demonstrates a new technique for precise, continuous tracking of the spacecraft.

Further information regarding the major source of errors determining the dynamic height have been summarised by Park and Gamberoni (1995).

- March – April 1997

Images for the months March-April 1997 have been used in order to show the development of the two eddies prior to the MIOS 2 survey. Between 5 March and 25 April 1997 a positive anomaly believed to represent the warm eddy identified in the hydrographic dataset (Figure 7.3) is seen to advect southeastwards from beyond 35°E and through the Prince Edward Island region. In addition, an intense negative anomaly centred at 47°S and 41°E representing the cold eddy observed in Figure 7.3. Between 15 May and 12 August 1997, the warm eddy appears to narrow and propagate southwards from 48°S to south of 50°S, squeezed it seems by the meandering dynamics of the APF which lie on either side (Figures 7.6 a - f). The southward advection of this eddy is consistent with findings by Gouretski and Danilov (1994), in which a warm ring was found south of the APF. In contrast the cold eddy gradually weakens until July when it can no longer be identified in the surface altimetry images (Figures 7.6 a - f). It has been suggested by Perissinotto et al. (2000) that food necessary to sustain the enormous community of top predators on the Prince Edward Islands may be washed into the island region from further upstream. Indeed biological studies conducted during MIOS 2 identified a similarity in the zooplankton groupings between the upstream region and the warm anticyclonic eddy downstream of the Prince Edward Islands (Froneman et al. 1999). Extensive research has also indicated that eddies shed from the Subantarctic front may actually be advected into the island vicinity from further afield by the ACC (Lutjeharms and Baker 1980).



Figures 7.6 a-f: TOPEX/ERS SSHA altimetry for the period March to August 1997. The advection of the mesoscale features into the Prince Edward Island region is evident.

The blended SSHA altimetry images (Figures 7.6 a - f) clearly show a horseshoe pattern associated with a region of enhanced variability extending from 35 - 40°E. It appears that positive anomalies associated with warm eddies are advected into the region from further upstream and then bend southwards along 40°E. It is not known what may cause this southward shift. Duncombe Rae (1989b) has suggested that the flow associated with the ACC in the vicinity of the Prince Edward Islands could be largely controlled by the number of seamounts located to the northwest of the island group (Figure 7.7).

Predicted topography charts drawn by Smith and Sandwell (1994) have shown that immediately east of the islands an arc of seamounts line the northern edge of a deep basin centred at 39°E. The position of this basin corresponds to the northern boundary of the warm eddy (Figure 7.7). Unfortunately, the direct impact these seamounts may have on the flow dynamics surrounding the islands has never been studied in detail.

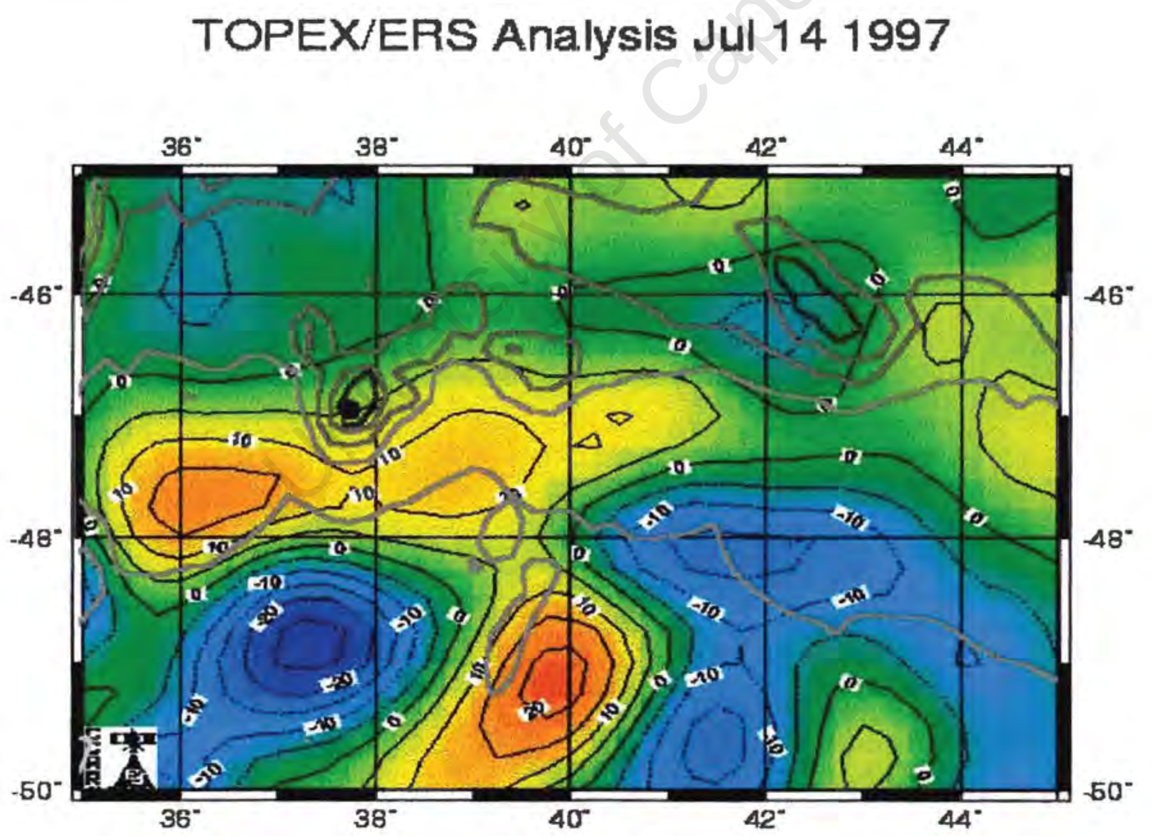


Figure 7.7: Regional bathymetry (contours every 1000 m) superimposed on SSHA for July 14 1997. The position of the positive anomaly appears to correlate with the arc of seamounts that lie to the northeast of the Prince Edward Islands.

The local dynamics of the region between the Southwest Indian Ridge and the Prince Edward Islands remain poorly understood. It has long been recognised that the Southwest Indian Ridge exerts strong topographic control over the pathways of the ACC and its associated fronts. Research carried out by Pollard and Read (2000) has shown that immediately downstream of the Southwest Indian Ridge the pathway of the ACC fragments into 7 jets flowing southeast, east and northeastwards. Hydrographic surveys upstream of 35°E (Read and Pollard 1993, Park et al. 1997) have shown that along the Southwest Indian Ridge the positions of the Subantarctic and Antarctic Polar Fronts are highly variable, often temporarily converging. Modelling results (Craneguy and Park 1999) have also indicated that the position of the APF is dependent on the velocity at which the Antarctic Circumpolar Current approaches the Southwest Indian Ridge. In addition, Gordon et al. (1978) have shown from hydrographic measurements that the ACC fragments into a northerly and southerly branch east of the Ridge. The southerly branch has been observed as far south as 60°S and between 30 - 50°E (Khimitsa 1976). Both branches represent regions of high SSH variability and indicate continued eddy activity after crossing the Southwest Indian Ridge.

The Prince Edward Islands lie along the northern boundary of this region. Altimetry data (Figure 7.2) and hydrographic data (Park and Charriaud 1997, Read and Pollard 1993, Pollard and Read 2000) have all confirmed this. Consequently, such spin-off eddies may subsequently be advected into the island vicinity.

Analysis of blended TOPEX/ERS altimetry data for the period January 1993-April 1998 reveals the formation of many positive anomalies in the vicinity of the Southwest Indian Ridge. We ascribe these anomalies to warm, anticyclonic eddies which have been detached from the ACC. Once formed these anomalies tend to drift downstream, towards the Prince Edward Islands, their trajectories on the whole following the bathymetry (Figure 7.8).

The easterly extension of this region of variability appears to be restricted to the channel that separates the Conrad Rise from the Del Cano Rise and Crozet Plateau. These results agree with recent investigations (Pollard and Read 2000). It has been shown from current measurements that approximately 69% of the volume transported by the Antarctic Circumpolar Current continues south of the Del Cano Rise. In that region the degree of variability appears to weaken considerably. Elevations of mean sea level, associated with the positive anomalies, go up sharply at about 30° E after which they exhibit a slow but not uninterrupted decline with distance eastward from 30° E (Figure 7.9).

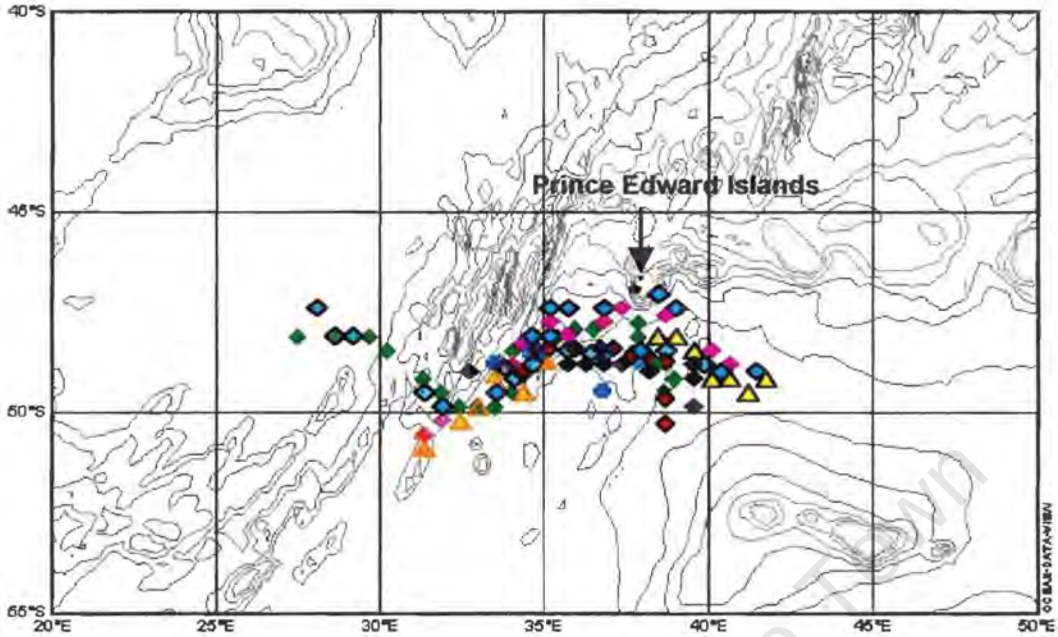


Figure 7.8: The trajectories of positive anomalies identified from TOPEX/ERS altimetry data, for the period January 1993- April 1998. It is more than likely that these are all anti-cyclonic eddies. The anomalies appear to be restricted to the channel that separates the Del Cano Rise from the Conrad Rise.

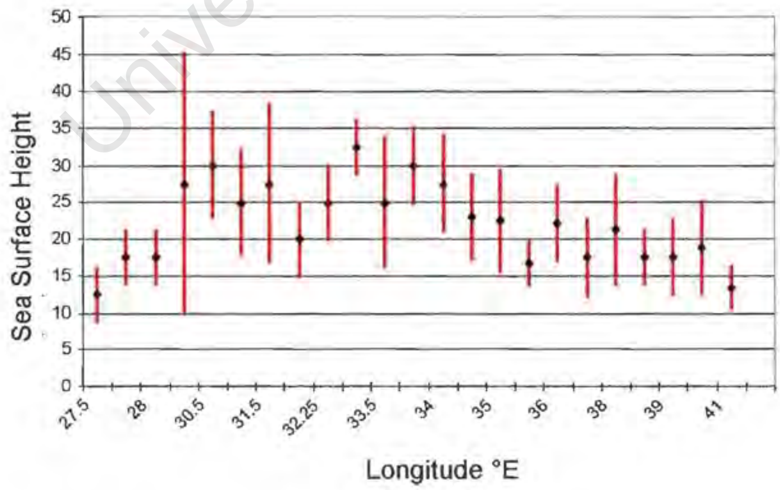


Figure 7.9: Decrease in SSH (sea surface height) elevation of positive anomalies tracked from the Southwest Indian Ridge eastward.[68] The mean height and standard deviation of the anomalies are shown.

The hydrographic validation of some of these altimetric observations as cyclonic and anticyclonic eddies gives us confidence that the analyses of the behaviour of other altimetric anomalies may indeed represent the behaviour of eddies. This has far-reaching consequences for the understanding of the oceanic environment of the Prince Edward Islands.

In conclusion, there is a good correlation between the warm and cold eddies identified in the hydrographic dataset and the positive and negative SSHA observed in the TOPEX/ERS altimetry images. TOPEX/ERS SSHA images have shown that mesoscale features may be advected into the region by the meandering dynamics of the frontal systems. Over a period of three months (May-August) the warm eddy appears to squeeze southwards possibly steered by the meandering APF, which lies on either side. In contrast, the cold eddy dissipates over a period of 2 months. A factor controlling the trajectory of these features may be the local bathymetry, which prevents the advection of these features further north (Figure 7.7).

One limitation in identifying and tracking mesoscale features with satellite altimetry data is that various assumptions need to be considered. Any change in speed or direction in the current will immediately show as a patch of enhanced variability. In addition in spite of the usefulness of altimetric data, high resolution hydrographic sections are needed to resolve their internal structure, time evolution and associated property anomalies (Gouretski and Danilov 1994).

Future investigations

The clear implication of the altimetric results so far is that the Prince Edward Island region has an enhanced eddy presence not so much because of the islands themselves, 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. If correct, this is a new concept that has to have a fundamental impact on the development of future research strategy for the region. It builds on previous work, but puts all the hypotheses on the oceanic environment of the islands - proposed before and discussed above - in a totally new perspective. How would these new concepts influence a blueprint for further studies in the region?

It is becoming clear that the MIOS 2 and MOES 2 data sets suffer from serious limitations. Their spatial coverages did not extend west of 35°E. TOPEX/ERS altimetry has now shown that mesoscale features are most probably advected downstream from a genesis region at about 50° S, 30° E. It is also clear that a proper understanding of the processes involved would require a research cruise extending from the region downstream of this spot, along the eddy corridor, to beyond the Prince Edward Islands. The manner in which these presumed eddies decay with time, the behaviour of plankton in their waters and the manner in which they are used by higher organisms all need to be investigated. The impact the Prince Edward Islands may have on the mesoscale features that pass them needs to be studied. The influence these eddies may have on the meridional exchange of water masses and the background biological productivity near the islands also needs to be further addressed.

A three-year proposal, the *"Dynamics of Eddy Impacts on Marion's Ecosystem – DEIMEC"*, to extend the MOES/MIOS-type survey upstream of the islands, guided by contemporaneous altimetry, has therefore been put forward (Figure 7.10). The aim would be to follow the advection of mesoscale features from upstream to the island vicinity and to study the direct effect these features have on the physical environment and biological productivity of the region.

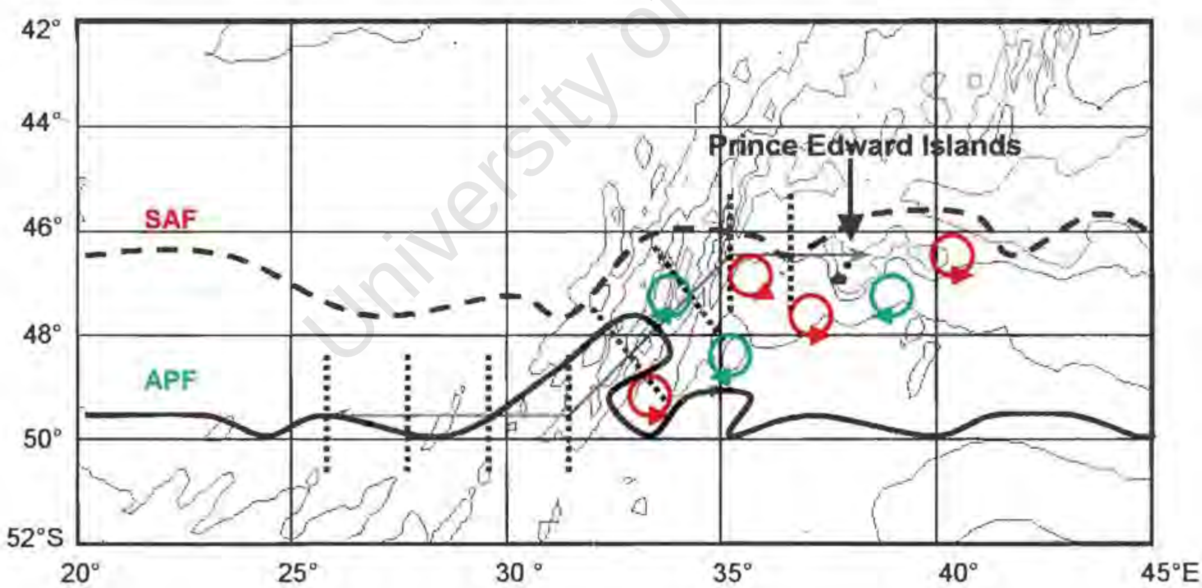


Figure 7.10: Distribution of hydrographic stations for the proposed DEIMEC 1 (Dynamics of Eddy Impacts on Marion's Ecosystem) survey in 2001.

Chapter 8

Conclusions: Future research and ideas

Extensive surveys around the Prince Edward Islands have shown them to lie sandwiched between the Subantarctic Front and the Antarctic Polar Front, in a region surrounded by numerous seamounts, fracture zones and an extensive ridge system. Further studies (Valentine and Lutjeharms 1984, Lutjeharms 1990, Nagata et al. 1988, Duncombe Rae 1989 a,b) have also shown that the SAF and APF demonstrate a high degree of latitudinal variability in this region. The shifts in the position of the fronts suggest that foreign water masses may intrude from the north or south as tongues of Subantarctic or Antarctic Surface waters (Parker 1984, Perissinotto et al. 2000). The processes resulting in the exchange of these water masses may be further enhanced by topographical influences. The Prince Edward Islands lie in a region of complex bathymetry and consequently mesoscale disturbances such as meanders and eddies may be generated.

It has been suggested (Perissinotto et al. 2000) that the geographic position of the SAF may play a crucial role in forming the macro- and mesoscale oceanographic conditions surrounding the islands. The presence of >5 million birds and seals on the islands (Williams et al. 1979), raises the important question of whether the islands create their own localised enhanced biological ecosystem, the so called "Island Mass Effect" (Doty and Oguri 1956). Alternatively biological productivity of the ambient waters may instead be affected by changes in the oceanic environment due to the meandering dynamics of the SAF and APF (Perissinotto et al. 2000).

In an attempt to explain the cause of this enhanced productivity various hypotheses have been put forward. These are:

- Upwelling of Antarctic Surface water in the lee of the islands (Allanson et al. 1985)
- Generation of vortex fields resembling a von Kàrmàn street in the lee of the islands (Allanson et al. 1985)
- Occurrence of a Taylor column over the island shelf (Perissinotto and Duncombe Rae 1990)

- Finally it has been recently suggested by (Perissinotto et al. 2000) that food necessary to sustain such an enormous community might also be washed into the island region from further upstream.

Although these hypotheses are well established, our understanding of the processes and the mechanisms involved is poor. To try and resolve this it has been essential to concentrate on the variability and dynamics of the SAF and to study in detail its influence on the oceanographic environment and the background productivity surrounding the Prince Edward Islands. Analysis of hydrographic data collected during a number of surveys to the islands (MOES 2 and MIOS 2) has enabled the following key questions to be addressed.

1. **What is the oceanographic environment surrounding the Prince Edward Islands?**
2. **What water masses can be found in the ocean surrounding the Prince Edward Islands?**

The oceanic environment upstream of the Prince Edward Islands during the MOES 2 survey showed the location of the SAF and its associated flow around the northern edge of the islands. Three grid lines occupied upstream show the surface expression of the SAF to lie further south at 46°38'S, 35°48'E during the first transect, but as a result of the shallow plateau on which the islands lie, its path is deflected northwards to lie closer to the islands at 45°55'S, 37°55'E. Upstream of the islands the SAF appears to be zonal, the meridional decrease in surface temperatures and densities is gradual and uniform ranging from 7.5°C and 26.42 kg m^3 at 46°S, to 5.5°C and 26.60 kg m^3 at 48°S. The APF was not encountered in the upstream region at all, instead an eddy consisting of cold ~2°C and fresh < 33.9 water, indicative of Antarctic Surface Water was observed immediately south of the islands.

Downstream of the islands the surface position of the front remained within a narrow band, lying at approximately 46°S, while by contrast the subsurface expression of the SAF exhibited a distinct broad wake. The 6°C isotherm, marking the subsurface axis of the SAF (Lutjeharms and Foldvik 1986) shows this wake to be broad, extending between 46°10' S and 47°30' S. The dimensions of the wake increase with distance downstream, its wavelength extending 150 km (Perissinotto et al. 2000). As a consequence, warm > 7°C SASW from north of the SAF was advected southwards across the PFZ, while cooler < 7°C waters, which had been modified in the transitional band of the PFZ were advected northwards. However, in comparison to transects upstream of the islands, downstream waters remain warmer (~1°C) with surface temperatures ranging across the PFZ from 7.8°C to 6.2°C. In this region a deep (> 1500 m), warm eddy was also found. Surface temperatures and salinities within this eddy are higher than the surrounding waters, > 7.5°C and > 33.8, suggesting its source may be north of the SAF. In the southern region of the PFZ, a tongue of cold < 5°C and fresh 33.7 water, characteristic of Antarctic Surface Water, was also observed.

In comparison, the oceanic environment surrounding the Prince Edward Islands during the MIOS 2 survey proved to be very different. Upstream of the islands the SAF was found to lie much further south at 47°20'S where it formed an intensive surface frontal feature combined with the APF. Surface temperatures and salinities across this front ranged from 8°C to 5.8°C and from 33.94 to 34 and fall into the band of values given by Holliday and Read (1998). It is believed that only the surface expression of the APF was encountered in this region as the temperature minimum 2°C associated with the subsurface APF was not observed. Extensive observations by Lutjeharms and Valentine (1984) have shown that in the region south of Africa the surface and subsurface expressions of the APF rarely coincide. Closer to the islands the frontal feature appears to branch resulting in a sharp northward deflection of the SAF, while the APF meanders southwards. The SAF continues its northward deflection, steered by the shallow topography, where it lies along the northern edge of the islands at 46°15'S.

Downstream of the islands, subsurface isotherms (6°C) and isopycnals (26.80 kg m^3) representing the axis of the SAF, show the front to remain predominantly zonal, flowing through the deep > 2500 m channel, which separates the Gallieni Knoll and the Del Caño Rise. It is possible that the northern position of the SAF, in contrast to the meandering dynamics observed during MOES 2, maybe due to the existence of two contra-rotating eddies, forcing it to bulge northwards. A cold cyclonic (< 6°C, 33.85) eddy consisting of Antarctic Surface Water lies in the north of the survey grid. While to the south and extending the entire length of the survey, an anti-cyclonic eddy can be found. It appears to have been spawned from north of the SAF, its surface chemical properties are characteristically SASW (> 6.8°C, > 33.95). This eddy also appears to be wedged between the meandering bands of the APF. Sharp thermal gradients (7.4 - 4.8°C between 37 - 38°E and 6.6 - 4.8°C between 41 - 42°E) on either side of the warm eddy are observed throughout the water column. Both eddies appear to be insular features extending to depths of 1500 m. The exact genesis of both eddies is unknown, however it is possible that they have been generated from instabilities within the meandering SAF and APF.

3. **What impact do the Prince Edward Islands have on the flow of the Antarctic Circumpolar Current?**

Geostrophic velocities during MOES 2 exceeded 26 cms^{-1} (ref 1500 db) at the high-speed core of the SAF. Downstream, geostrophic velocities show strong (> 16 $cm\ s^{-1}$ - ref 1500 db) alternating westward and eastward flows around pools of weaker currents (5 $cm\ s^{-1}$ - ref 1500 db) indicative of a meander within the PFZ. In comparison, results obtained during MIOS 2 showed the SAF to exceed 25 $cm\ s^{-1}$ – (ref 1500 db) however, closer to the islands the SAF and APF appeared to branch, reducing speeds substantially to 11 $cm\ s^{-1}$. Immediately east of the islands geostrophic velocities (6 - 9 $cm\ s^{-1}$) were anticyclonic associated with the warm eddy, while a cyclonic motion existed in the northeastern corner associated with the cold eddy. The strongest surface flow > 30 cms^{-1} observed in the whole survey was associated with the coupling between the warm and cold eddy. Here a strong thermal gradient with temperature ranges from 4.5 - 6.5°C was seen in the subsurface layer as well as extending throughout the water column. The APF was encountered in the southeastern corner of the survey exhibiting speeds of 24 $cm\ s^{-1}$ (ref 1500 db).

The oceanic environment in the leeward side of the Prince Edward Islands thus represents an area of enhanced meridional exchange of physico-chemical properties, resulting from the interaction between the ACC and the complex bottom topography associated with the Prince Edward Islands. It is well documented that zooplankton community structures are strongly determined by the prevailing oceanographic regime (Pakhomov and Froneman 1999) and consequently would also reflect the variability of this region. It would therefore be interesting to study the effect spatio-temporal variability has on the distribution and community structure of the biological zooplankton and to see whether there is a strong physical-biological coupling in the waters surrounding the Prince Edward Islands.

4. **What impact does the physical environment have on the distribution and community structure of the zooplankton?**

5. **Does the species distribution reflect the variability of the oceanographic regime around the islands from one year to the next?**

Although the oceanographic regime differed between the two surveys, the effect on the zooplankton community appeared to be similar. Generally, zooplankton assemblages within the PFZ were characterised by species of both Subantarctic and Antarctic origin, reflecting the meridional exchange of water within the region. In the upstream region during MOES 2 a distinct grouping of stations designated the Polar Front Zone Group were identified. Within this grouping of stations, typical Subantarctic copepod species numerically dominated suggesting that these stations were occupied within the PFZ water proper. This is supported by the oceanographic data, which showed the gradual transition from Subantarctic Surface to Antarctic Surface Waters. Downstream of the Prince Edward Islands and associated with this wake and the advection of water masses from outside the PFZ, a distinct zooplankton grouping was identified. Within these waters, zooplankton species composition was comprised of typical Subantarctic and Antarctic species. The presence of both species from north and south of the PFZ suggest that Subantarctic and Antarctic waters were being exchanged within the meander.

The absence of a distinct zooplankton grouping associated with the cold-core eddy downstream of the islands during MIOS 2 is surprising as it is well documented that eddies have specific planktonic communities associated with them (Froneman et al. 1995a,b). Analysis of the zooplankton community within the region of the eddy, however, showed the presence of both Antarctic and zooplankton species. These data suggest that the warmer Subantarctic species were rapidly being entrained within the cold-core eddy made up of Antarctic surface waters. It is not unreasonable to suggest that the close proximity of the northern boundary of the eddy to the SAF may have facilitated the transfer of zooplankton species between the two features. Numerical analysis for the warm eddy did not identify a distinct zooplankton community associated with this feature either. Here, it appears that Antarctic zooplankton from a colder environment, possibly the APF south of the islands, were being entrained into the eddy. Indeed, directly south of the islands a strong thermal front exists between the APF and the western edge of the warm eddy.

The region downstream of the islands can be characterised as an area of high complexity. Warm and cold mesoscale features, which appeared to have been generated by the meandering frontal systems to the north and south of the islands, facilitate the transfer of water and plankton assemblages between the various water masses downstream of the islands.

The close proximity of the SAF to the northern edge of the Prince Edward Islands may possibly result in the islands representing a flow-through system with little or no water trapping over the island shelf. Such a system would enable the rapid advection of zooplankton species from upstream of the islands to the downstream region. However, our understanding of this flow-through system remains poor and as a consequence it is not known how often or how long this system may last. Analyses from CTD data collected during 6 cruises in the 1980s showed that anticyclonic eddies were present over the island shelf during 4 occasions (Perissinotto and Duncombe Rae 1990). The retention of water over the island shelf has been a topic of interest over a number of years with the belief that eddies generated upstream or over the island shelf may be advected downstream becoming the foci of nutrient sequestration and enhanced biological productivity. Transport of the ACC is concentrated at the high-speed cores of the SAF and APF. Where the SAF lies far to the north, the PFZ broadens and advective forces, associated with the PFZ are weak. As a consequence trapped eddies are observed over the shelf separating Prince Edward and Marion Island (Perissinotto and Duncombe Rae 1990). By contrast, when the SAF lies in close proximity to the islands, advecting forces, associated with the strong frontal flow, prevail and eddies no longer present in the inter-island region are observed further downstream (Perissinotto et al. 2000). Thus the geographic position of the SAF in relation to the Prince Edward Islands may largely control the dynamics of the productivity in the vicinity of the islands.

6. Is there evidence of synoptic pulsing through the islands?

During both surveys the SAF was observed in close proximity to the northern edge of the islands and water was not retained over the island shelf. However, a following cruise in the austral autumn 1998 revealed that over a period of 4 weeks, the SAF fluctuated considerably from 45°50'S to 45°15'S.
The location of the SAF to the north of the island plateau appeared to determine whether water trapping/retention would occur between the islands on the different

time scales. During this study short-term water trapping was observed when the SAF remained at its most northern position. However, even during the flow-through scenario (when the SAF was at its most southern position) some degree of water retention over the island's shelf occurred, indicating that the flow of water through the inter-island region may be pulsive. Biological consequences of such water pulsing, regarding the food supplied to the top predators, is not yet clear but seem to be minimal, at least during the time when the present investigation took place. Intensity of such pulses and their importance as possible carriers of macroplankton and nekton stocks over the inter-island saddle should be further investigated, particularly including a seasonal aspect of these events.

Data from over 30 crossings of the SAF in the upstream region of the Prince Edward Islands, despite substantial temporal variability indicate a southward migration in the geographic position of this front (Pakhomov et al. in review). This shift in location is consistent with changes in the composition of zooplankton around the Prince Edward Islands. Subantarctic species commonly found north of the SAF have increased by 20% suggesting warmer-water zooplankton are protruding into the PFZ more frequently. However the impact this shift may have on the inter-island region is still not known. It is expected that the southward shift in the position of the SAF would result in a more or less permanent flow-through regime in the inter-island region. This would have profound implications to the oceanic environment downstream of the islands as well as the zooplankton community structure and distribution. Recent studies (Pakhomov et al. in review) have now indicated that the population of the top predators may be declining, suggesting that stocks of large plankton necessary for their survival may be pulsive.

In order to understand fully the dynamics of the ocean circulation in the vicinity of the Prince Edward Islands and the impact this may have on the island's ecosystem, it is essential to monitor the flow of water passing the islands. The deployment of an array of current meters in the inter-island region would provide for a long term, high-resolution, time series of oceanographic data necessary to study the variability of flow in this region. A proposal has been laid out for a series of current meters to be left for a period of 10 to 12 months. Hourly readings of temperature, current velocity and direction will be recorded and the data downloaded the following year after retrieval of the meters. Such high quality data will provide vital information in studying the variability of water passing the islands on a day to day basis, as well as the impact of seasonal changes.

Our knowledge of the mesoscale circulation around the Prince Edward Islands has until now relied entirely on in situ hydrographic and biological measurements made during the MOES 2 and MIOS 2 surveys (Chapters 4 - 6). Both surveys have provided a snapshot of the flow disturbances downstream of the islands. As expected by the position of the islands in relation to the zone of variability these disturbances vary considerably between surveys; an extensive wake observed during MOES 2, while during MIOS 2 two contra-rotating eddies were observed. Unfortunately these two datasets present only a synoptic picture of the circulation at the islands at the time of each survey and consequently the development, advection or dissipation of these features can only be speculated. Comparative studies between altimetric and in situ data have previously been performed with GEOSAT measurements (Hallock et al. 1989, Willebrand et al. 1990). These studies have shown that satellite observation forms an accurate representation of the regional circulation and it may be possible to follow the development of mesoscale features.

7. **Is altimetry a good representation of the flow dynamics found at the Prince Edward Islands?**

8. **Is it possible to track the development and/or decay of mesoscale features for an extended period of time?**

There is a good correlation between the warm and cold eddies identified in the hydrographic dataset and the positive and negative SSHA observed in the TOPEX/ERS altimetry images. Images for the months March-April 1997, prior to the MIOS 2 survey show the southeastward advection of a positive anomaly believed to represent the warm eddy from beyond 35°E and into the Prince Edward Island region. Further confirmation is given by Froneman et al. (1999) who have identified a similarity in the zooplankton groupings between the upstream region and the warm anticyclonic eddy downstream of the Prince Edward Islands.

In addition, an intense negative anomaly centred at 47°S, 41°E represents the cold eddy. Following the survey the warm eddy appears to narrow and propagate southwards from 48°S to south of 50°S squeezed it seems by the meandering dynamics of the APF, which lie on either side. In contrast the cold eddy gradually weakens until July when it can no longer be identified in the surface altimetry images. A factor controlling the trajectory of these features may be the local bathymetry, which may prevent the northward movement of these features.

The question of whether the Prince Edward Islands generate their own disturbances downstream, or alternatively, as the TOPEX/ERS data suggest, that they lie at the tail end of a region of high variability needs to be further addressed. Extensive research has indicated that eddies shed from the Subantarctic Front may actually be advected into the island vicinity from further afield by the ACC (Lutjeharms and Baker 1980).

The SAF remains the least studied frontal system in the Southern Ocean (Pakhomov and Froneman 1999). Despite the advent of extensive multidisciplinary surveys undertaken during WOCE and JGOFS programs, very little is known of the nature and behaviour of the SAF between the Southwest Indian Ridge and the Prince Edward Islands. A limitation of the MIOS 2 and MOES 2 datasets is that their spatial coverage does not extend west of 35°E. Single line hydrographic surveys (Read and Pollard 1993, Park and Charriaud 1997) have shown the highly-time-variable flow regime close to the Southwest Indian Ridge.

Further studies by Pollard and Read (2000) have indicated that immediately downstream of the Southwest Indian Ridge the ACC fragments into 7 separate jets. The question of whether the Prince Edward islands create their own disturbance or whether they lie at the "tail end" of this region of variability still remains unresolved. Analysis of blended TOPEX/ERS altimetry data for the period January 1993-April 1998 reveals the formation of many positive anomalies in the vicinity of the Southwest Indian Ridge. We ascribe these anomalies to warm, anticyclonic eddies which have been detached from the ACC. Once formed these anomalies tend to drift downstream, towards the Prince Edward Islands, their trajectories on the whole following the bathymetry. The position of the islands directly in the path of the ACC would certainly play a role in the changing of the dynamics of the current flow, but how great a role is it? Extensive research (Lutjeharms and Baker 1980) have indicated that the SAF is characterised by the genesis of spinout eddies that may actually be advected into the island vicinity from further afield by the ACC (Lutjeharms and Baker 1980, Gouretski and Danilov 1994). In addition satellite altimeter studies have also shown the Prince Edward Islands to lie on the northern edge of a region of permanently enhanced variability. So it is perhaps not unreasonable that disturbances are found immediately downstream of the islands, and given their position in relation to the zone of enhanced variability one would certainly expect these disturbances to differ from one survey to the next.

The meridional shifts of the position of the SAF have substantial biological implications for the plankton species composition and biomass food available to the top predators, highlighting the close interaction between the oceanographic regime and the islands ecosystem. In order fully to understand the degree of impact the Prince Edward Islands may have on the position of the SAF and its influence on background productivity, a detailed upstream survey between the Prince Edward Islands and the Southwest Indian Ridge needs to be undertaken.

Chapter 10

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