

**THE HYDROGRAPHY AND
DYNAMICS OF RINGS AND EDDIES
OF THE AGULHAS
RETROFLECTION
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ABSTRACT

The Agulhas Retroflection south of Africa is a dynamic region from which mesoscale rings and eddies are shed. Hydrographic data collected simultaneously during two dedicated research cruises in the Agulhas Retroflection region in February - March 1987 are analyzed in conjunction with satellite data (Thermal Infrared Imagery and *Geosat* Altimetry). An unusual and possibly atypical situation is documented where a total of six Agulhas rings and eddies were present in the Retroflection region. Each of the six vortices exhibited characteristics specific to their age and location within the Retroflection region.

Three studies are described in this thesis. The first study is concerned with the general hydrography and dynamics of the Agulhas Retroflection.

- (i) The trapped volume of the six vortices extend from the surface to intermediate depths (1200 db), with ring and eddy transports ranging from 4,4 - 15,8 Sv ($1 \text{ Sv} = 1 \times 10^6 \text{ m}^3 \cdot \text{s}^{-1}$). A volume transport of around 11,5 - 18,48 Sv is estimated to enter the South Atlantic in the form of Agulhas rings and eddies per annum, assuming 5 - 8 rings and eddies per year.
- (ii) The southwest flux of Agulhas water into the Retroflection is $61 \times 10^6 \text{ m}^3 \cdot \text{s}^{-1}$ (relative to 1500 db), feeding the Retroflection at a western limit of around 17°E . The Agulhas Return Current flows eastward near 40°S , executing a "S-shaped" meander over the western edge of the Agulhas Plateau after interacting with an Agulhas eddy along its southern margin (42°S , 24°E).
- (iii) An important contribution to the total surface velocities within the Retroflection region is attributed to a barotropic signal. Around 56% and 40% of the total surface velocity (referenced to 1500 db) is identified as a barotropic signal within the surface flow of the Agulhas input and vortices respectively.

The second study is concerned with the identification of water masses observed within the mesoscale features of the Agulhas Retroflection region.

- (i) Detail of the core characteristics of all the waters masses and the property extrema associated with them are comprehensively identified for the first time.

- (ii) Saline surface waters ($S > 35,63$) are identified as Modified Subtropical Surface Water (MSSW), and are evident in all but one of the six Agulhas rings and eddies. These boosted salinities are a consequence of evaporative processing within the isolated vortices of the Retroflexion region.
- (iii) Intrusions of thick stads (200 - 300 m) of Red Sea Water (RSW) into the Retroflexion region are identified within the dynamic core of the Agulhas Current, concentrated on the $\sigma_t = 27,32$ density surface. None of the six vortices exhibit pure RSW remnants within their cores, yet all (except the western-most eddy) exhibit a blend of intermediate water which results from mixing of fresh Antarctic Intermediate Water (AAIW) with the more saline RSW.

Thirdly, the modification of Agulhas water within both the vortices and the immediate surroundings is investigated using an analysis of heat and salt anomalies.

- (i) Heat and salt anomaly calculations indicate that the Agulhas Current introduces Indian Ocean water masses into the Retroflexion region at density levels shallower than $\text{Sigma-}\Theta = 27,4$ (1000 - 1400 db). At greater depths heat and salt anomalies are weakly negative and approach zero at $\text{Sigma-}\Theta \geq 27,5$ (1200 - 1500 db), indicative of the Atlantic and Circumpolar Deep waters. Weakly positive salt anomalies are evident in the surface waters ($\text{Sigma-}\Theta = 24,2$ to $26,0$) of five of the six Agulhas rings and eddies, confirming the processes of salinity boosting caused by evaporation.
- (ii) The relative age of the six rings and eddies are estimated from heat : salt anomaly ratios. The results reveal a general trend with those vortices furthest from the Retroflexion exhibiting the lowest heat : salt ratios, indicative of an older feature.
- (iii) A two layer model is used to determine the modification of the surface mixed layer of an Agulhas eddy, where the mixed layer deepened from 130 to 164 db in two days. A nett heat flux of 379 W.m^{-2} and a temperature drop of $0,10^\circ\text{C}$ per day is estimated due to heat loss to the atmosphere. A temperature drop of $0,05^\circ\text{C}$ per day is estimated by mixing of cold water from beneath the thermocline.

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CHAPTER 1

INTRODUCTION

The ocean circulation south of Africa is recognized as a vital component in the interocean exchange of heat, salt and momentum in the global mass balance. Of particular interest is the interocean exchange of thermocline and intermediate water between the southwest Indian Ocean and the southeast Atlantic Ocean. In the region south of Africa this warm saline Indian Ocean water has an influence not only on the regional environment (eg. Walker and Mey, 1988; Mey *et al.*, 1990; Walker, 1990; Brundrit and Shannon, 1989; Duncombe Rae *et al.*, 1994) but also potentially on the global thermohaline circulation (Gordon, 1985, 1986; Gordon *et al.*, 1992). Understanding the global thermohaline circulation is important if we are to gain insight into the global climate system.

The conduit for Indian Ocean thermocline and intermediate water into the region south of Africa is the Agulhas Current. This western-boundary current flows south-westward along the east coast of southern Africa, closely following the continental shelf break (Figure 1.1). The source of water for the Agulhas Current is the Moçambique Channel (Harris, 1972; Fu, 1986) with additional input from the East Madagascar Current (Lutjeharms, 1976, 1988a; Lutjeharms *et al.*, 1981) and recirculation of Agulhas Return Current water (Harris, 1972). Near Algoa Bay the Agulhas Current moves away from the coast as the continental shelf widens (Harris and Bang, 1974; Lutjeharms, 1981b; Schumann and Van Heerden, 1988). On passing the Agulhas Bank, the current separates from the continental shelf as a free jet, develops oscillations of increasing amplitude (Harris and Bang, 1974) and turns eastward in an anticyclonic loop, termed the Agulhas "Retroflexion" by Bang (1970), returning into the South Indian Ocean as the Agulhas Return Current. The terminus of the Agulhas Retroflexion is the source region from which large anticyclonic rings and eddies are shed (Harris *et al.*, 1978; Lutjeharms, 1981a; Gordon, 1985) (see Figure 1.1). This eddy field is extremely dynamic and has been the subject of considerable research efforts because it is believed that it is these vortices that are the main mechanism for the interbasin exchange here. A thorough understanding of the nature and frequency of such vortex shedding events is therefore crucial if we are to estimate the contribution of this eddy field to both the regional and global scale circulation.

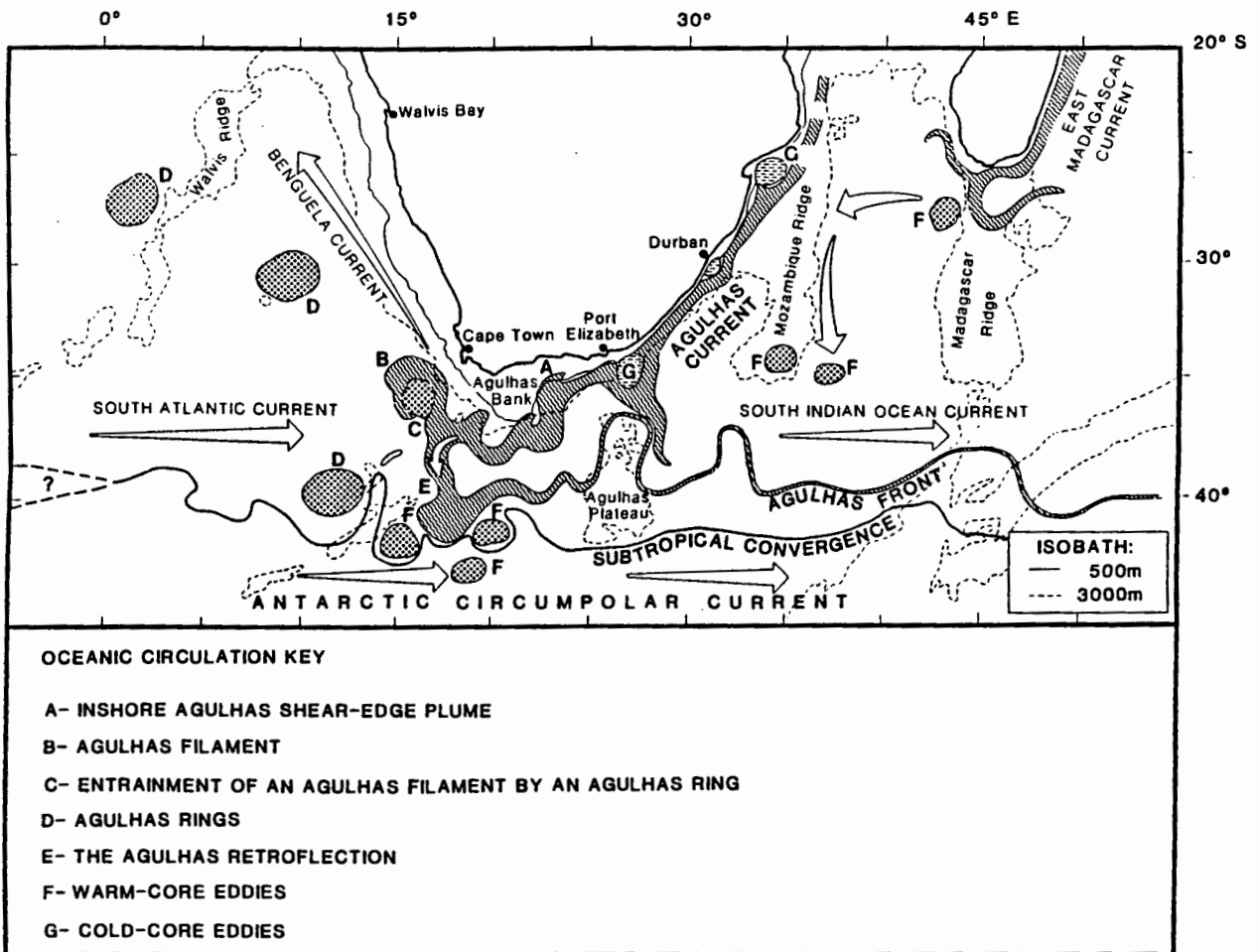


Figure 1.1: A conceptual diagram of the general mesoscale oceanographic features around southern Africa (adapted from van Ballegooyen *et al.*, 1991).

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- B - Agulhas filament
- C - Entrainment of an Agulhas filament by an Agulhas Ring
- D - Agulhas Rings
- E - The Agulhas Retroflection
- F - Warm-core Eddies
- G - Cold-core Eddies

However, not all rings and eddies shed from the Agulhas Retroflection enter the Atlantic, thus providing the mechanism for interbasin transfer of warm Indian Ocean water. Agulhas rings and eddies can also, alternatively, be shed southward across the Subtropical Convergence (STC) and introduced into the Antarctic Circumpolar Current, or be reabsorbed by the Agulhas Current. An understanding of the types of eddy leakages from the Agulhas Retroflection is therefore important in order to ascertain both the meridional and interbasin flux contribution by such features.

Addressing the problem of the nature and size of Agulhas rings and eddies, their impact on the regional environment and their subsequent modification requires a synoptic and directed data set of a number of these features. Such a data set is in fact available in the results of the *SCARC*. The Subtropical Convergence and Agulhas Retroflection Cruise (*SCARC*) data used in this thesis provide insight into the diversity of Agulhas rings and eddies observed in the Retroflection region at a specific time. Such a data set provides adequate information with which one can assess the nature of the exchanges south of Africa and its probable variability associated with this eddy field.

In order to familiarize the reader with the general hydrography of the Agulhas Retroflection region, a review of what is known about this region (**Water Masses, Rings and Eddies of the Agulhas Retroflection**) is presented, emphasizing the various scientific contributions that have led to our present understanding and knowledge. This review demonstrates the need for certain further studies which address identified knowledge gaps. Some of these limitations lead to the formulation of the primary objectives of this thesis and are presented in the **Research Objectives**. The **Data and Methods** chapter that follows outlines the data and methodology used to address these research objectives, leading to the **Results and Discussion** section.

The **Results and Discussion** chapter contains five sections. The first section presents the general hydrography of the Agulhas Retroflection as encountered during the period of the *SCARC*. The second and third sections address the detailed hydrography and dynamics of the features identified in the Retroflection region, whilst the fourth section identifies the detail of the water masses comprising the various mesoscale features. Finally, a heat and salt anomaly analysis is presented, quantifying the modification of Agulhas water through the Retroflection.

A summary of the results and a few concluding remarks are presented in the **Conclusion** chapter.

CHAPTER 2

WATER MASSES, RINGS AND EDDIES OF THE AGULHAS RETROFLECTION

The Global Thermohaline Conveyor Belt

The Deep Water of the World's ocean basins forms in the North Atlantic Ocean (Warren, 1981; Killworth, 1983) as a result of heat loss to the atmosphere. This heat loss causes the cool, saline water to sink, forming North Atlantic Deep Water. The Deep Water formed in the North Atlantic flows southward within the deep western boundary currents (Warren, 1981) through the Atlantic, to occupy the deep part of both Indian and Pacific Oceans. Upwelling of this water occurs principally in the Equatorial Pacific Ocean (Kawase, 1987). The compensatory flow to the North Atlantic returns as warm thermocline water, thus replacing the loss of mass and salt to the Deep Water (see Figure 2.1).

Two routes for the return flow are possible. Water from the Pacific Ocean can enter the Atlantic via the Drake Passage to join the South Atlantic gyre. This route is called the "cold-water path" (Georgi, 1979; Piola and Georgi, 1982; Rintoul, 1991). The second possible route is from the tropical Pacific across the Indonesian Seas into the tropical Indian Ocean. The Agulhas Current provides the conduit to this water reaching the southern point of Africa - the "warm-water path" (Gordon, 1986; Piola and Gordon, 1986). At this point the importance of Agulhas rings and eddies to the global thermohaline circulation is realized.

The warm thermocline waters enter the South Atlantic as rings shed from the Retroflection (Lutjeharms, 1981a; Gordon, 1985, 1986). Water may also enter the South Atlantic as intermittent or direct leakage of Agulhas water (Harris and van Foreest, 1978; Gordon, 1985; Shannon *et al.*, 1990; Lutjeharms and Cooper, 1995). This intermittent flow may occur in association with the passage of an Agulhas ring, as was documented by Gordon *et al.* (1987). Estimates of the heat and salt budgets for the Atlantic Ocean indicate a net northward flux of heat through the South Atlantic (Gordon and Piola, 1983). Rintoul (1991) and Piola and Gordon (1989) suggest that a significant contribution to this return-flow is through the Drake Passage, however, Lutjeharms (1981a), Gordon (1985, 1986) and Shannon *et al.* (1990) indicate that the

"warm-water path" makes a significant contribution to the flow. The ocean circulation models of Semtner and Chervin (1991) and FRAM (Stevens and Thompson, 1994) seem to favour the Indian - Atlantic "warm-water path", without excluding the other.

Although there therefore are two schools of thought concerning the relative importance of the two return-flow routes, it is likely that the return-flow is self-regulatory, with the "warm water" path possibly more variable than the "cold water" path. This variability may be mainly associated with the eddy field of the Agulhas Retroflection.

What are Agulhas rings and eddies?

Agulhas rings and eddies are vortices of relatively warm water of anti-cyclonic rotation. The size of these mesoscale vortices vary from 150 - 350 km in diameter and can extend to depths exceeding 1500 db. For the purposes of this thesis, a distinction between Agulhas rings and eddies is made. Agulhas rings are considered to consist of an annulus of warm surface water with cooler surface water in the center of the vortex. A cross-section through such a feature should reveal a U-shaped isotherm structure at depth with a slight doming of the near-surface isotherms in the centre. Agulhas eddies, on the other hand, consist of a single body of warm water located within cooler surrounding water. A cross-section through such a feature reveals a classic U-shaped isotherm structure (Figure 2.2). It is important to note that the cooler surface core within an Agulhas ring will rapidly be eroded by lateral mixing with the surrounding warm annulus comprising the ring, the dynamics of which have been modelled by Williams (1988) for Gulf Stream rings. For this reason there has been no positive hydrographic identification of "true" Agulhas rings outside the immediate vicinity of the Retroflection region.

Two classes of Agulhas vortices have thus been identified and their contribution to the global thermohaline circulation has been recognized. The geographic distributions and shedding mechanisms for these two types of vortices may be distinctly different.

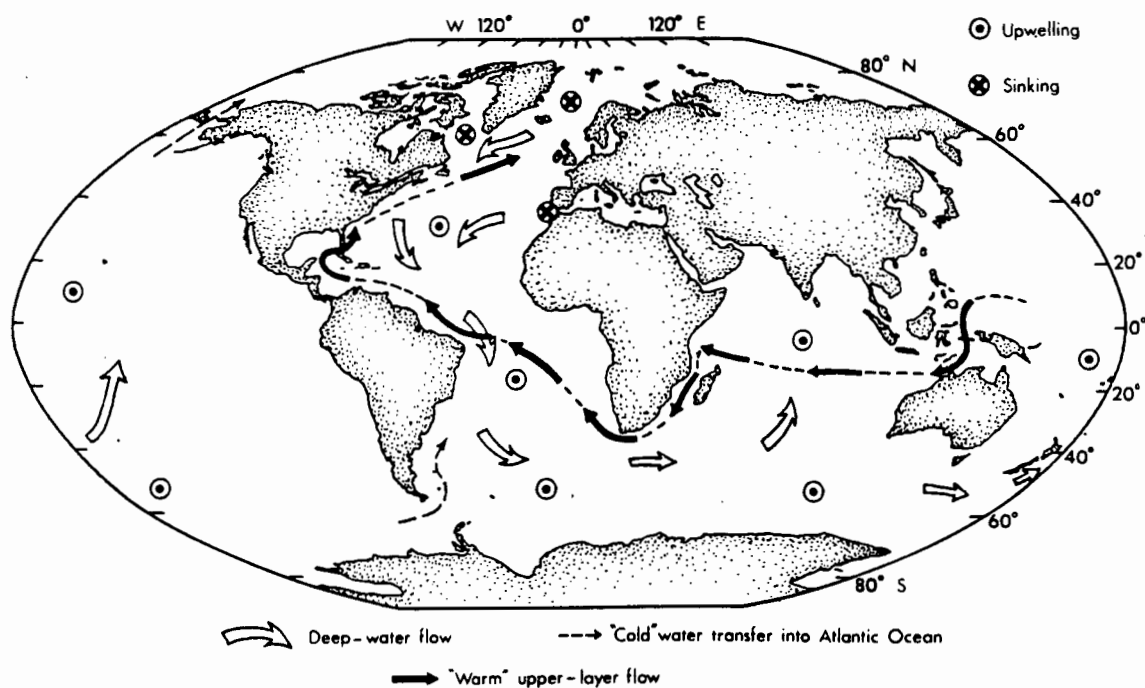


Figure 2.1: The global thermohaline circulation of the deep water through the World's oceans (from Gordon, 1986).

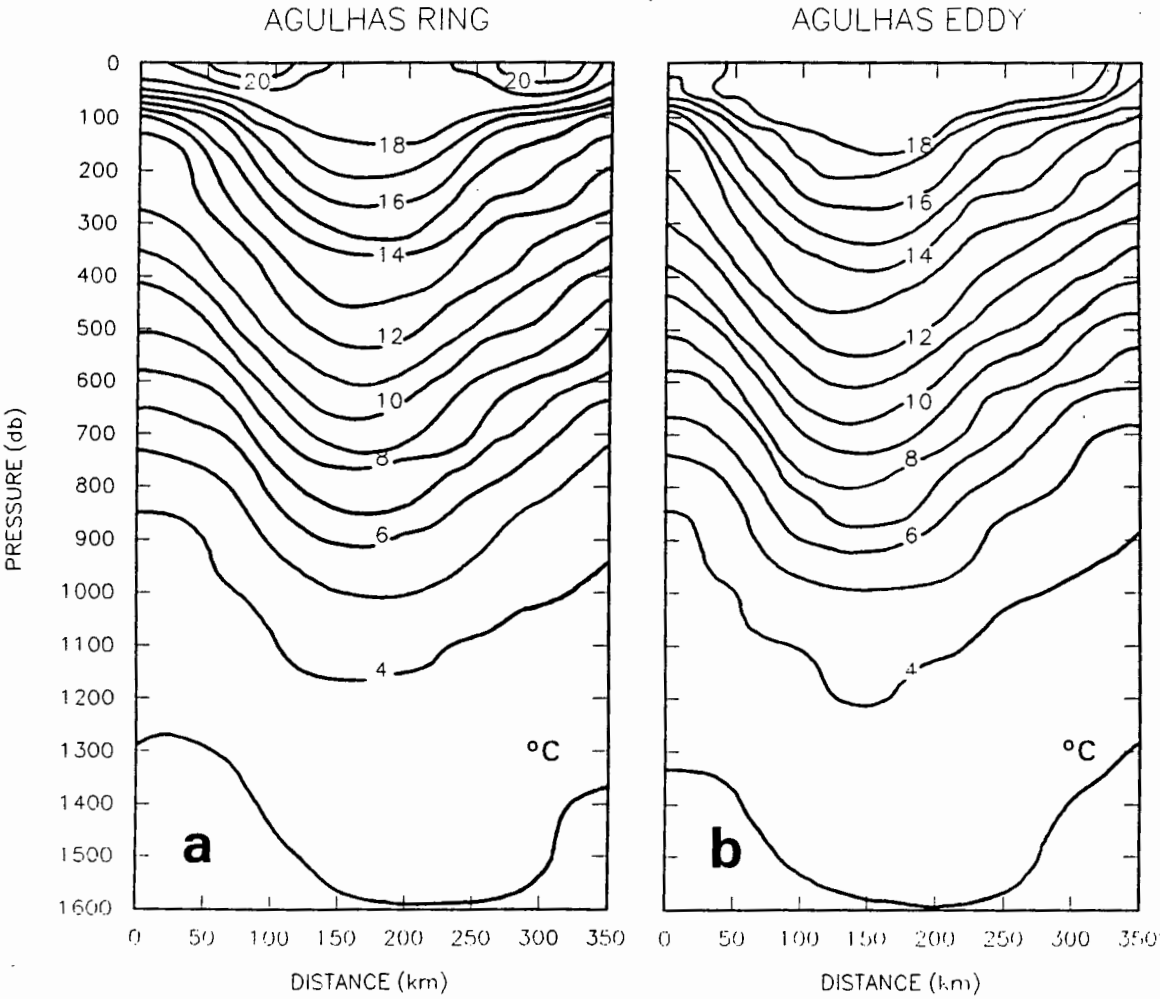


Figure 2.2: A schematic representation illustrating the differences between Agulhas rings and eddies. For the purposes of this thesis vortices are defined as rings if they exhibit a warm annulus of surface water as illustrated in (a).

Where are Agulhas rings and eddies formed and how are they shed?

Shedding regions

Agulhas rings and eddies which can potentially enter the South Atlantic are shed from the western and southern terminus of the Agulhas Retroflection. Warm-core eddies shed from the Agulhas Return Current downstream of the Retroflection (as documented by Lutjeharms and Valentine (1988b)) have not been observed to enter the South Atlantic and will therefore not be discussed. Agulhas vortices shed from the Retroflection can either move westward into the South Atlantic or south across the Subtropical Convergence (STC).

Shedding mechanisms

The process of ring and eddy shedding can be observed using satellite remote sensing. Both thermal infrared imagery (eg. Lutjeharms, 1981a) and altimetric analysis (eg. Feron *et al.*, 1992) have been used to describe the shedding process. Ring-separation from the Retroflection has been documented by Lutjeharms and van Ballegooyen (1988) from *Meteosat* imagery alone. Within each ring-shedding event, westward penetrations of the Retroflection loop show an increased rate of progress with time, followed by a relatively rapid eastward regression as the antecedent Retroflection loop is short-circuited. The result of this rapid eastward progression is the shedding of an Agulhas ring to the west of the "new" Retroflection loop. This event is then accompanied by flow of Subantarctic or South Atlantic water northwards to fill the gap, forming a cold, anvil-shaped wedge between the Retroflection and the recently spawned ring (see Figure 2.3). Lutjeharms and Gordon (1987) described for the first time the shedding of a ring from the Agulhas Retroflection observed at sea, using both hydrographic cruise data and concurrent thermal infrared (T.I.R) imagery.

Altimetric analysis by Feron *et al.* (1992) show *Geosat* evidence of 16 to 20 dominant ring-shedding events taking place over a period of three years in the Agulhas Retroflection region. Periodic Agulhas Front (thermal front over the southern edge of the Agulhas Return Current) movements were observed, culminating in the formation of large Agulhas rings, with sharp changes (pulses) in the stability of the sea level pattern. hypothesized to determine the pinch-off time of the ring.

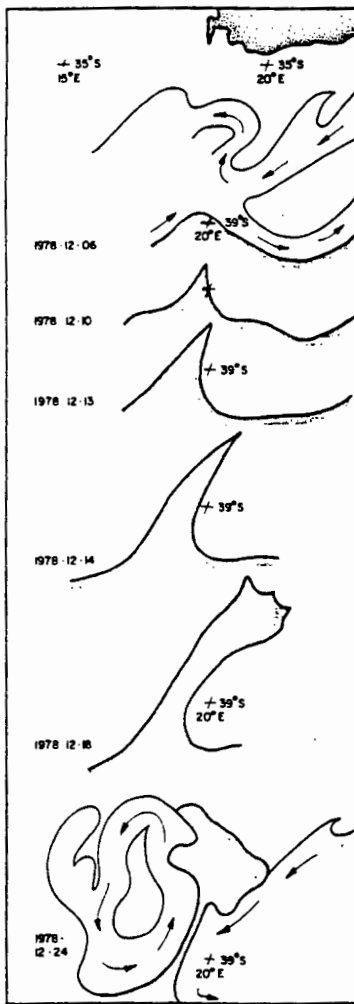


Figure 2.3: The rapid development and penetration of a cold wedge of Subantarctic Surface Water forming an inherent part of the shedding of an Agulhas ring. Thermal data were from *Meteosat I* (from Lutjeharms and van Ballegooyen, 1988).

What causes a ring or eddy to be shed from the Retroflection region? Various modelling studies have attempted to provide insight into the mechanisms involved in ring and eddy-shedding at the Agulhas Retroflection. A free inertial jet model (Lutjeharms and van Ballegooyen, 1984) simulated increased westward penetration of the Retroflection loop when a decreased volume flux of the Agulhas Current was imposed. De Ruijter and Boudra (1985) and Boudra and de Ruijter (1986) also showed in single-layer and multi-layer wind-driven models that a westerly wind field located further to the north than usual would allow for greater westward penetration of the Retroflection into the South Atlantic Ocean. Boudra and Chassignet's (1988) multi-layer modelling studies of the wind-driven South-Atlantic / Indian Ocean circulation and the Agulhas Retroflection region exhibited a ring-formation process. The instability required for ring-formation in their model depended on the shape of the Agulhas Bank shelf-break. Increasing inertia reduced the number of rings formed. Boudra *et al.* (1989) refined these models further.

Interesting work on alternative eddy-shedding mechanisms has been done by Stanton (1976), Andrews *et al.* (1979) and Nilsson and Cresswell (1981) for warm-core eddies shed from the East Australian Current (EAC). Nilsson and Cresswell (1981) have suggested that a westward propagating baroclinic Rossby wave along the Tasman Front causes warm-core eddies to pinch off the EAC adjacent to the Sydney coast (see Figure 2.4). Similarly, westward propagation of a Rossby wave along the Agulhas Return Current may possibly induce an increased meridional component in the meanders of the Return Current, causing these meanders to coalesce as the non-linearity of the baroclinic wave increases on reaching the Retroflection. Pinching off of a ring in the region of the Agulhas Plateau may result as the disturbance "negotiates" the cyclonic loop of the Retroflection. However, altimetric analysis by Feron *et al.* (1992) seems to indicate that the westward-travelling Rossby wave hypothesis is unlikely to be the primary mechanism determining ring-shedding in the Agulhas system because the periodicity of the Rossby wave disturbance downstream of the Retroflection does not seem to correspond to the observed periodicity of ring-shedding events at the Retroflection (de Ruijter, *personal communication*). Nevertheless, this hypothesized mechanism may still contribute, together with a host of other mechanisms, to the shedding of rings from the Retroflection region.

The Agulhas Retroflection is a highly variable region, oscillating between stable and unstable periods, and returning to stable conditions after a certain period. Such a sequence of events was observed by Feron *et al.* (1992) when they combined a statistical approach to *Geosat* altimetry data in the region of the Agulhas Retroflection. An average of six pulses were observed to occur each year (which is similar to the ring formation rate 5 per year estimated by Gordon and Haxby (1990)). After shedding, the Agulhas Retroflection region was observed to return to a similar pattern or position prior to ring shedding.

Spawning rates

The frequency with which Agulhas rings and eddies are shed is uncertain and probably highly variable (Feron *et al.*, 1992). Using satellite T.I.R imagery, Lutjeharms and van Ballegooyen (1988) have suggested that 6 - 9 substantial bodies of warm water are shed annually from the Agulhas Retroflection (an average of one feature every 1,3 - 2,0 months), although not all drift into the South Atlantic. Recent altimetric analysis by Feron *et al.* (1992) in turn suggests that about 6 rings are shed from the Agulhas Retroflection annually. Similarly, different altimetric analyses of the same data set by

Byrne *et al.* (1994) and by van Ballegooyen *et al.* (1994) indicate that about 6 rings per annum are shed from the Retroflection.

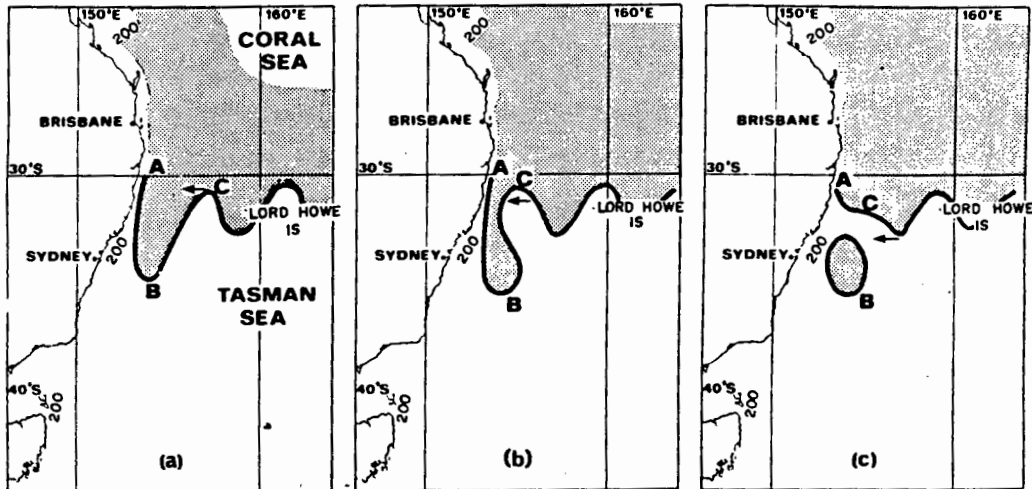


Figure 2.4: An illustration of how the westward propagation of the Tasman Front might control the flow of the East Australian Current and cause warm-core eddies to pinch off south into the Tasman Sea (from Nilsson and Cresswell, 1981).

The 1987 population of rings in the South Atlantic and their mean drift velocity suggests an average shedding-rate of about 5 rings per year (Gordon and Haxby, 1990). This is a lower number than that determined by other altimetric work over the Retroflection region over the same period (eg. Feron *et al.*, 1992; Byrne *et al.*, 1994; van Ballegooyen *et al.*, 1994). However, not all rings shed from the Retroflection enter the South Atlantic, which may explain the discrepancy between the two sets of results. Van Ballegooyen *et al.* (1994) have noted that the eddies shed to the south of the Agulhas Retroflection were all observed to ultimately move westwards into the South Atlantic, rather than southwards across the Subtropical Convergence. The rate of shedding of Agulhas vortices may therefore be expected to lie in the range of 5 - 9 rings shed from the Agulhas Retroflection annually, with the number of rings successfully entering the South Atlantic approaching the lower end of the scale.

Dimensions of Agulhas rings and eddies

Horizontal Dimensions

The horizontal dimensions of Agulhas rings and eddies can be measured according to a variety of methods which are listed in the **Data and Methods** chapter. Depending on the method employed, the horizontal dimensions of a particular ring / eddy may vary. Most Agulhas rings and eddies exhibit dimensions ranging from 180 to 380 km in diameter (see Tables 1 and 2 and Figure 2.5). However, many Agulhas rings and eddies display some eccentricity in horizontal (and vertical) dimensions, thus providing for a disparity in their zonal and meridional dimensions.

Shape of Agulhas vortices

Agulhas rings and eddies have been observed to assume a variety of shapes. Many are elliptical, some display "umbilical cord - like" appendages connecting them to their source. Some even exhibit attendant plumes that, when observed with the aid of thermal infrared (T.I.R) satellite imagery, hint at their direction of rotation. Because of their varied shapes, Agulhas rings and eddies have received much descriptive attention (eg. Lutjeharms and Valentine, 1988b; Lutjeharms *et al.*, 1992).

As with Gulf Stream rings (eg. Fuglister, 1977; Brown *et al.*, 1983), it has been proposed that Agulhas rings and eddies evolve from elliptical to more circular shapes as they are shed and start to move away from their parent current. Such was the case when Lutjeharms and Gordon (1987) documented what was initially an elliptical ring shed at sea, which later assumed a more circular, stable configuration. Vastano *et al.* (1980) attribute eccentricity in the vortex shape to the dynamic processes (current-ring and ring-ring interaction) that can be expected to occur near the source current. Spence and Legeckis (1981) found that the elliptical shape rotates because of the presence of a wave propagating around the perimeter of the eddy. As this wave decays, the flow becomes more circular.

Asymmetrical warm-core vortices are common within the immediate vicinity of the Agulhas Retroflection. Olson and Evans (1986) have documented a large asymmetrical eddy that had recently been shed from the Agulhas Retroflection, the asymmetry of which was probably associated with the formation process and subsequent adjustment to a quasi-equilibrium state. An example of an Agulhas ring of extreme horizontal eccentricity has been described by Duncombe Rae *et al.* (1989, 1992). Its zonal and

meridional dimensions were 330 km and 165 km respectively, relative to the 16°C isotherm at 200 m depth.

Table 1: A list of rings encountered hydrographically in the South Atlantic Ocean. The rings are named chronologically according to the year encountered. The position refers to the time at which hydrographic measurements were made (from Duncombe Rae, 1991).

Ring	Vessel	Voyage	Date	Lat. (°S)	Long. (°E)	Source	Comment
R64.1	<i>Africana II</i>	?	64-3	40.5	15	Duncan 1968	Wide station spacing. Reversing bottles
R69.1	<i>Africana II</i>	?	69-3	35	15	Harris & Van Foreest 1978	Wide station spacing. Reversing bottles
R83.1	<i>Knorr</i>	104-5	83-11	35.5	15.4	Olson & Evans 1986	ARC (Cape Town eddy)
R83.2	<i>Knorr</i>	104-5	83-11	38.9	18.3	Olson & Evans 1986	ARC (Retroflection eddy)
R83.3	<i>Oceanus</i>	133	83-2	23.0	-5.0	McCartney & Woodgate-Jones 1991	Detected on CTD line along 23°S
R85.1	<i>Thomas Washington</i>	?	85-3	35	15.5	Bennett 1988	CTD line (Cape Town eddy 85)
R87.1	<i>S.A. Agulhas</i>	48	87-2	34.8	15.8	Lutjeharms 1987. Valentine <i>et al.</i> 1988	2 lines SCARC (ring Susan)
R87.2	<i>S.A. Agulhas</i>	48	87-2	35.9	11.6	Lutjeharms 1987. Valentine <i>et al.</i> 1988	1 line SCARC (ring Rosemary)
R87.3	<i>S.A. Agulhas</i>	48	87-2	37.7	9.5	Lutjeharms 1987. Valentine <i>et al.</i> 1988	2 lines SCARC (ring Mariaan)
R87.4	<i>S.A. Agulhas</i>	48	87-2	38.0	15.0	Lutjeharms 1987. Valentine <i>et al.</i> 1988	2 lines SCARC (ring Erina)
R87.5	<i>S.A. Agulhas</i>	48	87-2	40.9	14.4	Lutjeharms 1987. Valentine <i>et al.</i> 1988	1 line SCARC (ring Helen)
R87.6	<i>Discovery</i>	?	87-4	27.0	7.5	Gordon and Haxby 1990	1 CTD line
R89a	<i>Africana</i>	71	89-4	32.1	10.8	Duncombe Rae <i>et al.</i> in press a	1 XBT line (Vema ring)
R89b	<i>Benquela</i>	246	89-5	30.5	9.2	Duncombe Rae <i>et al.</i> in press a	R89a revisited. 3 lines (Vema ring)
R90.1	<i>Melville</i>	?	90-1	30	2	Gordon <i>et al.</i> in prep.	CTD line SAVE-4
R90.2	<i>Melville</i>	?	90-1	30	6	Gordon <i>et al.</i> in prep.	CTD line SAVE-4
R90.3	<i>Africana</i>	81	90-5	36.3	14.3	Personal observation	Feature on return from South America. Ring?
R90.4	<i>Africana</i>	85	90-7	35.3	11.7	Duncombe Rae and Shillington in prep.	Search for ring (Winter ring)

Table 2: Parameters measured for some of the rings listed in Table 1. Radius is the radius of the maximum radial velocity, with values in parentheses indicating estimates; h_{10} is the depth of the 10°C isotherm at the ring centre; δh_{10} is the difference between the depth of the 10°C isotherm at the centre and at the edge of the ring; v_t and v_r refer to the translation and maximum radial speeds respectively (negative speeds indicate anticyclonic flow) (from Duncombe Rae, 1991).

Ring	Radius (km)	h_{10} (m)	δh_{10} (m)	v_t (cm·s ⁻¹)	v_r (cm·s ⁻¹)	APE ($\times 10^{-15}$ J)	KE ($\times 10^{-15}$ J)
R83.1	115	750	370	4.8	-60	30.5	6.2
R83.2	130	740	420	8.5	-90	51.4	8.7
R83.3	90	560	140	?	-29	?	?
R87.1	(130)	425	145	?	?	?	?
R87.2	(150)	700	350	?	?	?	?
R87.3	(100)	650	300	?	?	?	?
R87.4	(115)	770	455	?	?	?	?
R87.5	(140)	520	370	?	?	?	?
R87.6	145	520	300	8.3	-43	?	?
R89b	145	600	300	6.4	-55	38.8	2.3
R90.4	90	870	510	?	-60	26.2	2.6

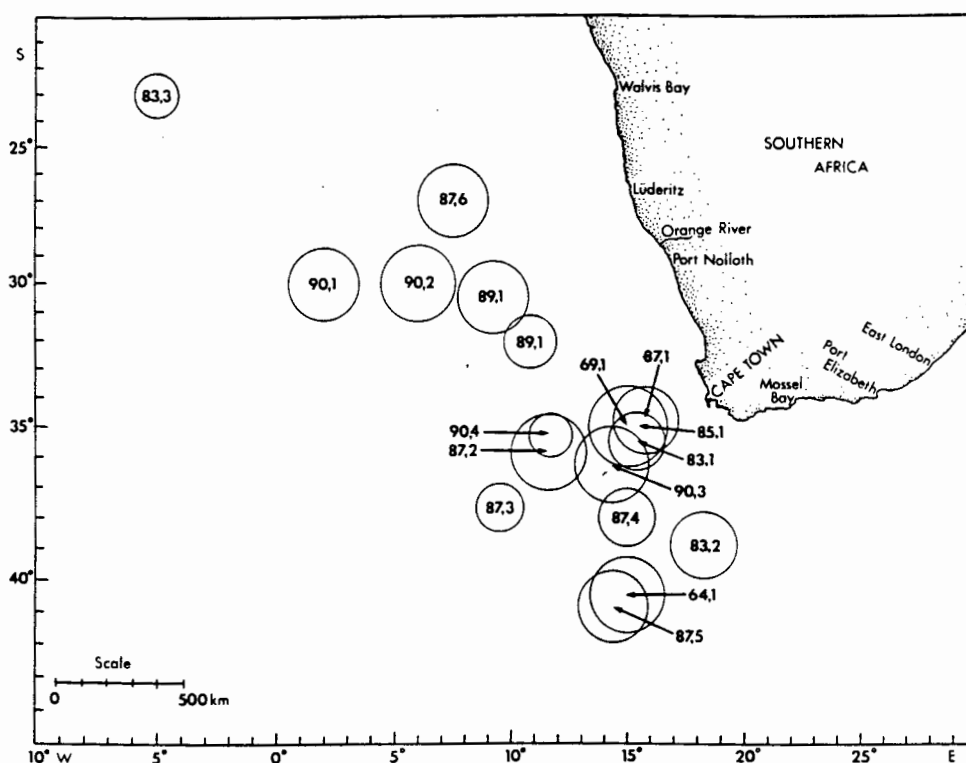


Figure 2.5: The positions of Agulhas rings detected hydrographically in the South Atlantic Ocean. The vortices are numbered according to Table 1. The circle indicates the diameter of maximum azimuthal velocity for each ring (from Duncombe Rae, 1991).

Vertical dimensions of Agulhas vortices

The isopycnal slopes characteristic of the Agulhas Retroflection are well-defined, reaching the sea-floor (Jacobs and Georgi, 1977). This explains the fact that rings and eddies when shed from the Retroflection can have a top-to-bottom dynamic signature. In most cases where a ring or eddy has been hydrographically sampled, the signature of the vortex (displayed by the bowl-shaped isopycnals characteristic of anti-cyclonic shear) extends to depths exceeding the sampled depths (eg. Lutjeharms, 1988b; Duncombe Rae *et al.*, 1989; Gordon and Haxby, 1990; McCartney and Woodgate-Jones, 1991).

There may be different methods for defining the vertical extent of these features (see the **Data and Methods** chapter). The depth of the 10°C isotherm has proven to be useful since this isotherm has been identified to best denote the dynamic structure of mesoscale features in the Agulhas Retroflection region (eg. Olson and Evans, 1986). Duncombe Rae (1991) gives a summary of the depth of the 10°C isotherm within various Agulhas rings located in the South Atlantic (see Table 2).

Translational velocities of Agulhas rings and eddies

Agulhas rings and eddies shed from the Retroflection eventually either move off westward into the South Atlantic or become reabsorbed by the Agulhas Current. Satellite altimetric analyses (eg. *Geosat* - Gordon and Haxby, 1990; *Seasat* - Cheney *et al.*, 1983) have identified a region of high sea-level variability associated with the Agulhas Retroflection and tracks of variability extending from the Retroflection, probably indicating the translational routes of rings and eddies that have separated from the Retroflection. Rings and eddies tend to move off in a westerly to northwesterly direction after being shed from the Retroflection. There seems to be a noticeable tendency for these features to be often observed just southwest of Cape Town (Bang, 1970; Olson and Evans, 1986; Lutjeharms and Valentine, 1988a). They may typically be found here because of the proximity to their spawning source and because of the west to northwest translation path from the Retroflection region into the South Atlantic.

Duncombe Rae (1991) has compiled a map with the locations of some warm-core rings hydrographically sampled in the South Atlantic to date (Figure 2.5). Satellite altimetry suggests that only significantly large rings escape the immediate proximity of the Retroflection. However, this phenomenon may be ascribed solely to the better "visibility" of larger, more intense vortices in the altimetry data (van Ballegooyen *et al.*, 1994).

From the above review it is clear that many vortices shed from the Agulhas Retroflection are observed to enter the South Atlantic. In addition, these vortices are known to penetrate well into the South Atlantic. McCartney and Woodgate-Jones (1991) have described an Agulhas ring in the mid-Atlantic. Gordon and Haxby (1990) went further and suggested that Agulhas rings shed into the South Atlantic may traverse the entire South Atlantic, to be absorbed into the Brazil Current once they have crossed the Cape Basin. Stramma (1991) has inferred that Agulhas rings could even join the North Brazil Current and take a more direct route across the equator. Altimetric analysis by Byrne *et al.* (1994) has indicated that Agulhas rings and eddies can be tracked as far as 40°W (25° - 40°S) in the South Atlantic and still have 15 - 40% of their initial altimetric amplitude remaining. This result supports Gordon and Haxby's (1990) hypothesis that Agulhas rings and eddies may be absorbed into the Brazil Current, but seems to preclude Stramma's (1991) idea that they may traverse far enough north to be absorbed into the North Brazil Current.

It has been surmised that exchange of heat and salt can occur across the Subtropical Convergence (STC) by such eddies (Lutjeharms, 1988b; Lutjeharms and Valentine, 1988b). Wakker *et al.* (1990) have noted that some of the eddies tracked during their altimetric survey of the Retroflection region crossed the STC. This mesoscale and active meridional exchange of heat (and salt) could be more effective than other mechanisms at this latitude (40° - 45° S) and could therefore play an important role in the local and basin-scale heat (and salt) balance. Heat and salt anomalies in eddies that have crossed the STC would be larger than the calculated anomalies for the same eddies entering the southeast Atlantic.

Relatively few estimates of the drift velocity of eddies shed to the south have been made. The reason for the apparent lack of drift estimates for eddies shed south across the STC are two-fold. Firstly, most estimates of eddy translation are done using satellite altimetry. Unfortunately the background signal in the region of the STC is extremely "noisy", owing to the high variability associated with the region. The signal-to-noise ratio is low and thus tends to mask the ability for such eddies to be identified and tracked using altimetry data. Secondly, thermal infrared satellite imagery (which is also used in synoptic feature-tracking) unfortunately is not very useful due to the extensive and persistent cloud cover over the region of the STC (around 42° - 45° S). This is particularly true during the winter months, when the average storm track distribution of the mid-latitude cyclones shifts northward, overlying much of the area. Nevertheless, satellite data, and in particular satellite altimetric data, are extremely useful in tracking the second class of rings and eddies that are shed to the west of the Retroflection, entering the relatively quiescent waters of the South Atlantic, since satellite altimetry has the ability to "see through" cloud cover.

It has been established that Agulhas rings shed to the west of the Retroflection drift in a west to northwest direction into the South Atlantic at a rate of between $4,4$ - $9,0 \text{ cm.s}^{-1}$ (Olson and Evans, 1986; Gordon and Haxby, 1990; Duncombe Rae *et al.*, 1989, 1992; Byrne *et al.*, 1994; van Ballegooyen *et al.*, 1994). As was mentioned earlier, satellite data are convenient tools for tracking rings and eddies. Theoretical β computations have also been used to estimate the translation rate of such vortices. The rate of translation can be computed from a two-layer model adopted by Olson and Evans (1986) and a formulation introduced by Nof (1981) and Flierl (1984), based on momentum integrals over the ring. However, these estimates are often inaccurate since ring and eddy translation is a combination of self-induced translation (β -effect) and

steering by the mean background flow. An example of the importance of the background flow is highlighted by the theoretical results obtained by Duncombe Rae *et al.* (1992) on the translation velocity of a ring sampled in the South Atlantic. Its theoretical translation rate was $2,1 \text{ cm.s}^{-1}$ with an actual velocity of three times that, implying that the background flow must be an important additional effect. Byrne *et al.* (1994) have obtained similar results for a host of Agulhas rings in the South Atlantic, where about half of the observed velocity was due to self-induced translation and the remainder to advection by the mean background flow.

So in summary, Agulhas rings and eddies shed from the Retroflection either move off westward into the South Atlantic, southward across the STC, or become reabsorbed by the Agulhas Current. Rings shed westward can penetrate well into the South Atlantic, guided by self induced translation and the mean background flow. Translation rates of these vortices vary from $4,4 - 9,0 \text{ cm.s}^{-1}$.

Rotational velocities of Agulhas rings and eddies

Rings and eddies shed from the Agulhas Retroflection are all anti-cyclonic and exhibit peak rotational velocities ranging from $29,0 - 90,0 \text{ cm.s}^{-1}$ (Olson and Evans, 1986; Gordon and Haxby, 1990; McCartney and Woodgate-Jones, 1991; Duncombe Rae *et al.*, 1992; Duncombe Rae and Shillington, 1994). The rotational velocity of a ring or eddy reaches a maximum at its perimeter, and diminishes in magnitude on nearing the center of the vortex. The rotational velocity of Agulhas vortices generally diminish in magnitude with increasing distance from their source (see Table 2 and Figure 2.5). Results from Byrne *et al.* (1994) altimetric analysis of a host of Agulhas vortices that had traversed the South Atlantic indicate that their Agulhas vortices exhibited an amplitude of 15% to 40% of their initial amplitude once they had reached as far as 40°W . Such a result is indicative of a relaxation of the dynamic height of such vortices and consequent decay in rotational velocity over a period of 3 to 4 years.

Interactions of Agulhas rings and eddies with their surroundings

Bottom Topography

The translational response of rings and eddies to bottom topography is well known (as revealed in satellite altimetry data). Tracks of rings and eddies relative to bottom topography suggest that they tend to follow single contours and these interactions modify the size, shape and motion of the feature (Evans *et al.*, 1985). An example of topographic interaction is documented by Gordon and Haxby (1990) where an Agulhas ring was observed to slow down and deflect southward as it negotiated the Walvis Ridge, probably indicating the deep-reaching nature of Agulhas rings and the effects of bottom topography on the general circulation in which they are embedded (Olson and Evans, 1986). Byrne *et al.* (1994) have also emphasized that Agulhas rings in the South Atlantic do not simply follow the mean flow. Strong deflection was observed in the vicinity of the Walvis Ridge and Rio Grande Rise. Byrne *et al.* (1994) have observed a reduction in translational velocity over steep and shallow bathymetry and an increase in translational velocity over smooth and deep topography. A noticeable decrease in translational velocity was also observed when crossing the Walvis Ridge (in support of Gordon and Haxby's (1990) finding using the same data). McCartney and Woodgate-Jones (1991) hint at the possibility that an Agulhas ring will lose all water deeper than 3000 m as it crosses the Walvis Ridge. This is not necessarily the case since the dynamics of the vortex may extend to the ocean floor but the trapped anomalous water within the vortex of the ring is unlikely to extend as deep as 3000 m (Flierl, 1984). Unfortunately there has been little work done on the topographically induced effects on the dynamics of rings and eddies. In particular, studies concerning changes in such parameters as rotational velocity, thermocline modification and vortex stretching are now required.

Interactions of Agulhas vortices with the surrounding water

Agulhas rings and eddies can be expected to be continually interacting with the surrounding water within which they are embedded. This interaction may take various forms. Firstly, there is the general mixing of the eddy with the surrounding waters as the vortex spins down and decays. Secondly, a ring or eddy may interact with its source current, either being reabsorbed by the current or "refueled". An example of the Agulhas Current interacting with an eddy immediately to the south was observed during the *SAAMES-I* cruise in April-May 1991 (Rigg, 1991). Thirdly, a ring or eddy may

interact with another ring or eddy. The only evidence of this occurring in the Agulhas Retroflexion region has been documented by van Ballegooyen *et al.* (1994), based on *Geosat* altimetric data. Lastly, Agulhas rings may entrain upwelled water from the Benguela Upwelling Front (Duncombe Rae *et al.*, 1989; 1992). This Agulhas ring - upwelling filament interaction is peculiar to Agulhas rings since they are the only western boundary products that can be introduced into an eastern boundary system. This is not to be confused with smaller-scale eddy - filament interactions that are common in most upwelling systems; these smaller-scale eddies being products of conditional instability along the upwelling front.

From the above review it is clear that isolated Agulhas vortices are continually interacting with the environment within which they are embedded. What remains to be discussed is their interaction with the overlying atmosphere and the modification that this interaction may invoke.

Heat loss to the atmosphere

Heat loss from the upper ocean to the atmosphere results in a cooling of the surface waters, which in turn drives convective overturning and deepening of the surface mixed layer. The Agulhas Retroflexion region is continually losing heat to the atmosphere. Thermostads ("thermostad" coined by Seitz, 1967) can therefore develop here due to both winter and summertime convection, and not only during winter. The Agulhas Retroflexion region does not display a seasonality in the turbulent heat fluxes from the ocean to the atmosphere (Walker and Mey, 1988), although the magnitude of the net heat fluxes do display strong seasonality. This net heat flux from the ocean to the atmosphere (Höflich, 1984; Walker and Mey, 1988) is intensified during post-frontal, cold-air outbreak conditions (Mey *et al.*, 1990). This implies a year-round, but seasonally and regionally varying, loss of heat from the exposed surface waters of warm Agulhas rings and eddies. McCartney and Woodgate-Jones (1991) have documented a ring in the mid-Atlantic which exhibits a double thermostad in its core, which they have interpreted to be the product of two successive winters of convective overturning somewhere between the Agulhas Retroflexion and the location where the ring was found. Heat gain from the atmosphere, mixing at the edges, and upwelling from below, all contribute to the erosion of the thermostad as the ring or eddy moves away from the Retroflexion.

Winter convective cooling has been well-documented in other ring-shedding systems, most notably a "multi-cored", warm-core "eddy B" shed from the East Australian Current which was repeatedly hydrographically sampled over a period of eleven months (Nilsson and Cresswell, 1981). They have found that heat loss in warm-core eddies shed from the East Australian Current seem to be completely accounted for in terms of atmospheric cooling, and believe that this is the only mechanism for winter core formation. Such an intensive study of warm-core vortices in the Agulhas system has not been accomplished to date. Nevertheless, results from Duncombe Rae *et al.* (1989) concerning an Agulhas ring hydrographically sampled in April 1989 and again in May 1989 estimate a heat loss from the upper mixed layer of the ring to the atmosphere of 80 W.m^{-2} over the 42 days between sampling (compared to an average heat loss of 180 W.m^{-2} estimated by Walker and Mey (1988) for the entire Agulhas Retroflection region). In addition, van Ballegooyen *et al.* (1994) estimate an average heat loss of between $290 - 485 \text{ W.m}^{-2}$ for two vortices in the Retroflection region over a period of only a few days. Although these estimates seem large, they are well within the range of estimates of heat loss for individual mesoscale features published by Walker and Mey (1988) for the same features within the Retroflection. Considerable discrepancies between heat flux estimates are largely accounted for by varying spatial and temporal regimes. Estimates of heat fluxes over a larger area (eg. the entire Retroflection region) during a longer time period (eg. two months) results in lower heat flux estimates.

Heat gain from the atmosphere

Solar radiative heat gain within the upper waters of the ocean can cause a warmer summer surface "cap" (a term coined by Cheney, 1977) to develop, overlying the signature layer of a ring or eddy. Such a phenomenon has been documented by Cresswell (1982) for the East Australian Current system. However, summer "capping" events caused by solar heating in the Agulhas Retroflection region are unlikely since this region experiences a net heat loss to the atmosphere throughout the year. This is not to say that solar radiation induced "capping" events do not occur in the Agulhas Retroflection. If such an event were to occur the surface "cap" would most likely be an ephemeral feature, lasting perhaps two or three days before a local wind event would erode the protective warm "cap" overlying the ring or eddy, exposing the underlying waters. Hydrographic evidence of solar radiative "capping" of rings and eddies in the Retroflection region has not been documented although "capping" has been noticed by McCartney and Woodgate-Jones (1991) for a ring in the mid-Atlantic. Seasonal

"capping" of rings and eddies that have moved off into the South Atlantic can be expected to occur, since they are exposed to regions further north where the net heat flux from the atmosphere to the ocean is a more common phenomenon. Summer "capping" and winter "erosion" events should theoretically produce multi-level thermostads within the core of Agulhas vortices.

A more likely cause of "capping" in the Retroflection region would be the scavenging of warm surface water by a ring or eddy as it interacts with the source Agulhas Current. This can occur either in the form of warm filaments being entrained around the perimeter of the ring and drawn inward toward the eddy centre, or as a "plunging" episode whereby the Agulhas Current spills into the ring or eddy, refueling (or absorbing) the vortex (*personal citation*).

Having emphasized the many interactions that isolated Agulhas rings and eddies can be subjected to in the immediate vicinity of the Retroflection, one may begin to appreciate the diverse nature of the water masses comprising such vortices - each a product not only of its source current but also a product of a host of modification events. In order to distinguish between the original water properties at vortex-formation and water masses that come about as a result of subsequent modification, it is important to establish what core water masses comprise such vortices and with what water can one expect these vortices to mix.

The waters within Agulhas rings and eddies

Rings and eddies from the Agulhas Retroflection trap water of Indian Ocean origin. Gordon *et al.* (1987) have found that the trapped water is confined for the most part to Surface and Central Waters. However, the waters contained within such vortices are not of "pure" Indian Ocean origin. Chlorofluoromethane and hydrographic data studied by Fine *et al.* (1988) indicate that South Atlantic and Indian Intermediate and Central Waters are mixed within the Agulhas Retroflection. It is therefore probable that Agulhas rings and eddies do not consist of pure Indian Ocean water, but rather a combination of these water masses. Chapman *et al.* (1987) have also noted this in their analysis of upper-layer nutrient and oxygen data. Not only can Agulhas rings and eddies be expected to comprise a variety of water masses but they may also mix with the surrounding waters through which they travel. The originating water masses of the ambient systems therefore hold the key to what may be found within Agulhas vortices.

Water Masses of the Retroflexion Region

The Agulhas Retroflexion region is a passageway for water masses from several different geographical regions. The Retroflexion region thus embraces a unique combination of water masses, illustrated by the wide range of scatter of temperature and salinity on a property - property plot (Figure 2.6).

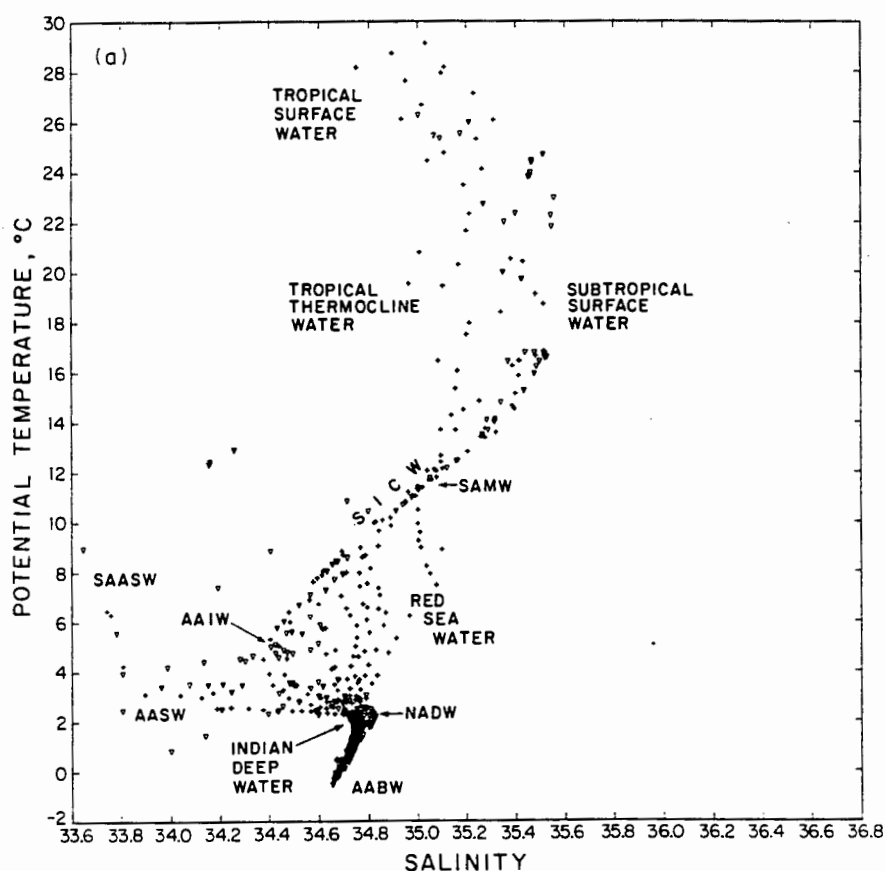


Figure 2.6: Potential temperature versus salinity distribution for the western Indian Ocean. SICW, South Indian Central Water; SAMW, Subantarctic Mode Water; NADW, North Atlantic Deep Water; AABW, Antarctic Bottom Water, AASW, Antarctic Surface Water; AAIW, Antarctic Intermediate Water; SAASW, Subantarctic Surface Water (from Gordon *et al.*, 1987).

Surface Water

The surface waters of the Agulhas Retroflection region are complex as a result of being introduced from three disparate regions. The Agulhas Current introduces Tropical Surface Water (TSW), Subtropical Surface Water (SSW - local salinity maximum) and Tropical Thermocline Water (TTW) from the southwest Indian Ocean, whilst Subantarctic Surface Water (SAASW) is introduced from south of the Subtropical Convergence. South Atlantic Surface Water (SASW) is introduced from west of the Retroflection, formed from a combination of South Atlantic Thermocline Water and Subantarctic Surface Water (SAASW).

Tropical Surface Water (TSW) has its origin in the tropical zone of the Indian Ocean and is consequently warm and fresh as a result of excess precipitation in the Tropics. Remnants of TSW are introduced into the Retroflection by the Agulhas Current, usually restricted to a thin surface layer within the thermal core of the Current.

South Indian Tropical Thermocline Water (TTW - local oxygen minimum; $O_2 < 4.2 \text{ ml.L}^{-1}$; Bennett, 1988) has its origin in the tropical zone of the Indian Ocean. The water in the tropical zone is relatively fresh as excess precipitation and inflow from the Pacific through the Indonesian Seas depress salinities. As the water flows south, excessive evaporation in the Subtropical zone ($25^\circ - 35^\circ\text{S}$) causes the water to become dense and sink, producing a subsurface salinity maximum at temperatures near 19°C throughout the southern Indian Ocean (Gordon, 1981). This water is called South Indian Subtropical Surface Water (SSW; $T = 17.7^\circ\text{C}$; $S = 35.60$ - Bennett, 1988) and is transported by the Agulhas Current into the Retroflection region. Below this water lies the Central Water.

Subantarctic Surface Water (SAASW) forms between the Subtropical Convergence (STC) and the Subantarctic Front (SAF), and extends from the surface to a depth where the Antarctic Intermediate Water (AAIW) or Subantarctic Mode Water (SAMW) are encountered.

Central Water

Central Water is formed at the Subtropical Convergence region by the sinking and northward spreading of mixed subtropical and subantarctic water masses (Sverdrup *et al.*, 1942; Orren, 1963; Orren, 1966). This water is identified as the linear part of the Θ/S curve (as a result of its constant density ratio (Schmitt, 1981), see Figure 2.6).

The Central Water of the Retroflection region consists predominantly of South Indian Central Water (SICW), which occupies the entire South Indian thermocline and includes the Subtropical Mode Waters (Schmitt, 1981; Bennett, 1988). Subtropical Mode Water (STMW) is the product of wintertime deep convection at the sea surface within the subtropical gyre, and thus have anomalously thick isopycnals and oxygen maxima associated with them ($T = 17,4^{\circ}\text{C}$; $S = 35,58$; $\text{O}_2 = 4,8 - 5,2 \text{ ml.L}^{-1}$; Bennett, 1988).

South Atlantic Central Water (SACW) can be identified in the western region of the Retroflection and is formed from a combination of South Atlantic Thermocline and Subantarctic Surface Water (Gordon, 1981) and enters the Retroflection from the south. The potential temperature - salinity (Θ/S) characteristics of South Indian and South Atlantic Central Water are very similar (Orren, 1963; Shannon, 1966). However, Valentine (1990) indicates that "fresh" South Atlantic can be distinguished from its "saline" South Indian Central Water counterpart on the basis of its Θ/S characteristics with good quality data. Gordon *et al.* (1987) define South Indian Central Water (SICW) as thermocline water which spans the interval from the more saline surface water to the salinity minimum of the Antarctic Intermediate Water (AAIW). This water is also transported by the Agulhas Current into the Retroflection area.

Subantarctic Mode Waters are formed at the sea surface during winter-overturning. They are capped during spring by warming of the upper layer, allowing them to enter the thermocline (McCartney, 1977). They appear as anomalously thick isopycnal layers with weak stratification within the thermocline and are associated with oxygen maxima. During winter, convective overturning in the northern reaches of the Antarctic Circumpolar Current in the Subantarctic zone creates Subantarctic Mode Water (SAMW - local oxygen maximum; $4,9 - 5,4 \text{ ml.L}^{-1}$; Bennett, 1988) in the south-western Atlantic and southern Indian Oceans. This water migrates northwards, generating a thick, nearly isopycnal layer which may form part of the Central Water thermocline (McCartney, 1977; Georgi, 1979). In the Agulhas Retroflection, this feature is observed in the SICW part of the Θ/S curve around $10^{\circ} - 12^{\circ}\text{C}$ (see Figure 2.6).

Intermediate Water

The Intermediate Waters of the Agulhas Retroflection are dominated by Antarctic Intermediate Water (AAIW - local salinity minimum). AAIW is found at the base of

the Central Water and is formed at the Antarctic Polar Front (APF), which lies around 50° - 55° S. AAIW is the dominant water mass of the subantarctic zone in the South Atlantic, characterized by a relative oxygen maximum (Deacon, 1933) and a relative salinity minimum $<34,6$ at temperatures between 4° - 6° C (Clowes, 1950; Duncan, 1970). AAIW is formed from water at the APF (of about $2,2^{\circ}$ C and 33,87) sinking and spreading northward into the Atlantic, Indian and Pacific Oceans (Sverdrup *et al.*, 1942). The salinity range for AAIW in the South Atlantic as well as the South Indian Ocean is around 33,80 - 34,80, whilst the temperature ranges for the two oceans are $2,0^{\circ}$ - $6,0^{\circ}$ C and $2,0^{\circ}$ - $10,0^{\circ}$ C respectively (Emery and Meincke, 1986). The large range of salinity values within the AAIW in the Retroflection region indicates the influence of Red Sea Water (RSW). In the southwest Indian Ocean AAIW and RSW intermingle but their opposing characteristics (low temperature / salinity and higher temperature / salinity respectively) allows one to distinguish between them.

Southward spreading Red Sea Water (RSW) escapes from the Red Sea and remains at 500 - 600 m, deepening to 800 - 1100 m as it moves south through the Somali and into the Agulhas System (Gründlingh, 1985). The limit of its southward extension is normally 21° to 25° S in the Moçambique Channel (Lutjeharms, 1976; Wyrski, 1971). During its southward progression, the core salinity of RSW reduces from 38,0 at the Red Sea exit to about 34,7 in the Moçambique Channel (Gründlingh, 1985). The western Indian Ocean therefore represents a region where AAIW and RSW mix. Traces of RSW can be found as far south as 40° S at intermediate depths in the Retroflection region (Clowes and Deacon, 1935). However, the salinity maximum is reduced as a consequence of mixing with the fresher ambient surroundings. Gründlingh (1985) has observed a decrease in salinity from 34,8 to 34,5 over four degrees of latitude (28° S to 32° S) in the Agulhas system.

Deep Water

Below the Intermediate Waters of the Retroflection region are the Indian Deep (IDW), North Atlantic Deep (NADW) and the Circumpolar Deep Waters (CDW). In the Southern Ocean NADW lies between two layers of CDW (subdivided into Upper (UCDW - local oxygen minimum) and Lower (LCDW - local oxygen minimum)). NADW marks the relative salinity (and oxygen) maximum of the Retroflection region (slightly more saline than IDW - see Figure 2.6). The NADW signature decreases in intensity from the Atlantic into the Indian Ocean (Wyrski, 1971), consistent with its Atlantic origin. Indian Deep Water is associated with much lower oxygen

concentrations than NADW, resulting in NADW and IDW forming two distinct modes in the temperature - oxygen curve. As was mentioned in **The Global Thermohaline Conveyor Belt** section, NADW water originates from the North Atlantic Ocean and is found as far south as 56°S (Clowes, 1950). Its Θ/S range is 1,5° - 4,0°C and 34,80 - 35,00 (Emery and Meincke, 1986) and it dominates the Deep Water, not only in the North Atlantic but also within the western Indian Ocean. The geographic range of NADW is clearly defined by highly oxygenated water ($>5,0 \text{ ml.L}^{-1}$) at 3000 m depth (Olbers *et al.*, 1992).

In the southwest Atlantic, Circumpolar Deep Water (CDW) is split into UCDW and LCDW (with UCDW exhibiting a slightly higher oxygen minimum compared to LCDW) by the relatively warm, saline, oxygen-rich NADW (Reid *et al.*, 1977), thus allowing these three deep water masses to be differentiated in Θ/O_2 plots.

Bottom Water

The deep water layers overlie cold, oxygen-rich Antarctic Bottom Water (AABW) in the Retroflexion area. This water mass has a Θ/S range of -0,9 to 1,7°C and 34,64 to 34,72. Most AABW is formed in the southeastern Weddell Sea and spreads north throughout the World's ocean basins at abyssal depths (Deacon, 1937). A clear indication of the geographic distribution of highly oxygenated ($>5.2 \text{ ml.L}^{-1}$) AABW is evident in the *Southern Ocean Atlas* (Olbers *et al.*, 1992) at a depth of 4000 m.

In summary, the waters of the Agulhas Retroflexion region encompass a variety of thermochemical properties, as a result of the introduction of water from three disparate oceans. These "pure" water masses are further modified within the Retroflexion region from both lateral mixing between adjacent waters as well as vertical mixing induced through convective heat loss to the overlying atmosphere. Water mass modification is accentuated through the dynamic processes characteristic of the eddy field of the Agulhas Retroflexion. Modification of these waters returns us to the question: what are the anomalous quantities associated with volumes of water trapped within the vortices of Agulhas rings and eddies (with respect to interbasin transfer of heat and salt) and how does this impact on the global thermohaline circulation?

Interbasin exchange by Agulhas rings and eddies

Volume, heat and salt flux estimates

A near-surface volume transport of $15 \times 10^6 \text{ m}^3 \cdot \text{s}^{-1}$ between the southern Indian and South Atlantic oceans is necessary in order to balance the global heat and salt budgets for the world (Hastenrath, 1982; Gordon and Piola, 1983). Much of this transport must be round the southern tip of Africa, although there may be a small contribution through the Drake Passage (Olson and Evans, 1986). Transfer of Indian Ocean Central Water into the South Atlantic Ocean is accomplished by eddy-shedding at the Agulhas Retroflection (Olson and Evans, 1986; Lutjeharms and Gordon, 1987; Lutjeharms and van Ballegooyen, 1988) and by intermittent streams, plumes and filaments of Indian Ocean water injected into the Atlantic, perhaps encouraged by the presence of Agulhas eddies (Harris and van Foreest, 1978; Gordon, 1985; Olson and Evans, 1986; Lutjeharms, 1988b; Lutjeharms and Valentine, 1988a; Shannon *et al.*, 1990; Lutjeharms and Cooper, 1995).

The major mechanism for the injection of salt (and heat) into the South Atlantic is therefore through the Agulhas ring and eddy field. Estimates of volume flux contributions by Agulhas rings and eddies into the South Atlantic have been attempted, the results of which are dependant on the number of rings and eddies that enter the South Atlantic in one year and the volume contained within their vortices. Satellite altimetry data over the Retroflection suggests that between six and eight vortices enter the South Atlantic per annum (eg. 6 - Byrne *et al.*, 1994; 6 - van Ballegooyen *et al.*, 1994; 7 or 8 - Feron *et al.*, 1992). These are useful estimates of the number of rings and eddies entering the South Atlantic. However, the interbasin volume flux contribution of these vortices varies dramatically depending on how the background, larger-scale circulation is defined. Volume estimates range from 2 - 20 Sv ($1 \text{ Sv} = 1 \times 10^6 \text{ m}^3 \cdot \text{s}^{-1}$) per annum (eg. 5 Sv - Harris and van Foreest, 1978; 19 Sv - Whitworth and Nowlin, 1987; 10 Sv - Gordon *et al.*, 1987; 10 - 15 Sv - Gordon and Haxby, 1990; 2 - 5,5 Sv - McCartney and Woodgate-Jones, 1991; 2 - 20 Sv - Gordon *et al.*, 1992; 7,3 Sv - van Ballegooyen *et al.*, 1994). Similarly, heat and salt flux estimates vary but are typically of the order of 0,045 PW ($1 \text{ PW} = 1 \times 10^{15} \text{ Watts}$) and $78 \times 10^{12} \text{ kg}$ per annum respectively (van Ballegooyen *et al.*, 1994).

Transfer of water from the Indian Ocean into the Southeast Atlantic has been observed in global ocean circulation models (eg. Semtner and Chervin, 1988; FRAM Group, 1991). Preliminary results from the FRAM model of the Southern Ocean estimate a volume flux of 10 Sv and a heat input of 0,2 PW from the Indian Ocean into the Southeast Atlantic Ocean via Agulhas eddies (FRAM Group, 1991). More recent results from the prognostic phase of the model estimate that 23 - 30 Sv (and a mean heat flux of around 0,5 PW) enter the South Atlantic per annum (Stevens and Thompson, 1994). However, the eddies in the FRAM model seem to be too large and are shed at a rate of approximately 2 per year which does not agree particularly well with observations. This is probably due to sensitivity to a smoothed bottom topography, an invariant yearly wind cycle and the lack of sub-mesoscale turbulence in the model (Lutjeharms and Webb, 1992).

In summary, the important contribution made by Agulhas rings and eddies in the interbasin transfer of heat, salt and momentum from the Southwest Indian to Southeast Atlantic Ocean has been recognized by contemporary scientific researchers. The western and southern terminus of the Agulhas Retroflection has been identified as the region from which these mesoscale features are shed. The process of vortex shedding is relatively easily observed with the aid of satellite data, whilst the mechanisms responsible for this shedding process are beginning to be revealed with the aid of numerical modelling studies. Numerous hydrographic surveys of the Agulhas Retroflection region have identified Agulhas rings and eddies - emphasizing the variability associated with the morphology and hydrography of such features. Despite all the attention the Retroflection region has received through scientific research over the last decade, numerous key questions remain unanswered. The following chapter identifies a selection of knowledge gaps that require further research. In particular, **Chapter 3** identifies those key questions addressed in this thesis.

CHAPTER 3

RESEARCH OBJECTIVES

As is clear from the review of the literature, the Agulhas Retroflection region has been the focus of a considerable number of investigations. This particular region is the meeting place for water masses from three distinct oceans and forms a "bottleneck" as two opposing flows (shallow / warm from Indian to Atlantic and deep / cold from Atlantic to Indian Ocean) are restricted to a limited area south of Africa (Gordon, 1986). Of particular interest in this circulation is the inter-ocean exchange of heat, salt and momentum between the southwest Indian Ocean and southeast Atlantic Ocean in the form of rings and eddies shed from the Agulhas Retroflection.

Despite this recognized importance of the region and the large number of publications on the Retroflection, certain limitations in our knowledge and understanding of this area clearly emerge from a perusal of the literature. One such limitation concerns the nature of the anomalous quantities associated with Agulhas rings and eddies shed from the Retroflection.

Publications stemming from the *ARC* hydrographic data (eg. Lutjeharms and Gordon, 1987; Gordon *et al.*, 1987) describe only two Agulhas vortices present within the Retroflection at that time. However, the *ARC* data set lacks the geographic extent required to identify a wider range of anomalies associated with Agulhas vortices. Ideally one would want a hydrographic data set which resolves a large number of Agulhas rings and eddies present in the Retroflection region at one time. The general hydrography of a suite of vortices gathered in this way would provide the detail necessary to define the range of attributes that can be expected of such features, and thus contribute to a better understanding of the nature of the exchanges south of Africa.

A second limitation in our knowledge of the Retroflection region concerns the detail of the water masses comprising it. Research efforts (eg. Gordon *et al.*, 1987; Bennett, 1988 and Chapman *et al.*, 1987) have identified the water masses observed within the Retroflection in a general way, yet failed to define the property extrema associated with each water mass in detail (with the possible exception of Bennett, 1988). It would be very valuable if a detailed analysis of the water masses of the Retroflection region, isolating property extrema associated with each water mass, as well as identifying water

mass properties unique to Agulhas rings and eddies could be achieved. This would be important in order to estimate the changes that vortices, originating in the Retroflexion, undergo with time, and thus their contribution to global heat and salt flux estimates. The results of such an analysis is presented in this thesis.

Thirdly, since much contemporary interest concerns the contribution of the "warm-water path" (Gordon, 1986; Piola and Gordon, 1986) to the Global Thermohaline Conveyer Belt, clearly the fate of Agulhas rings and eddies and their impact on thermocline salinity in the Atlantic is an important issue. However, in order to address this question the vast range of characteristics of these vortices must be better known, but this range is considerably extended as substantial modification of these vortices occurs within the Retroflexion region and immediate vicinity. This is true not only for the upper layers of these features in contact with the atmosphere, but also mixing with ambient water at greater depth. Investigating this modification using a much wider range of features than measured before (eg. Gordon *et al.*, 1987) would help in establishing the possible full extent of such modification.

From an inspection of the present knowledge on the Agulhas Retroflexion system, as evident in the scientific literature, these three shortcomings seem to be the most prominent: a lack of knowledge about the range of vortices shed from the region, inadequate information concerning the fuller detail of the water masses involved in these features and lastly, deficient understanding of the degree of modification these water masses could undergo in the Retroflexion region itself. To investigate this properly a very special data set would be required. This is available in the hydrographic data collected during the Subtropical Convergence and Agulhas Retroflexion Cruise (SCARC; Valentine *et al.*, 1988), outlined in the chapter that follows.

CHAPTER 4

DATA AND METHODS

Hydrographic data

The Subtropical Convergence and Agulhas Retroflection Cruise (SCARC)

The Subtropical Convergence and Agulhas Retroflection Cruise (SCARC) was undertaken from 12 February - 4 March 1987 and was designed specifically to investigate the range of characteristics of a number of rings and eddies in the Agulhas Retroflection region. Of particular interest were fluxes of heat, salt, nutrients and other tracers into the South Atlantic and across the Subtropical Convergence (STC). Air-sea interactions occurring within the Agulhas Retroflection region and at the Subtropical Convergence and the marine ecology within these frontal regions were also addressed. A description of the cruise and some preliminary findings have been given by Lutjeharms (1987). Interbasin heat and salt fluxes associated with the eddy field over the period of the cruise have been presented by van Ballegooyen *et al.* (1994).

In order to achieve the primary aim of resolving the Agulhas rings and eddies, a key element in the planning and execution of the cruise was the use of infrared satellite remote sensing. A number of mesoscale eddies were identified in this manner and an attempt was made to hydrographically survey as many of these features as possible. As a result a total of six warm-core eddies as well as the Agulhas Current itself were surveyed. Limited spatial resolution (both horizontally and vertically) was a result imposed by constraints such as the general requirement of extensive coverage of the Agulhas Retroflection region and the limited time available for the cruise. The data reported here consist of 121 T-7 expendable bathythermograph (XBT) profiles as well as 56 conductivity - temperature - depth - oxygen (CTD/O₂) profiles obtained using a NBIS MKIIIB CTD underwater unit fitted with a Beckman oxygen sensor. The XBT temperature profiles, extending to a nominal depth of 760 m, were not calibrated but were quality controlled using surface observations of temperature obtained using a Crawford Bucket (Crawford, 1972). The CTD/O₂ profiles extend to a pressure of 1500 db, except where the water depth was less than 1 500 m. In such cases, CTD casts extended to within 20 m from the ocean floor. The CTD/O₂ data were calibrated against an HP Quartz Thermometer for temperature and IOS standard seawater for

salinity. Further field calibrations were made using salinity and oxygen samples from bottle data collected at each station. A full account of the data processing, accuracy and complementary observations such as those of nutrients and chlorophyll-*a* are given in Valentine *et al.* (1988).

The Discovery 165A Cruise

The *SCARC* was specifically timed to coincide with a cruise by the *R.R.S. Discovery* over the Agulhas Retroflection. The *Discovery 165A* Cruise was undertaken from 28 February - 25 March 1987, and was designed mainly to recover ten moorings set two years previously in the Agulhas Current and Retroflection region. Ten full-depth CTD casts were done, one in the vicinity of each mooring and 3 700 km of *SeaSoar* sections were run in the Agulhas Retroflection region between moorings. Details of the CTD profile plots and listings, as well as contoured sections of *SeaSoar* data (potential temperature, salinity, density, chlorophyll-*a* and geostrophic shear) are reported in Read *et al.* (1987). The moored current meter data, AVHRR, CTD and drifter data are listed in a WHOI Technical report (Luyten *et al.*, 1990).

The data of the *Discovery 165A* cruise have been used in this investigation to complement the existing *SCARC* data since they cover a similar geographical area over the same period. These data are particularly useful in filling the data gap that exists in the *SCARC* data in the region of the Agulhas Retroflection (viz. Figure 4.1). It also provides valuable CTD data of the Agulhas Current input, that is used for inter-cruise comparisons and identification of the Deep and Bottom Waters of the Agulhas Retroflection region (since the *SCARC* CTD casts only extended to a maximum depth of 1 500 db). Hydrographic data collected in the *165A Discovery Cruise* were supplemented with satellite infrared imagery wherever possible and appropriate.

Satellite data

Thermal infrared satellite imagery

Geostationary *Meteosat* and orbiting *NOAA-9* (AVHRR) thermal infrared (T.I.R) images were used to identify the mesoscale surface thermal features of the Agulhas Retroflection region as described above. Images were analyzed spanning a period starting one month prior to the *SCARC* (1 January 1987) and extending to the end of the cruise (4 March 1987). A total of 62 *Meteosat* and 17 *NOAA-9* T.I.R images were analyzed, of which only 15 *Meteosat* and 3 *NOAA-9* images were considered to be fully

representative of the surface thermal patterns of the Retroflection region over the study period.

Geosat satellite altimetry

The *Geosat* satellite was launched on the 12 March 1985 and after its Geodetic Mission which lasted 18 months, collected altimetric data for more than three years during its Exact Repeat Mission (Douglas and Cheney, 1990). An analysis of this data over the Agulhas Retroflection region has been done by van Ballegooyen *et al.* (1994). A brief description of the results of their analysis, as applied to the hydrography of the *SCARC*, is used to corroborate the present results.

A graphic portrayal showing the periods during which individual features, such as vortices, were recognizable in the altimetric data and periods when each was hydrographically sampled during the *SCARC* and *Discovery 165A* cruise, is given in Figure 4.2. This clearly demonstrates the overlap of the two cruises in time and the subsequent longevity of each hydrographic feature. The fact that these two cruises, as well as three sets of satellite data were, partially fortuitously, all available for these features at the same time, has generated an unusual data set entirely appropriate to address the main shortcomings in our present knowledge, as identified in the **Research Objectives** of the previous chapter.

Methodology concerning the range of mesoscale features

Potential temperature, depth and density calculations

Potential temperature was calculated using the Bryden polynomial for the adiabatic lapse rate and the Runge-Kutta fourth order integration algorithm (Bryden, 1973; Fofonoff, 1977), referenced to the 1 500 db pressure surface. Pressure was converted to depth after the method used by Saunders and Fofonoff (1976) and the density of seawater was calculated from the international equation of state (UNESCO, 1983).

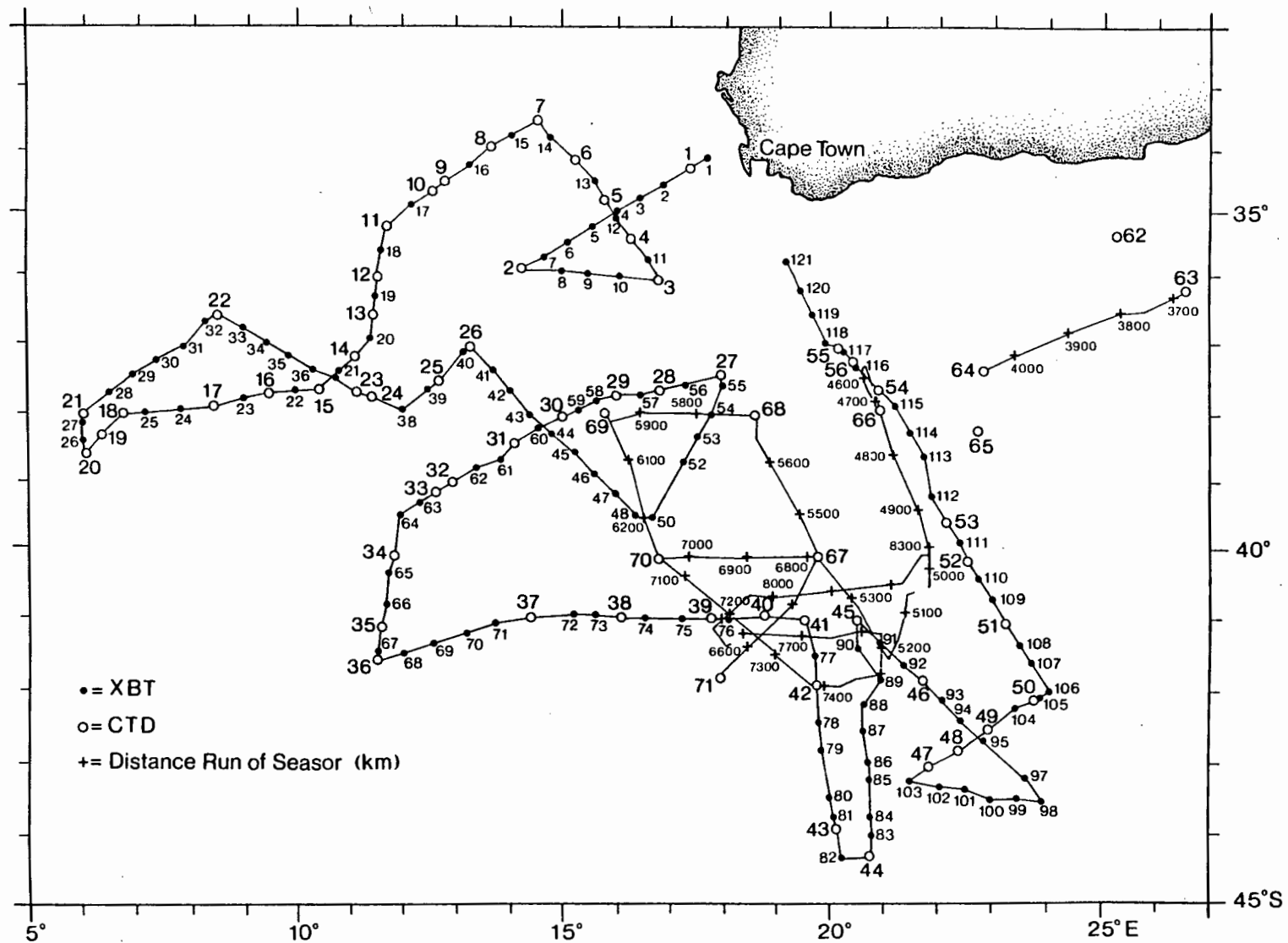


Figure 4.1: The cruise tracks of both *SCARC* and *Discovery 165A* hydrographic voyages. Open circles denote CTD stations, solid circles indicate XBT stations. Crosses indicate the distance run (in km) by the *Discovery 165A SeaSoar*.

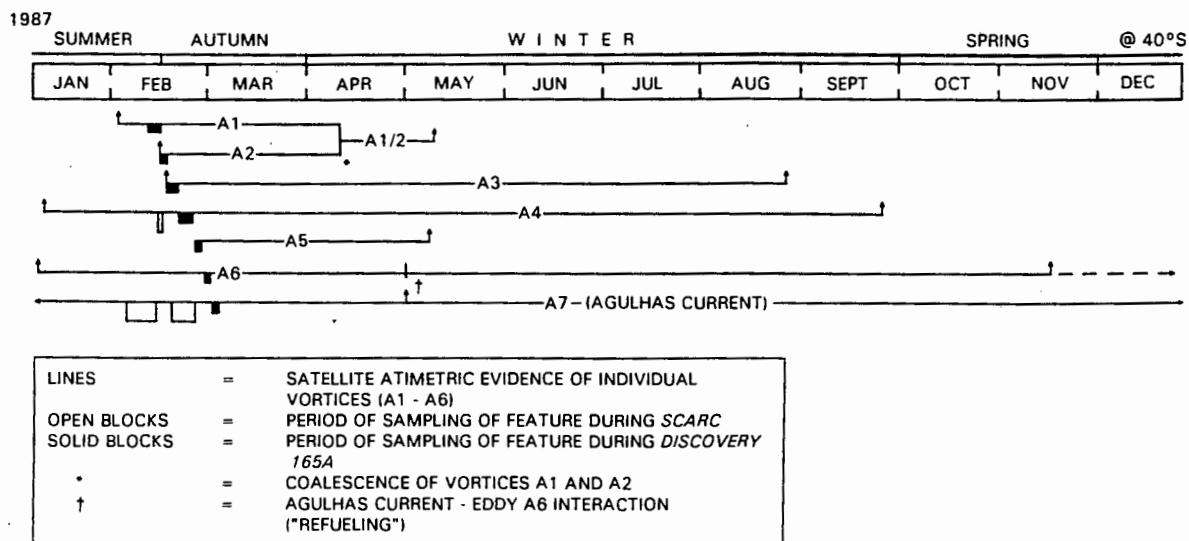


Figure 4.2: Chronological summary of the *SCARC* rings and eddies as observed in the hydrographic data and complementary altimetric data.

Generation of vertical sections

Vertical sections of temperature, potential temperature, salinity, potential density and sound velocity were obtained using a gridding and contouring software package called *SACLANT* on a *Unix* based mainframe computer (XBT data was included in the temperature sections). A combination of linear and polynomial interpolations of the gridded data were subjectively selected to ensure sufficient smoothing and elimination of spurious peaks. The resultant output plots are generated to the same horizontal and vertical scales.

Calculation of mixed layer depths

For the purposes of this thesis the depth of the mixed layer was calculated using the assumption of Priddle *et al.* (1986) that the pycnocline starts where the (potential) density gradient exceeds 0.03 kg.m^{-3} per meter. This definition adequately defines the depth of the mixed layer in the Retroflection region (viz. Figure 4.3). However, in some cases this definition underestimates the depth of the primary pycnocline where secondary pycnoclines are present. Since the rate of change of the potential density was calculated every 1 db through the water column, the depth of the mixed layer was therefore chosen when the rate of change of the potential density equalled or exceeded 0.03 kg.m^{-3} for at least 20 db (ie. the pycnocline must extend over a depth ≥ 20 db -

see Figure 4.3). This criterion eliminates sensitivity to "secondary pycnoclines", reaching a more realistic estimate of the mixed layer depth.

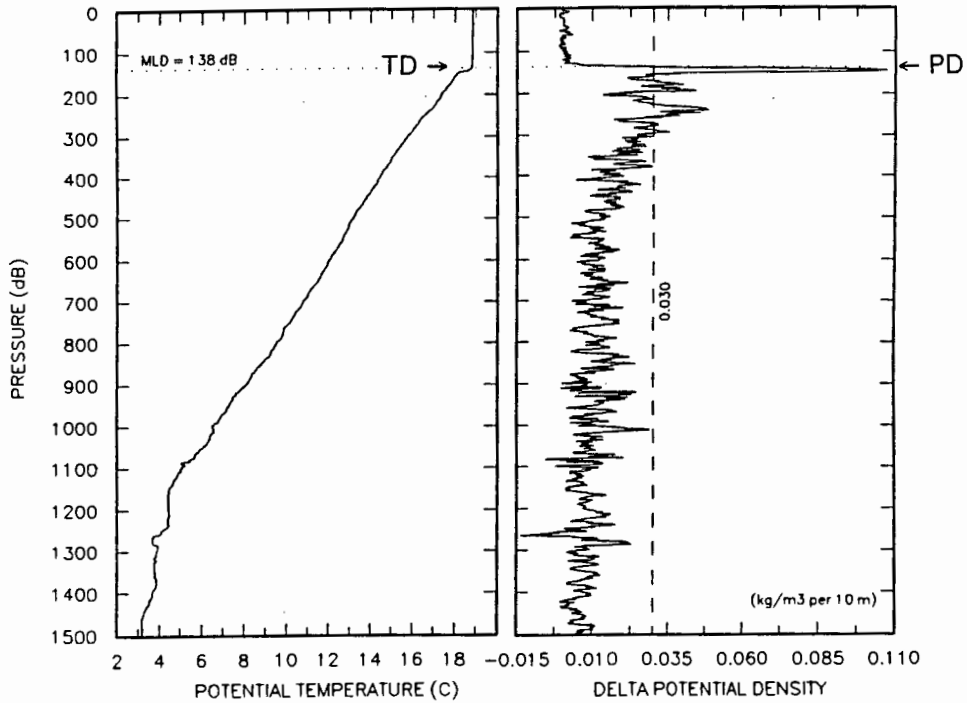


Figure 4.3: A comparison of the thermocline depth (TD) with the pycnocline depth (PD) at the center of Ring A4, as defined using Priddle's (1986) parameter.

Dynamic topography - the two-layer model

A two-layer model (Olson, 1980; Olson *et al.*, 1985; Olson and Evans, 1986; Bennett, 1988) is used to describe the circulation within the Agulhas Retroflection region. This model enables one to relate the depth of a particular surface to the geopotential anomaly at each station. In this manner, XBT data can be used to complement the CTD data in determining the dynamics of the region. The model was employed for the 8°C, 10°C and 12°C isotherms, the results of which are presented in the **Results and Discussion** section. Plan sections of the estimated geopotential anomalies calculated from the above results are contoured over the entire Retroflection region.

Geostrophic Calculations

Geostrophic velocities between hydrographic stations were calculated using Equations 1 and 2, referenced to 1 500 db.

Volume fluxes between station pairs were calculated at standard pressure layers by multiplying the thickness of the specific layers by the average velocity and the distance between the station pair. The sum of these layers (referenced to 1 500 db) gives the total volume transport between the station pairs. Similarly, heat fluxes in standard pressure layers were calculated by multiplying the volume transport associated with that specific layer by the heat content, knowing the average specific heat of the layer and its average temperature.

Great circle distances (gcd) between the hydrographic stations were calculated using Equation 3.

Geostrophic velocities between two depths were calculated for each station pair using Equation 1:

$$v_1 - v_2 = (1 / F \cdot \partial x) [\Delta \phi_B - \Delta \phi_A] \quad \text{.....Equation 1.}$$

Where:

$v_1 - v_2$ will be measured in meters per second
 ∂x is the distance between the station pairs in meters
 F is the Coriolis force at an average latitude for the two stations
 ϕ is the geopotential anomaly calculated for each station relative to a common reference such that:

$$\Delta \phi = \int_{p_1}^{p_2} \delta \cdot \partial p \quad \text{.....Equation 2.}$$

Where:

δ is the specific volume anomaly calculated using the UNESCO (1983) algorithm and ∂p is the difference between the pressure surfaces

The great circle distances (gcd) between the hydrographic stations were calculated according to the formula:

$$\text{gcd} = R \cdot \arctan \sqrt{\left(\frac{1}{\alpha^2} - 1 \right)} \quad \text{.....Equation 3.}$$

Where:

$$\alpha = \cos(\text{lat}_1) \cdot \cos(\text{lat}_2) \cdot \cos(\text{lon}_1 - \text{lon}_2) + \sin(\text{lat}_1) \cdot \sin(\text{lat}_2)$$

the latitudes and longitudes are given in radians

Defining the horizontal dimensions of the mesoscale features of the Agulhas Retroflection region

The horizontal dimensions of mesoscale features of the Agulhas Retroflection region can be measured according to a variety of methods. For the purposes of this thesis the main mesoscale features of the Retroflection region are identified using the intersection of the 10°C with the 300 db water depth, since the mean flow outside the influence of major mesoscale features is approximated by the 10°C isotherm located at an average depth of 300 db. This method thus measures the deviation of the 10°C temperature field within the feature from that of the surrounding water. A similar technique was successfully adopted by Olson and Evans (1986) and by van Ballegooyen *et al.* (1994) to define the horizontal extent of Agulhas rings.

Mesoscale features present within the Subantarctic regime sometimes exhibit a vertical thermal structure in which the 10°C isotherm is always deeper than 300 db. In such rare cases, the "flattening" off of the 10°C isotherm subsurface is used to define the horizontal dimensions of the feature. This second method is rather subjective since no actual slope value for the 10°C isotherm was chosen to represent the limit for "flattening" off.

Defining the vertical dimensions of the mesoscale features of the Agulhas Retroflection region

Since the majority of the mesoscale features of the Retroflection region exhibit a deflection in the vertical thermohaline structure over the entire sample depth (1 500 db), the depth of the 10°C was chosen to best represent the relative intensity of the different features. This technique has been used quite extensively in the Retroflection region (eg. Olson and Evans, 1986; van Ballegooyen *et al.*, 1994) with good effect. It is important to note that the depth of the 10°C isotherm does not necessarily coincide with the maximum depth of perturbation. Agulhas vortices usually extend much deeper than indicated by the depth of the 10°C isotherm.

Methodology concerning the detail of water masses

Water Mass Analysis

Temperature - salinity - oxygen plots were primarily used to identify the various water masses, complemented by nutrients where required. Preliminary water mass analysis was based on the property extrema identified by Duncombe Rae (1991) from Bennetts' (1988) analysis of the water masses of the Agulhas Retroflexion. Means and standard deviations of the core properties of density, potential temperature and salinity have been estimated using 1 db resolution *SCARC* data (and standard output *Discovery 165A* data - see Read *et al.*, 1987) with revised extrema pertinent to the water masses sampled during the period of the *SCARC*.

Isentropic analyses

Properties plotted along particular density surfaces are generally representative of distinct water types. This method was used to "trace" particular water types - the selection of the actual density surfaces used is loosely based on the property extrema of the water masses of the Agulhas Retroflexion region. Potential temperature, salinity, oxygen, nitrate and silicate are therefore contoured on the following surfaces:

$\text{Sigma-}\theta = 25,80$ (South Indian Subtropical Surface Water)

$\text{Sigma-}\theta = 26,80$ (South Indian Subantarctic Mode Water)

$\text{Sigma-}I = 31,80$ (Antarctic Intermediate Water)

$\text{Sigma-}I = 32,15$ (Deep North Indian Water [Red Sea Water])

$\text{Sigma-}t = 27,30$ (Deep North Indian Water [Red Sea Water])

These isolines of properties along specific density surfaces have been subjectively contoured in regions where hydrographic data is absent, relying on the inferred hydrography of the region using concurrent satellite data (both thermal infrared imagery and satellite altimetry).

Methodology to quantify the modification of water masses

Heat and salt anomalies

Although heat and salt fluxes between station pairs are useful for comparisons with other station pairs, a more useful quantity to use are heat and salt anomalies relative to a particular reference station. The anomalous quantities are thus essentially available

for isopycnal mixing, resulting in water mass modification. It is therefore best to determine the heat (and salt) anomaly within each density layer and then sum these throughout the vertical water column to obtain the total heat (and salt) anomaly contained within particular hydrographic stations. To use density as the vertical co-ordinate it is necessary that both temperature and salinity data are available to calculate the densities. In the absence of salinity data it is tempting to use known Θ/S curves of the water masses and infer a salinity and thus a density. However, it is in the surface waters where the anomalies are greatest, as is the variability of the Θ/S characteristics. Such an inference is thus likely to produce spurious results. Consequently, only CTD data is used to estimate the heat (and salt) anomalies.

In order to calculate the heat and salt anomalies associated with the hydrographic stations of the *SCARC* a reference station has to be chosen. Since the primary aim of this thesis is to describe the diversity of the Agulhas rings and eddies in the Retroflexion region and the modification of their waters, it is fitting that a station within the Agulhas Current input is chosen. Any anomalies calculated for the rings and eddies are therefore indicative of the modification of their waters relative to the source current. Since station CTD_055 was inshore of the Agulhas core, only two stations remain, namely CTD_054 and CTD_056. Station CTD_054 was chosen (rather than CTD_056) to be the best reference station of the Agulhas Current since it is located deep within the dynamical core of the Current (see **Addendum 2**, Section 16).

The formulae used to determine the heat and salt anomalies of the individual CTD stations of the *SCARC* are based on the available heat and salt anomalies put forward by Joyce *et al.* (1981), contained within discrete potential density layers (assuming a 1m x 1m column throughout the sample depth of 1 500 db, referenced to the Agulhas input station CTD_054). From the results of this analysis a two-layer model is implemented. Total heat and salt anomalies are calculated for the centre stations of the Agulhas rings and eddies for an upper and lower layer. The upper layer extends from the surface to a potential density surface of $26,9 \text{ kg.m}^{-3}$, whilst the lower layer extends from $27,0 - 27,5 \text{ kg.m}^{-3}$. No anomalies integrated over the entire volume of the Agulhas rings and eddies are computed since the anomalies within the two layers tend to oppose each other.

Calculation of the volume of Agulhas rings and eddies

Volume estimates for rings and eddies are difficult to make. Although their dynamic signature may extend to the bottom, the anomalous waters comprising the vortex may be much shallower. Most volume calculations of rings and eddies have been done using the volume enclosed within a particular isotherm. Olson and Evans (1986) applied a two layer model based on the radial structure of the depth of the 10°C isotherm (further discussion can be found in Olson *et al.*, 1985). However, care must be taken when estimating the volume enclosed within a vortex since the result is directly dependant on the choice of the isotherm. For the purposes of this thesis the volume of the individual *SCARC* rings and eddies are estimated using a variety of methods. The volume of water $\geq 10^{\circ}\text{C}$ and $\geq 6^{\circ}\text{C}$ is calculated, assuming the vortex to be a symmetrical parabola, with the diameter determined by the flattening off of the isotherms. A second method was employed to determine the volume trapped within the vortex, based on the theoretical results of Flierl (1981). According to him the trapping depth extends from the surface to a depth where the azimuthal speed equals the translational velocity of the vortex. The diameters of the vortices are identical to those determined in the first method. Once again, the shape of the trapping was assumed to be parabolic and symmetrical. The translational velocity of the individual vortices were determined from the altimetric study of van Ballegooyen *et al.* (1994).

The results of the applications of all these methods follows in **Chapter 5**, starting with a general description of the Agulhas Retroflection region observed during the *SCARC*, leading on to a detailed analysis of the dynamics of the individual mesoscale features hydrographically sampled within the Retroflection region. Thereafter, a detailed water mass analysis examines the thermochemical properties comprising these features, the results of which set the scene for the final section, namely a heat and salt anomaly analysis, quantifying the thermohaline modification each feature experiences within the Retroflection region.

CHAPTER 5

RESULTS AND DISCUSSION ON THE GENERAL HYDROGRAPHY OF THE AGULHAS RETROFLECTION REGION

Since the research objectives of this thesis are threefold, the presentation of the results and discussion are done accordingly. Firstly, the general hydrography of the Retroflection region is described in **Chapter 5**, with particular attention to defining the dimensions and dynamics associated with a range of six Agulhas vortices present in the Retroflection region at one time. Secondly, having ascertained the morphology and dynamics of these vortices, a detailed analysis of the water masses comprising these features follows in **Chapter 6**, defining the thermochemical extrema characteristic of each water mass.

Finally, having described the vortices and the waters masses comprising them, it will be evident that substantial modification of these water masses occurs within the Retroflection. In order to quantify this modification, a heat and salt anomaly analysis is presented in **Chapter 7**, highlighting the importance of mixing processes within the Retroflection region. A summary and conclusion of the major findings of this thesis is presented in **Chapter 8**.

5.1) General hydrography of the Agulhas Retroflection region as observed by satellite

5.1.1) Introduction

The Retroflection region exhibited a unique combination of rings and eddies during the period of the *SCARC* (February - March 1987). A suite of six warm-core vortices were hydrographically sampled, each with its own peculiar characteristics. This situation may have been atypical, since the *SCARC* took place immediately after a major perturbation of warm Agulhas Water entered the Southeast Atlantic (Shannon *et al.*, 1990). Only in late 1987 did Shannon *et al.* (1990) consider the Agulhas Retroflection region to have returned to normal.

Before describing the hydrography of each warm-core ring and eddy, the Agulhas Current at this time and the diverse surrounding waters in which they are all embedded, a general description of the Retroflection region as observed by satellite is given.

5.1.2) Satellite data

Thermal Infrared Imagery

Thermal Infrared (T.I.R) Satellite Imagery was available for every day, both prior to and during the *SCARC*. Indeed, such satellite support enabled the cruise track to be designed to hydrographically sample as many rings and eddies during the limited time available. The T.I.R imagery identified all but one of the warm-core rings and eddies sampled during the *SCARC*. As mentioned in the **Data and Methods**, only three suitable *NOAA AVHRR* and fifteen *Meteosat* images have been chosen to represent the surface thermal pattern over the period of the *SCARC* (Figures 5.1a, 5.1b, 5.1c, 5.2). Figures 5.1a - 5.1c clearly show the dynamic nature of the Retroflection region over a relatively short period of 30 days. Features such as the Agulhas Current (AgC), Agulhas Return Current (AgRC), cold surface filaments (C1 and C4), and a variety of rings and eddies (A2 - A6) can all be identified. Notice the S-shaped meander of the Return Current (23°E) and the predominance of at least five warm-core vortices within the Retroflection at one time (Figure 5.1b). Never before has such an abundance of mesoscale vortices been reported to exist within the Retroflection region at any one time.

A series of 15 *Meteosat* T.I.R images spanning a period of 54 days (Figure 5.2) illustrates the temporal evolution of the mesoscale features within the Agulhas Retroflection region prior to and during the period of the *SCARC*. Figure 5.2 shows the shedding of Eddy A4 in early January (08/01/87), followed by an eastward retreat of the Retroflection to reach its most eastern position 10 days later. Thereafter, the Retroflection prograded southwestward, plunging deep within the Subantarctic region to the south. By the 27 February 1987 Eddy A4 had presumably lost its surface thermal signature and could not be identified in the T.I.R. imagery. The improved spatial resolution of the *NOAA AVHRR* data provided greater resolution of the mesoscale features of the Retroflection. A period of only 29 days (Figures 5.1a and 5.1b) had seen the shedding of a substantial warm-core eddy (A4) from the southwestern extremity of the Agulhas Retroflection, as well as the northward growth of two attendant cold filaments (C1 and C4) of Subantarctic water from the south. It is these

cold surface filaments that often locate the warm-core Agulhas rings and eddies, since the vortices entrain these colder waters around their perimeter. Entrainment of cold water not only helps to locate these warm-core vortices, but also identifies their anti-cyclonic rotation.

It is important to recognize the temporal disjunction between the T.I.R images and the *SCARC* cruise track. For example, the location of the surface thermal expression constituting Eddy A4 (Figure 5.1b) is some 14 days prior to the *SCARC* hydrographic sampling of the feature (and some 9 days prior to the *SeaSoar Discovery 165A* sampling of the southeast sector of Eddy A4). Care is to be taken when interpreting Figures 5.1b and 5.1c since the T.I.R image line drawing is a "snapshot" of the surface thermal pattern over the entire Retroflection region, whilst these features evolve spatially during the execution of the hydrographic stations comprising the *SCARC* grid. The Agulhas Retroflection should therefore be seen as a highly dynamic region, where dramatic evolution of mesoscale oceanic features can occur during the period of a cruise such as the *SCARC* (20 days). Nevertheless, the satellite derived location of the majority of the mesoscale features of the Retroflection correspond closely to that observed in the hydrography (Figures 5.1b and 5.1c).

In summary, T.I.R imagery was able to resolve the surface thermal pattern of the major mesoscale features present within the Retroflection region prior to and during the *SCARC*. However, interpretation of the T.I.R imagery requires a fair amount of subjectivity on behalf of the user, and for this reason is used primarily to complement the interpretation of the hydrographic data presented in this thesis. Although one may infer a spatial and temporal evolution of individual mesoscale surface thermal features with somewhat limited success, the value of this data is severely restricted by extensive cloud cover and the fact that warm-core features within the Retroflection region rapidly lose heat to the overlying atmosphere, rendering them invisible to satellite T.I.R detection. However, a second satellite product was also available over the period of the *SCARC* - a product that does not suffer the shortcomings of T.I.R imagery.

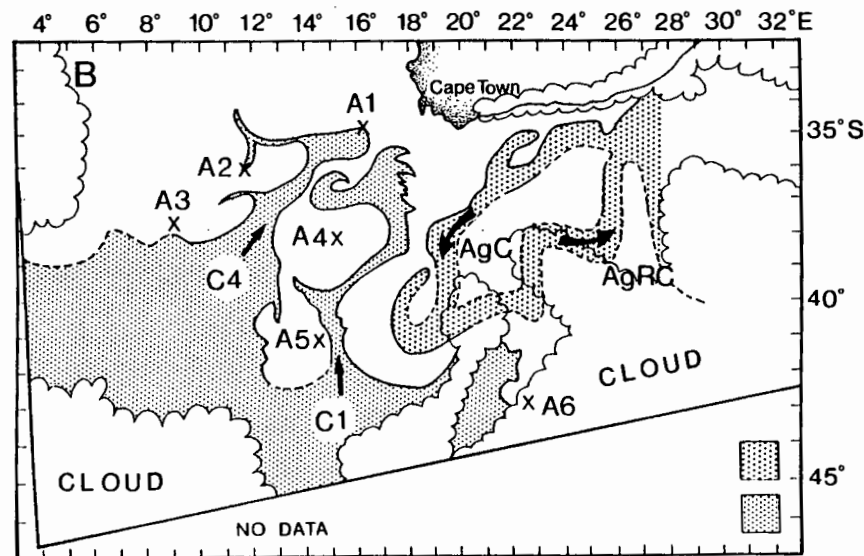
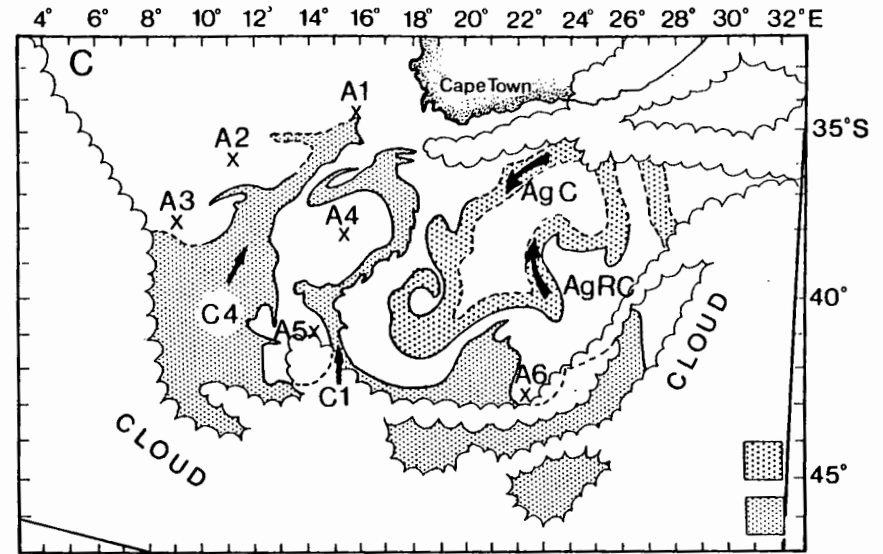
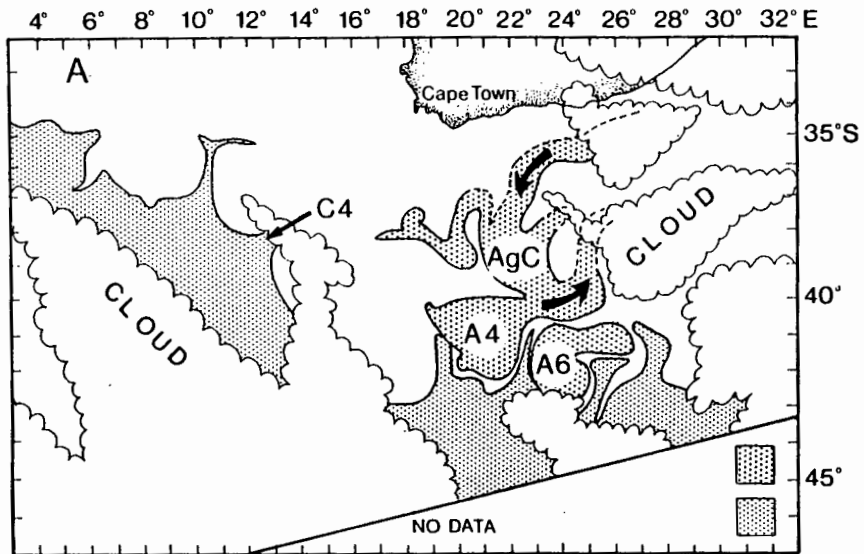


Figure 5.1a: Line drawing interpretation of the sea surface temperature as revealed by *NOAA-9 AVHRR* (08/01/87) imagery, showing the shedding of warm-core Eddy A4 from the south-western extremity (41°S; 21°E) of the Agulhas Retroflection. Notice the double surface thermal structure comprising Eddy A6 located just to the south of the Retroflection.

Figure 5.1b & 5.1c: Interpretation of the sea surface temperature as revealed by *NOAA-9 AVHRR* (06/02/87 and 07/02/87 respectively) imagery. The hydrographic centre positions of the various Agulhas rings and eddies have been shown by a cross.

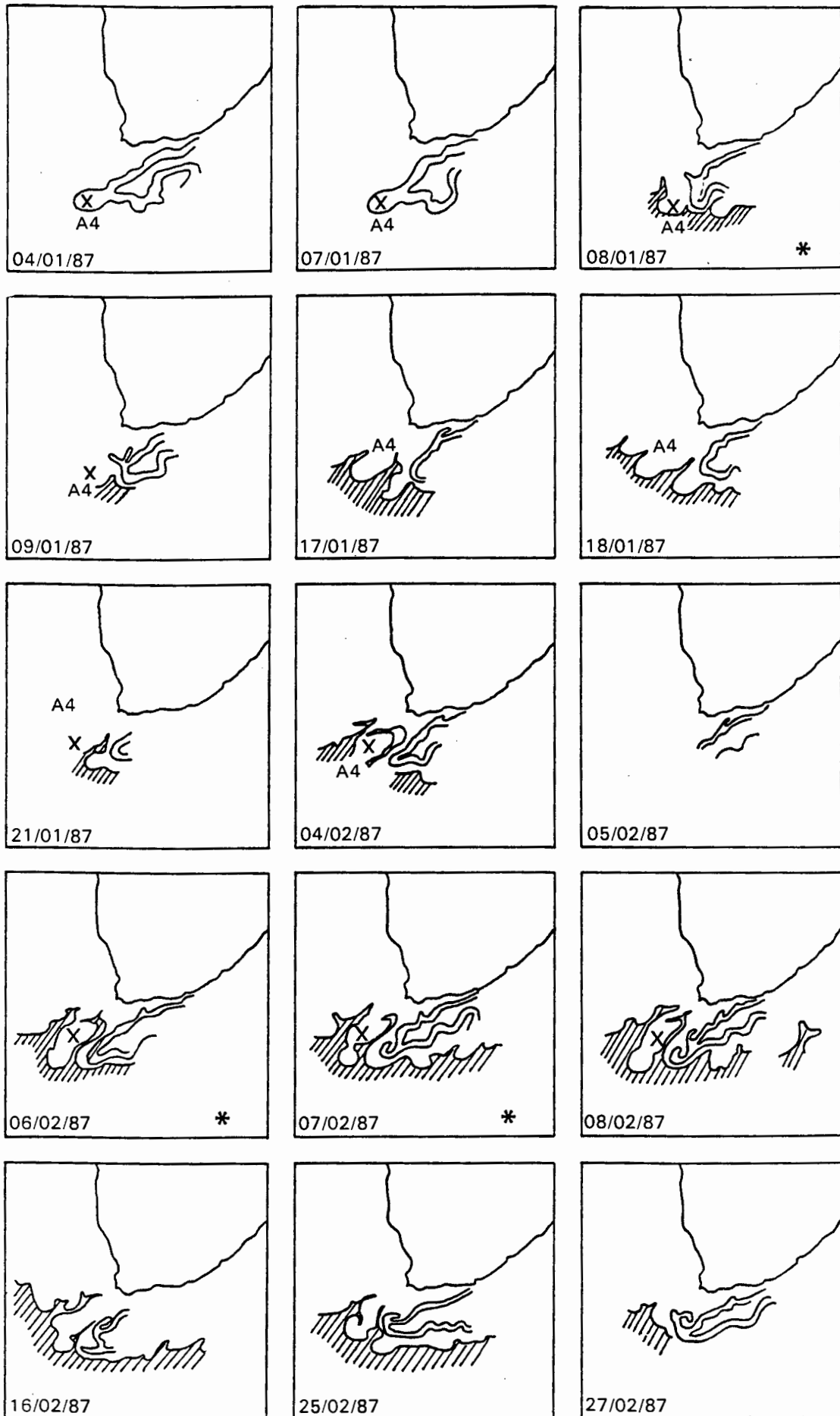


Figure 5.2: A series of line drawing interpretations of *Meteosat* thermal infrared imagery of the Agulhas Retroflexion region spanning a period of 54 days, prior to and during the SCARC. The cross indicates the approximate position of Eddy A4. The asterisk indicates corresponding days shown in the NOAA AVHRR imagery (Figures 5.1a, 5.1b & 5.1c).

Geosat Altimetry

As was mentioned above, Agulhas rings and eddies are difficult to track for lengthy periods of time using T.I.R imagery since they lose their surface heat and therefore their contrasting surface thermal signature. However, satellite altimetry provides a useful alternative for tracking such features since it is not affected by extensive cloud cover and surface heat loss, and can therefore trace particular mesoscale vortices from the shedding region of the Agulhas Retroflection, across the entire South Atlantic - a journey in excess of 2 years (McCartney and Woodgate-Jones, 1991). Other altimetric studies, most notably the tracking of Agulhas eddies across the Walvis Ridge and northwestward across the South Atlantic Ocean, have been done by Gordon and Haxby (1990). Similarly, Wakker *et al.* (1990) tracked eddies located in the Retroflection from July 1987 to July 1988. Satellite altimetry data presented by van Ballegooyen *et al.* (1994) show the drift and decay of all the rings and eddies hydrographically sampled during the *SCARC* (as well as a host of others not considered in this thesis). Here I present but a précis of van Ballegooyen *et al.*'s (1994) work, directly relevant to the hydrographic results of the *SCARC*. Of particular interest is the positive altimetric identification of all the mesoscale features evident in the hydrographic results of the *SCARC*, as well as the temporal evolution of these features prior to, during and after the *SCARC*.

A composite altimetric "snapshot" of the surface topographic anomaly (relative to the mean sea surface) for February 1987 is given in Figure 5.3. Notice the relative positions of all six anti-cyclonic vortices (A7 is the Agulhas Retroflection itself). The location of the 20,0 cm isoheight closely resembles the location of the intersection of the 10°C isotherm with the 500 db depth observed in the *SCARC* (Figure 5.3). The cold surface filament (C4) is noticeably absent in the altimetry data. A possible reason why filament (C4) is not identified in the *Geosat* altimetry data may be because this feature may not be an anomaly, but rather present at this particular location for the greater part of the year, thus contributing to the altimetrically derived mean sea surface. The surface thermal expression of this feature was observed in the summer of 1986/87 and is suggested by Shannon *et al.*, 1989 that it may be a semi-permanent feature, with the Agulhas Ridge acting as a barrier to the easterly zonal flow, causing a equatorward intrusion of Subantarctic Waters along the southwest to northeast axis of the Agulhas Ridge (Figure 5.4).

The other major filament of Subantarctic origin is filament (C1), which was entrained from the south along the eastern perimeters of Eddies A5 and A4 (Figures 5.1b, 5.1c, 5.3 and 5.5). Notice the westward-leaning sinusoidal translation of this feature from east to west in Figure 5.5 (January - December 1987). The altimetry data seem to suggest that the northerly extension of the Subantarctic waters (which constitutes C1) is perhaps the consequence of a westerly propagating wave along the Subtropical Convergence. A similar feature has been observed in the East Australian Current along the Tasman Front (Nilsson and Cresswell, 1981).

The altimetry data show that Rings A1 and A2 are observed to coalesce shortly after being sampled during the *SCARC*, and "lost" two months later (Figure 5.5). Eddy A3 was tracked, moving in a westerly and then northwesterly direction until August 1987 before it was no longer evident in the altimetry. Eddy A4 was observed in the thermal infrared imagery to be shed from the Retroflection on the 8 January 1987 (Figure 5.1a). It then moved off rapidly westward to the position where it was hydrographically sampled during the *SCARC*, thereafter moving northwards to become indistinguishable in the altimeter data by September 1987 (Figure 5.5). Eddy A5, which was hydrographically located southwest of the Retroflection, was tracked moving in a general westerly direction for three months before being "lost" in the altimetry (Figure 5.5). Caution must be taken when trying to track features such as Eddies A5 (and A6) since they are located in close proximity to the Subtropical Convergence (STC). This region is characterized by an elevated noise-to-signal ratio due to the high variability of the STC (van Ballegooyen, *personal communication*), rendering difficulties in tracking.

Eddy A6, which was shed in early January 1987, was found to be at its most southerly latitude ($42,5^{\circ}\text{S}$) at the time of the *SCARC*. Two months later (May) this eddy had interacted with the southward migrating Retroflection (A7), "refueled" and was re-shed as Eddy A6/7, which moved westwards and then northwards to be "lost" in November 1987 (Figures 5.5 and 5.6). It is important to note that although the particular features may be eventually "lost" in the altimetry data, it does not necessarily imply that the features no longer exist. Indeed, Byrne *et al.* (1994) in their analysis of the same *Geosat ERM* (Exact Repeat Mission) data for the Agulhas Retroflection and South Atlantic were able to track the same major rings some 1900 km further westward across the Mid-Atlantic. A compendium of the primary characteristics of the rings and eddies as revealed by *Geosat* are listed in Table 3.

In summary, the altimetric data presented above not only identifies all the mesoscale features hydrographically sampled during the *SCARC*, it also provides valuable insight into when each feature was formed, its subsequent translation, and eventual decay. A range of behaviors are observed. All the vortices (with possible exception of A5) are identified to eventually move off from the Retroflection in a west - northwesterly direction, at velocities ranging from 3,7 - 9,0 cm.s^{-1} . However, not all six vortices remained isolated within the Retroflection region. Rings A1 and A2 coalesced shortly after being sampled during the *SCARC*, whilst Eddy A6 interacted with the Agulhas Current and was re-shed as Eddy A6/7. The observation of ring - ring and eddy - current interaction has never before been observed in the Retroflection region. Consequently, I propose that the altimetric data presented here is probably a fair representation of the range of behaviors that can be expected of Agulhas vortices in the Retroflection region, and highlights the value of the *SCARC* data set, encompassing a whole spectrum of these features at one time.

Table 3: Altimetric drift speeds and height anomalies of the rings and eddies encountered during the *SCARC*

Feature	Altimetric Height* (cm)	Period	Drift Speed (cm.s^{-1})
Ring A1	<20	Jan '87 - Apr '87	4,7
Ring A2	30 - 40	Jan '87 - Apr '87	6,0
Eddy A3	<20	Feb '87 - Aug '87	4,0
Eddy A4	50 - 60	Dec '86 - Nov '87	9,0
Eddy A5	35 - 40	Jan '87 - May '87	3,7
Eddy A6	30	Jan '87 - Nov '87	5,4
Agulhas Retroflection (A7)	40 - 50	Dec '86 - Nov '87	6,4
Subantarctic Filament (C1)	-40	Jan '87 - Dec '87	4,6
* Obtained from interpolated altimeter data as an altimetric height in (cm) above the altimetric mean sea level (adapted from van Ballegooyen <i>et al.</i> , 1994)			

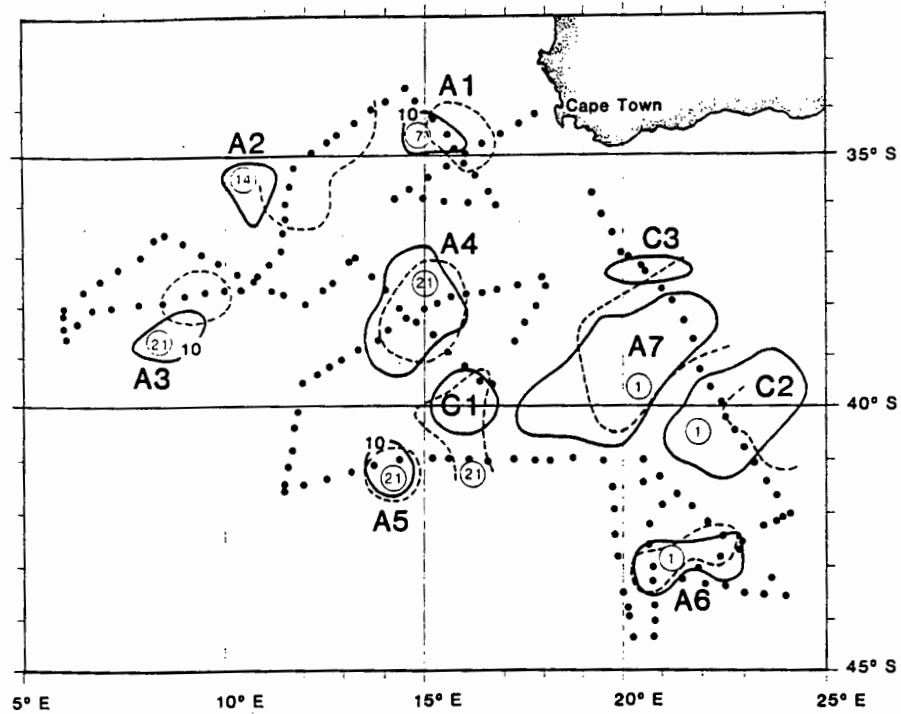


Figure 5.3: A composite altimetric snapshot of surface topographic anomaly (relative to mean sea surface) for February 1987. Indicated are the 20 cm isoheights above mean sea level (bold contours), except Rings A1 and A2 where the 10 cm isoheight is portrayed. Also indicated are intersections of the 10°C isotherm depth with the 500 db isobar from the SCARC data (dashed contours). Individual mesoscale features have been identified (A = anticyclonic; C = cyclonic); the encircled number represents the date (7, 14, 21 February and 1 March) of the individual snapshot closest to the hydrographic observation (from van Ballegooyen *et al.*, 1994).

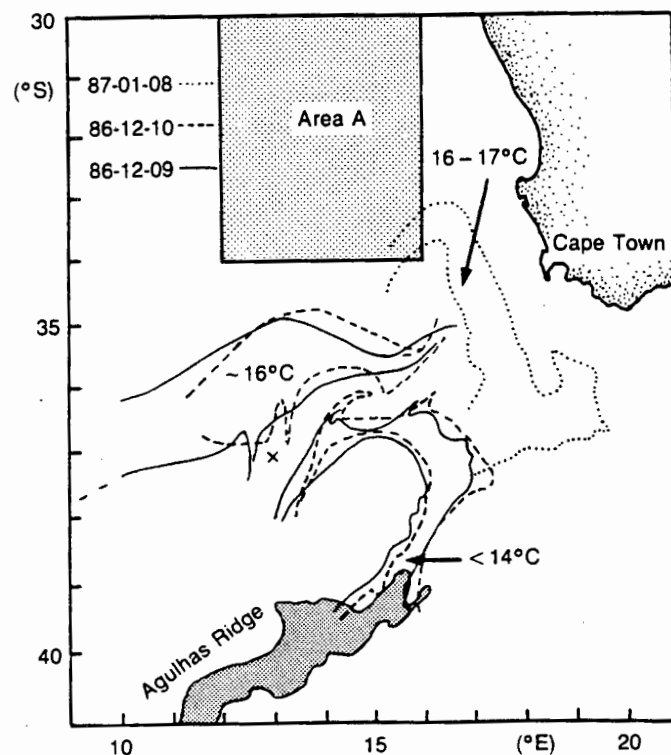


Figure 5.4: Changes in the location of the fronts associated with the intrusion of Subantarctic water during December 1986 and January 1987 (prior to the SCARC). The Agulhas Ridge is shaded (from Shannon *et al.*, 1989).

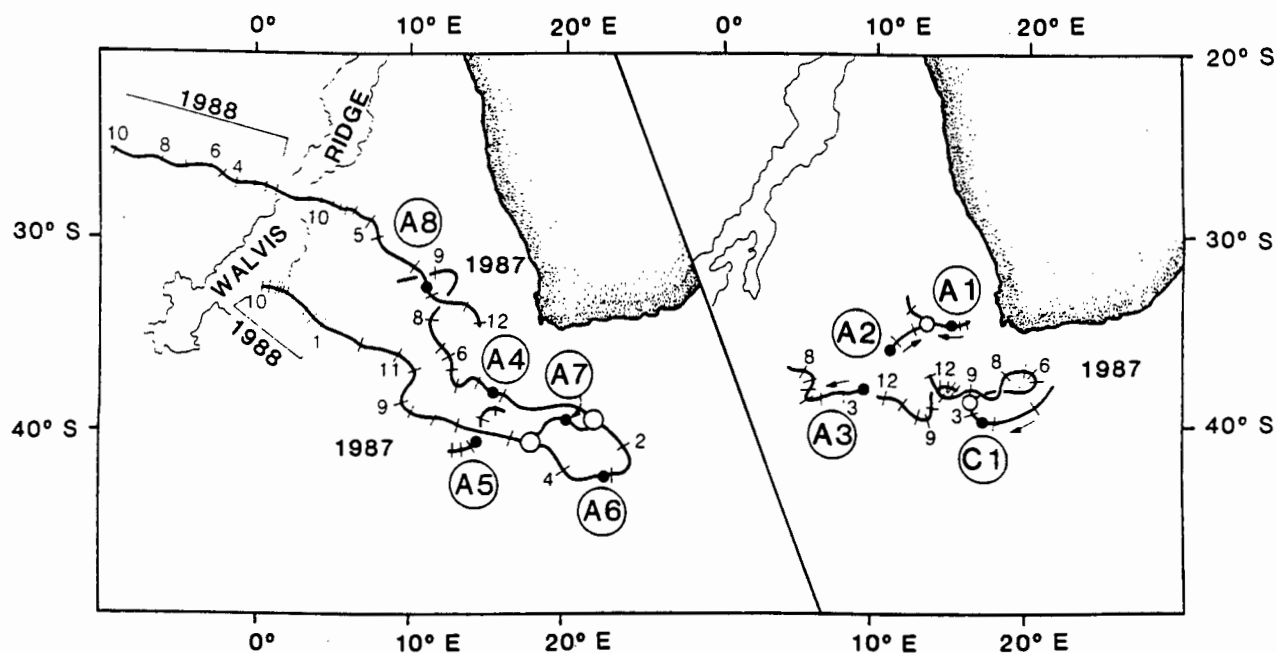


Figure 5.5: The movement of the SCARC rings and eddies as observed in *Geosat* altimetry. Dashes indicate the position at the first of each month, dots indicate the positions of the eddies at the time of the SCARC (February - March 1987) and the circles indicate the positions of separation or coalescence (from van Ballegooyen *et al.*, 1994).

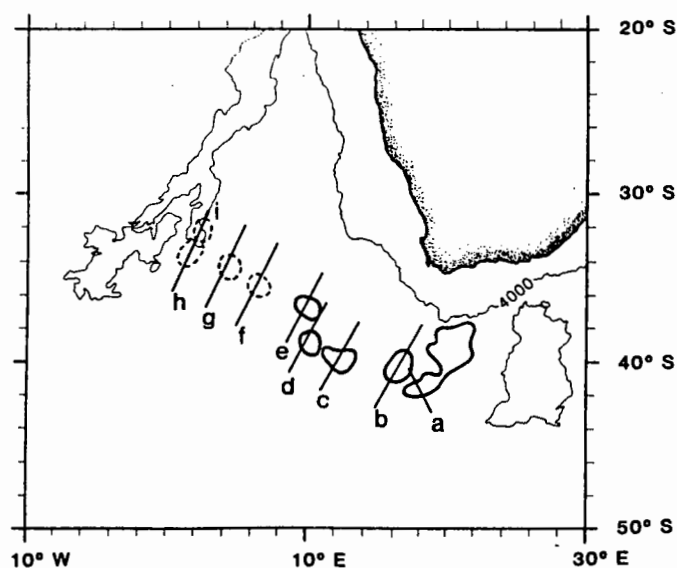


Figure 5.6: The movement of SCARC eddy A6/A7 as observed in *Geosat* altimetry contours. The coalescence of the eddies is reflected by the eastern-most contour (from van Ballegooyen *et al.*, 1994).

5.2) General hydrography and dynamics of the Agulhas Retroflection region during the *SCARC* (and *Discovery 165A*) cruises

5.2.1) Thermohaline Pattern

Having identified the Agulhas Current, two major cold-core filaments (C1 and C4) and six warm-core vortices (A1 - A6) from the satellite data presented above, the hydrographic analysis which follows investigates the vertical extent of these features. To this end, the general thermohaline pattern encountered during the *SCARC* is presented on four near-surface depths (0, 50, 100 and 200 db) and using specific core density surfaces (outlined in the **Data and Methods**).

Thermohaline Pattern in the Surface Layers

0 db Surface (Figures 5.7 and 5.8)

The sea-surface thermal pattern (Figure 5.7) closely resembles that observed in the T.I.R imagery (Figures 5.1b and 5.1c). The surface thermal core of the Agulhas Current is located along the near-shore edge of the Current (CTD_056 and XBT_116), with temperatures exceeding 26°C. The Agulhas Current extends to a western limit of about 17°E where it executes an anti-cyclonic turn, its warm surface waters flowing off eastward. Since the major source of salt into the surface waters of the Retroflection is via the Agulhas Current, a pattern emerges with high salinity water (>35,40) entering the Retroflection from the northeast, invading the less saline South Atlantic waters to the south and west (Figure 5.8).

Thermal signatures in excess of 20°C are evident in Ring A2 and Eddies A3 and A4. Interestingly, Ring A2 displays the highest surface temperatures (>21°C), comprising the two warm poles of the ring. This saddle-like morphology is evident in the vertical hydrographic section (see **Addendum 2**, Section 4). The surface thermal signatures of Ring A1 and Eddy A5 are poorly defined. Water cooler than 17°C clearly delineates the Subantarctic influence from the south, with a well defined filament (C4) extending as far north as 36°S. Eddy A6 seems to exhibit a double lobe surface thermal pattern, with Subantarctic water bisecting the warm surface signature of the eddy. Adopting the definition used by Lutjeharms and Valentine (1984) for the surface thermal expression of the Subtropical Convergence ("where the 14°C breaks the surface"), this front can be seen to exhibit great poleward deviation in its mean zonal location (typically

between 42° - 45°S in this region), varying in location from as far north as 39,5°S in the west to about 44°S in the eastern parts of the *SCARC* grid.

Maximum surface salinities (>35,60) are located within the warm cores of Ring A2 and Eddies A3, A4 and A5. The maximum surface salinity of their source is identified at the Agulhas input station CTD_054 (35,55), some 0,65 - 2,55 less saline than the core waters of the vortices mentioned above. "Boosted" surface core salinities within these vortices are attributed to evaporation as these discrete pools of warm water invade the cooler environment of the South Atlantic. "Fresh" surface waters are located to the south of the Subtropical Convergence (eg. CTD_044), comprising the Subantarctic Surface Waters. This fresh water enters the Retroflexion region from the south, aided by entrainment along the eastern perimeter of the individual warm-core rings and eddies. Most notably, cold Subantarctic filaments (C4 & C1) are entrained from the south along the eastern edges of Ring A2 & Eddy A3 and Eddies A4 & A5 respectively. The lack of a high surface salinity signal in Ring A1 is in agreement with the lack of a warm surface signature noted earlier. The surface salinities of Eddy A6 are similar to those of the Agulhas Current input, suggesting that the eddy has either been shed recently (ie. insufficient time for salinity "boosting" in the surface waters due to evaporation) or is interacting with the Return Current. *SeaSoar* data from the *Discovery 165A* cruise is presented later which seems to support the latter scenario.

50 db Surface (Figures 5.9 and 5.10)

At a depth of 50 db the most noticeable change in the thermal pattern of the Retroflexion region from the surface is the marked subsurface signature of an intruding cold water filament (C1) denoted by waters cooler than 17°C and extending northwards to within 100 km of Cape Town (Figure 5.9). In contrast, the subsurface signature of the northeastward protruding cold filament (C4) is remarkably reduced, extending to only about 37°S. This indicates that the thermal signature of the main eastern limb (the limb between A2 and A4) of the filament (C4) is restricted to the surface waters (0 - 50 db). The salinity pattern bears similar trends to that of the thermal signature at the same depth. Subantarctic filament (C4) has decreased its northward extension whilst (C1) exhibits greater northward penetration (Figure 5.10) at this depth.

The thermal signatures of Ring A2 and Eddies A3, A4, A5 and A6 are also evident at 50 db. Both Ring A2 and Eddy A6 have lost their saddle-like morphology whilst the thermal signature of Ring A1 is not evident at this depth. The intrusion of cold water

over the southeastern sector of Ring A1 could possibly constitute the northern extension of the cold Subantarctic filament (C1). The consequences of this intrusion of cold (and less saline) water into the surface waters of A1 is dealt with later in **Thermohaline Modification** section. Notice that the thermal core of the Agulhas Current at 50 db ($\Theta_{(\max)} > 23^{\circ}\text{C}$) had shifted offshore to about station CTD_054. Horizontal thermal gradients at 50 db have increased markedly as compared to the surface. Salinities in excess of 35,60 are identified within Ring A2 and Eddies A3, A4, A5 and the Agulhas Current (Figure 5.10). Notice the low salinity water (35,29; $18,11^{\circ}\text{C}$) along the near-shore edge of the Agulhas Current input (CTD_055). Low salinity water ($< 35,00$) is located directly over Ring A1. The source of the low salinity water over A1 seems to be from the northern extension of the cold Subantarctic filament (C1).

100 db Surface (Figures 5.11 and 5.12)

The potential temperature at 100 db clearly delineates the Agulhas Current and its neighboring eddy field during the *SCARC* (Figure 5.11). The typical "bull's-eye" thermal pattern of Ring A2 and Eddies A3, A4, A5 and A6 are plainly evident. All the rings and eddies sampled (excluding A1) exhibit similar core potential temperatures of between 17° and 18°C . Notice once again the absence of the "bull's-eye" isotherms in Ring A1. The characteristic high salinity water comprising the various warm-core vortices are well defined at the 100 db surface (Figure 5.12). High salinity water in excess of 35,60 is still present in the cores of Ring A2 and Eddies A3, A4 and A5, indicating that the "boosted" salinity due to evaporation is easily mixed to depths exceeding 100 db. A high-salinity signature within Ring A1 is still absent at 100 db depth. Eddy A6 displays some connectedness to the Agulhas Current, with maximum core salinities of about 35,59.

200 db Surface (Figures 5.13 and 5.14)

Figure 5.13 shows the thermal pattern of the Retroflection at 200 db, depicting a similar pattern to that at 100 db. Temperatures exceeding 15°C are shaded. Using the definition of Gründlingh (1983) for the dynamical core of the Agulhas Current (15°C isotherm intersection with the 200 db depth), the axis of the Current is located 30 km offshore of the surface thermal core depicted in Figure 5.7. Ring A2 and Eddies A3, A4, A5 and A6 all display water exceeding 15°C at this depth. Eddy A4 exhibits the greatest core potential temperature ($17,35^{\circ}\text{C}$; CTD_030), some $0,06^{\circ}\text{C}$ warmer than that of the Agulhas Current input (CTD_054) at the same depth.

The salinity pattern at 200 db is somewhat similar to that at 100 db. The most noticeable difference is the disappearance of high salinity water ($>35,60$) within the core of all the rings and eddies, except Eddy A4 (CTD_030) (Figure 5.14). The Agulhas input station (CTD_056) exhibits a maximum salinity of only 0,01 greater than that of Eddy A4, indicating the deep-reaching nature of Eddy A4.

In summary, the thermohaline pattern revealed from the *SCARC* data identifies a range of mesoscale features. The Agulhas Current is recognized - its western limit located at about 17°E , whereupon it initiates an anti-cyclonic turn (Retroflexion), its warm and saline ($>22^{\circ}\text{C}$; $>35,40$) waters flowing of westward as the Agulhas Return Current.

In addition to the Agulhas Current, a range of six Agulhas vortices are identified. From the above description it is apparent that each vortex exhibits particular thermohaline characteristics. However, some of their characteristics are not dissimilar and consequently can be loosely grouped into four classes, based primarily on their similarities identified above.

Eddies A3, A4 and A5 constitute the first class, all exhibiting a symmetrical, bowl-like thermohaline structure with depth, characteristic of a "normal" Agulhas vortex. Salinity "boosting" ($>35,60$) is evident in all three eddies to depths exceeding 100 db - some 0,65 - 2,55 more saline than the core waters of the Agulhas Current. Eddy A4 is an extreme example, with boosted salinities extending to a maximum depth of 200 db.

Ring A2 falls into the second class - a large ring exhibiting a saddle-like thermohaline morphology within the surface. A2 loses this bimodal morphology at depths exceeding 50 db, where its thermohaline signature becomes somewhat more symmetrical, tending toward those characteristics indicative of the first class of Agulhas vortices. In conjunction with the first class, A2 also displays boosted salinities to depths exceeding 100 db.

Eddy A6 is grouped into the third class, also exhibiting a double-lobe structure in the surface (although somewhat smaller than A2), losing this bimodal thermohaline structure at depths exceeding 50 db. A6 has similar core salinities to that of the Agulhas Current and it is therefore suggested that either the vortex had recently been shed from the Agulhas Current or the vortex was still interacting with the Current at the time. The altimeter data (see Figure 4.2) indicates that A6 may be the oldest of the six vortices (shed in early January 1987) and should theoretically exhibit "boosted"

surface salinities. In order for Eddy A6 to display similar core salinities to that of the Current either lateral mixing with the fresh Subantarctic water would have had to occur, thus compensating for the expected salinity "boosting", or the eddy would have to have been interacting with the Agulhas Current at the time. Indeed, the salinity pattern at 100 db does suggest some connectedness to the Agulhas Current. *SeaSoar* data presented later are in support of the Agulhas Current interacting with Eddy A6 at the time of the *SCARC* and *Discovery 165A* cruises.

Ring A1 falls into the fourth class of vortices. This feature seems to exhibit characteristics dissimilar to all other five vortices. A1 exhibits none of the expected surface thermohaline signatures expected of an Agulhas ring. In fact, the surface waters overlying A1 are decidedly fresh, possibly indicative of entrainment of a cold surface filament (C1) into the surface core of the feature. Nevertheless, C1 does display the bowl-shaped isotherms characteristic of an Agulhas vortex (see hydrographic Sections 1 and 3, **Addendum 2**) and is further identified as an Agulhas ring in the altimeter data presented above.

In addition to the Agulhas Current and its vortices, cold and fresh ($< 14^{\circ}\text{C}$; $< 34,6$) Subantarctic waters are identified. The thermohaline front separating these Subantarctic waters from the warmer waters to the north is the Subtropical Convergence (STC). Strong poleward deviation of the STC from its mean zonal location is observed, varying from as far north as $39,5^{\circ}\text{S}$ in the western part of the Retroflection region to as far south as 44°S in the eastern part. Much of this poleward deviation is attributed to entrainment of Subantarctic surface water along the eastern edges of vortices described above. Two major Subantarctic filaments are identified (C1 and C4). The former seems to be predominantly a subsurface feature in contrast to C4, which exhibits its greatest expression within the upper 50 db of the water column.

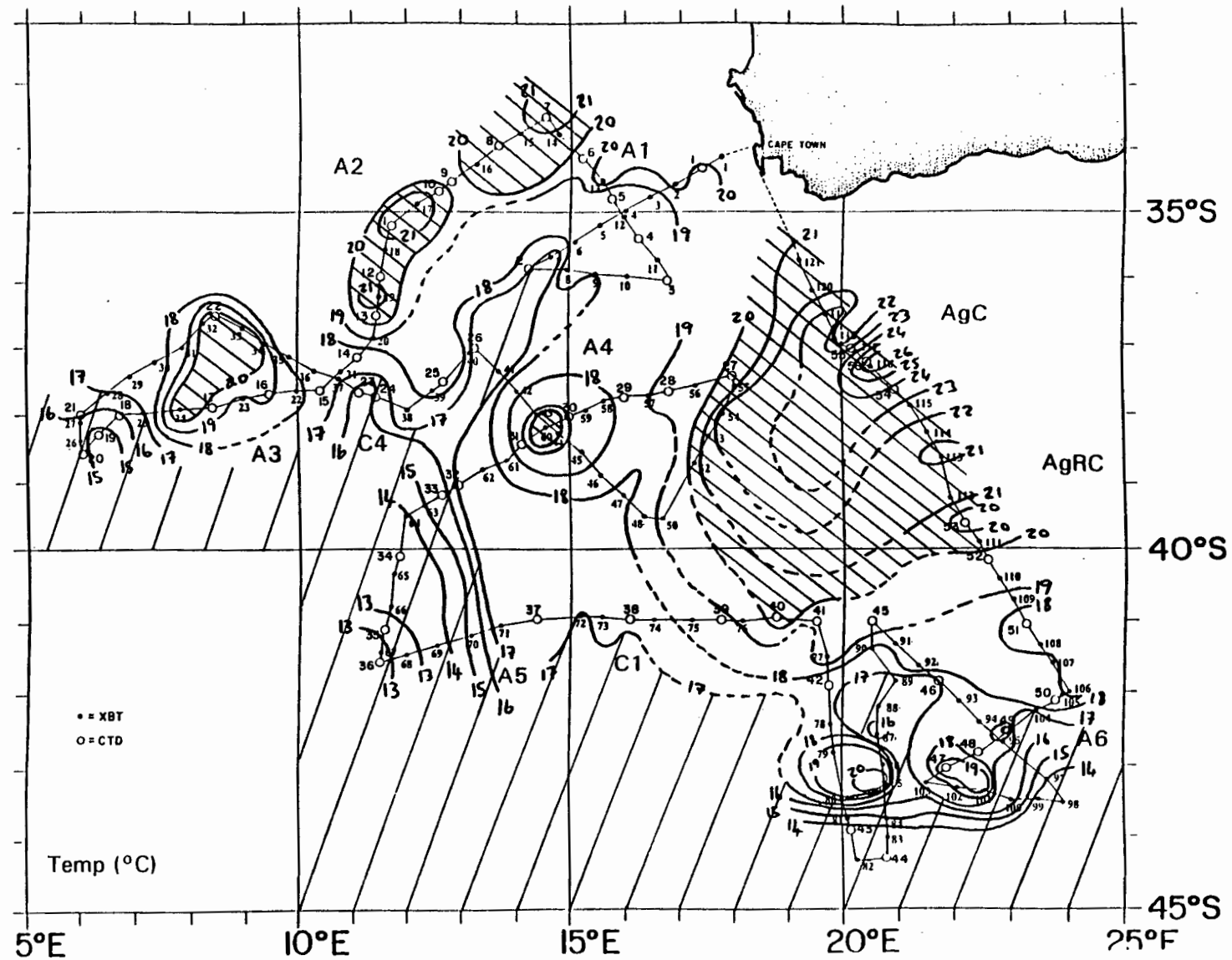


Figure 5.7: The potential temperature pattern at 0 db with an overlay of the *SCARC* cruise track. Temperatures $>20^{\circ}\text{C}$ and $<17^{\circ}\text{C}$ are shaded.

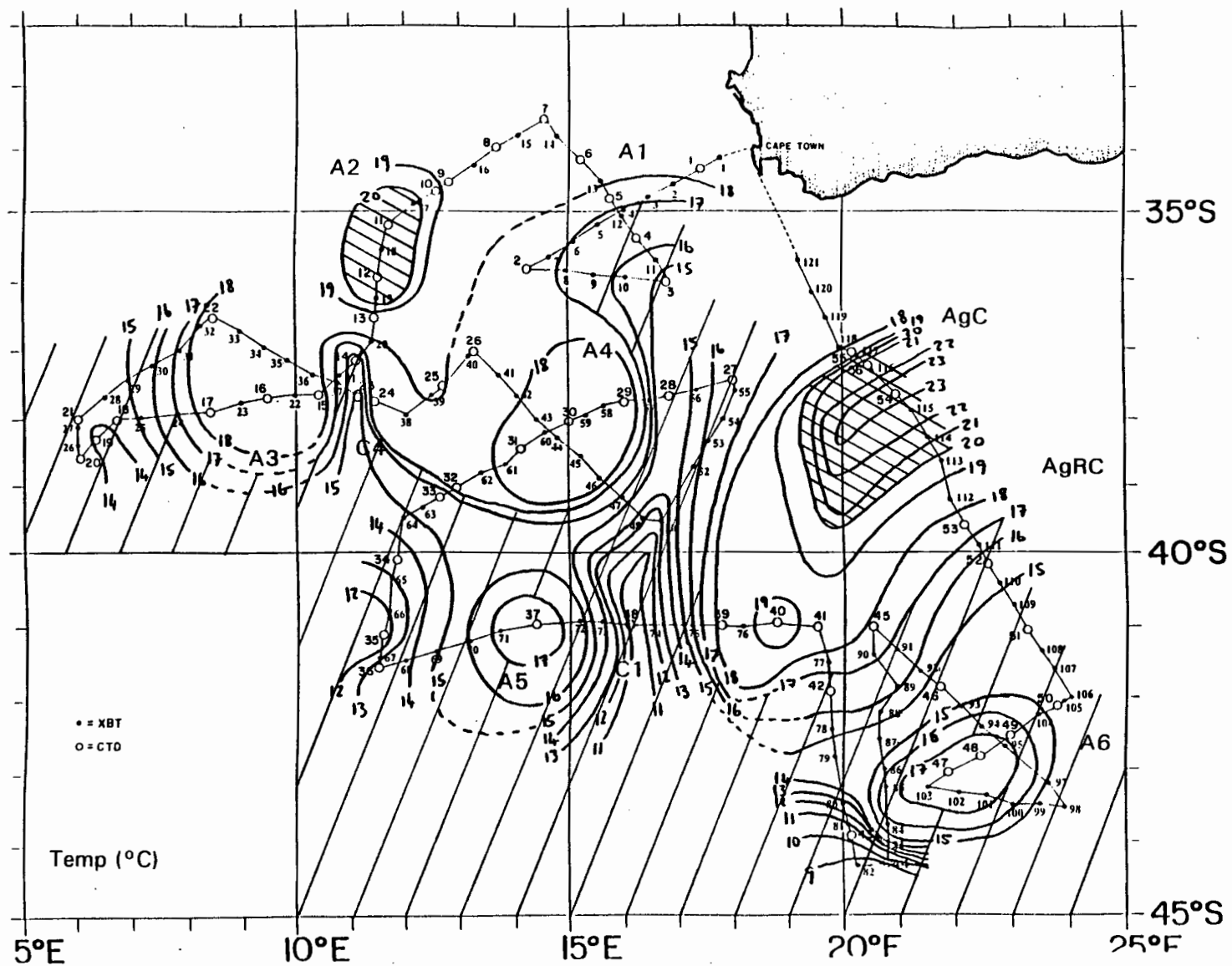


Figure 5.9: The potential temperature pattern at 50 db with an overlay of the SCARC cruise track. Temperatures $>20^{\circ}\text{C}$ and $<17^{\circ}\text{C}$ are shaded.

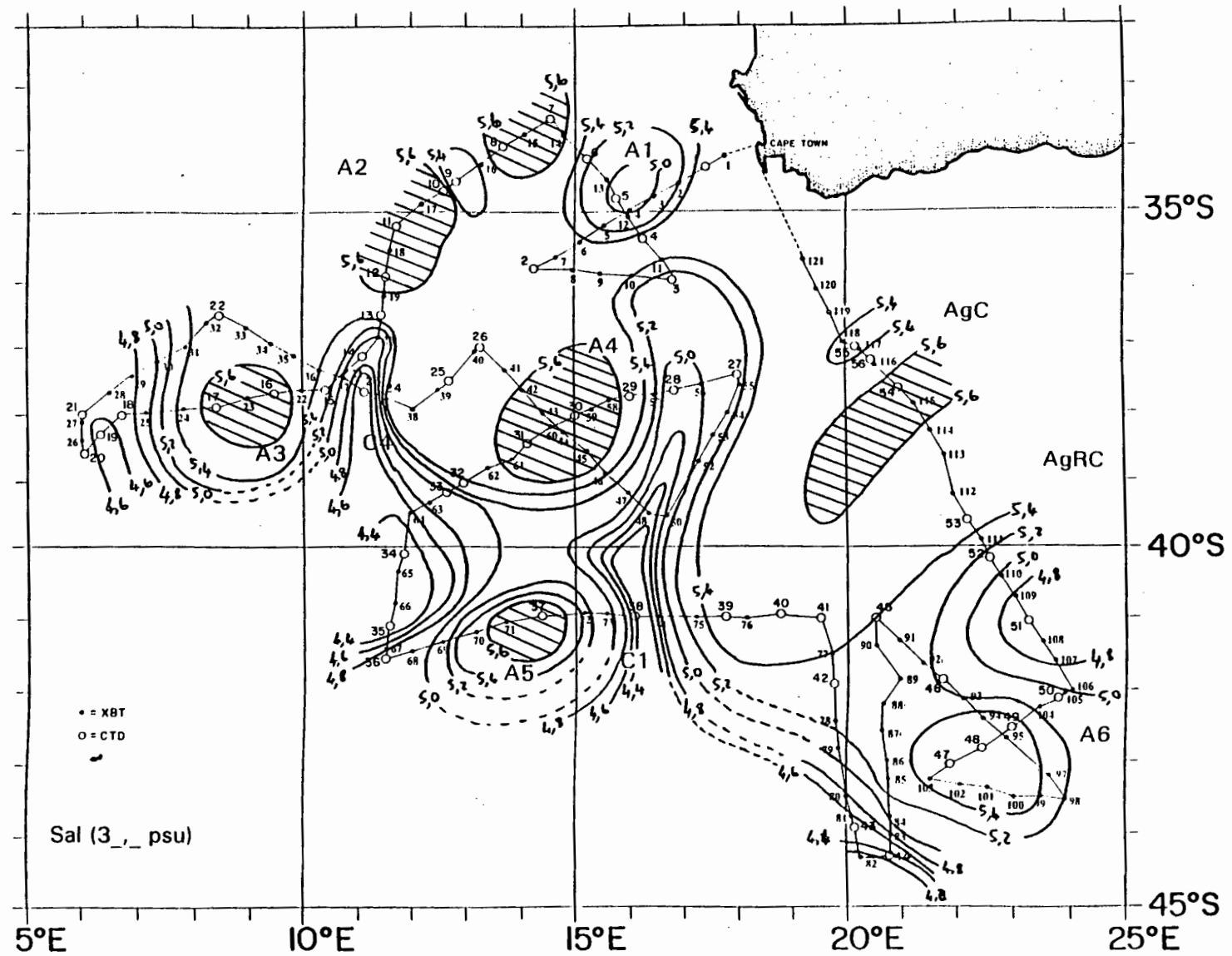


Figure 5.10: The salinity pattern at 50 db with an overlay of the *SCARC* cruise track. Salinities > 35,60 are shaded.

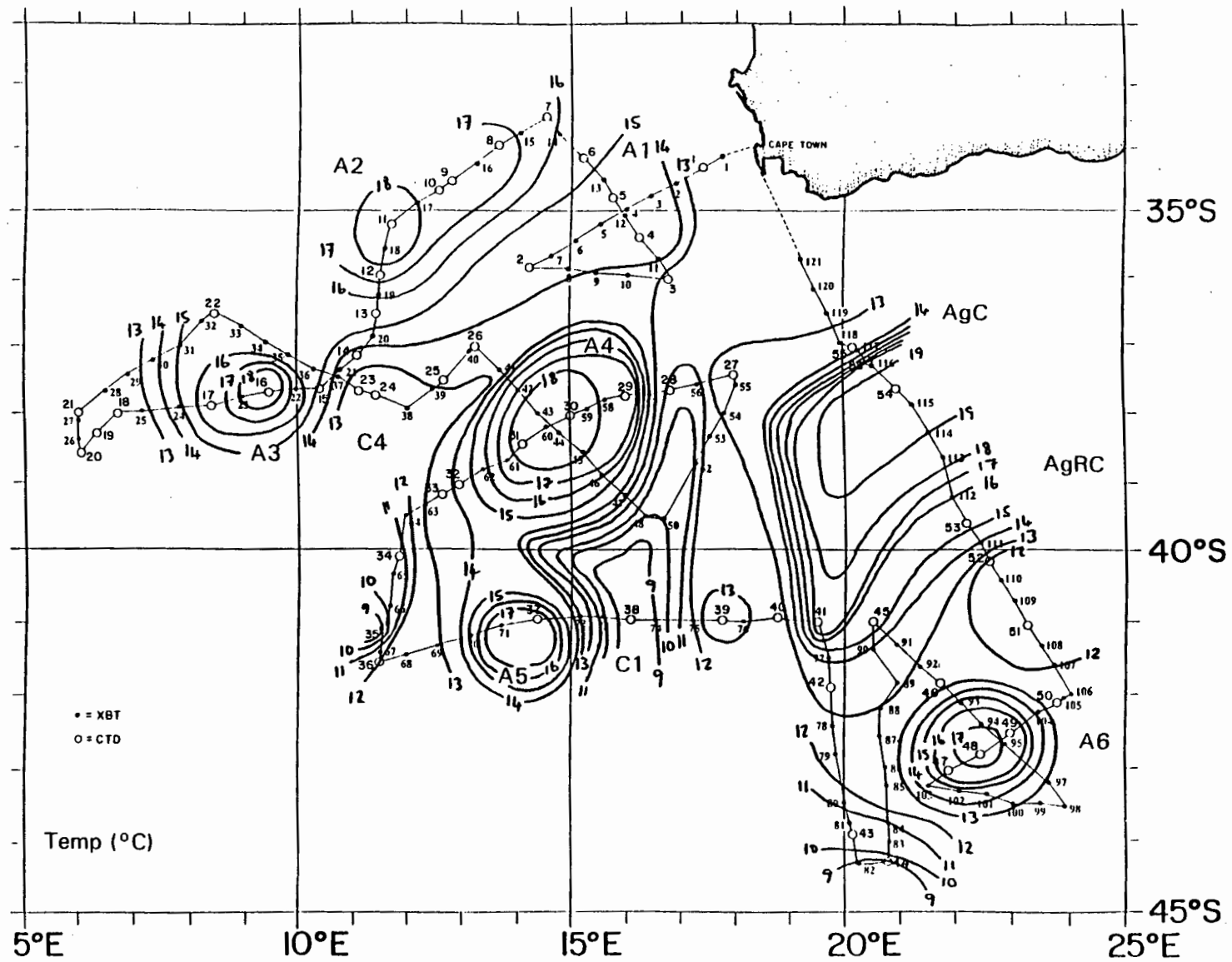


Figure 5.11: The potential temperature pattern at 100 db with an overlay of the SCARC cruise track.

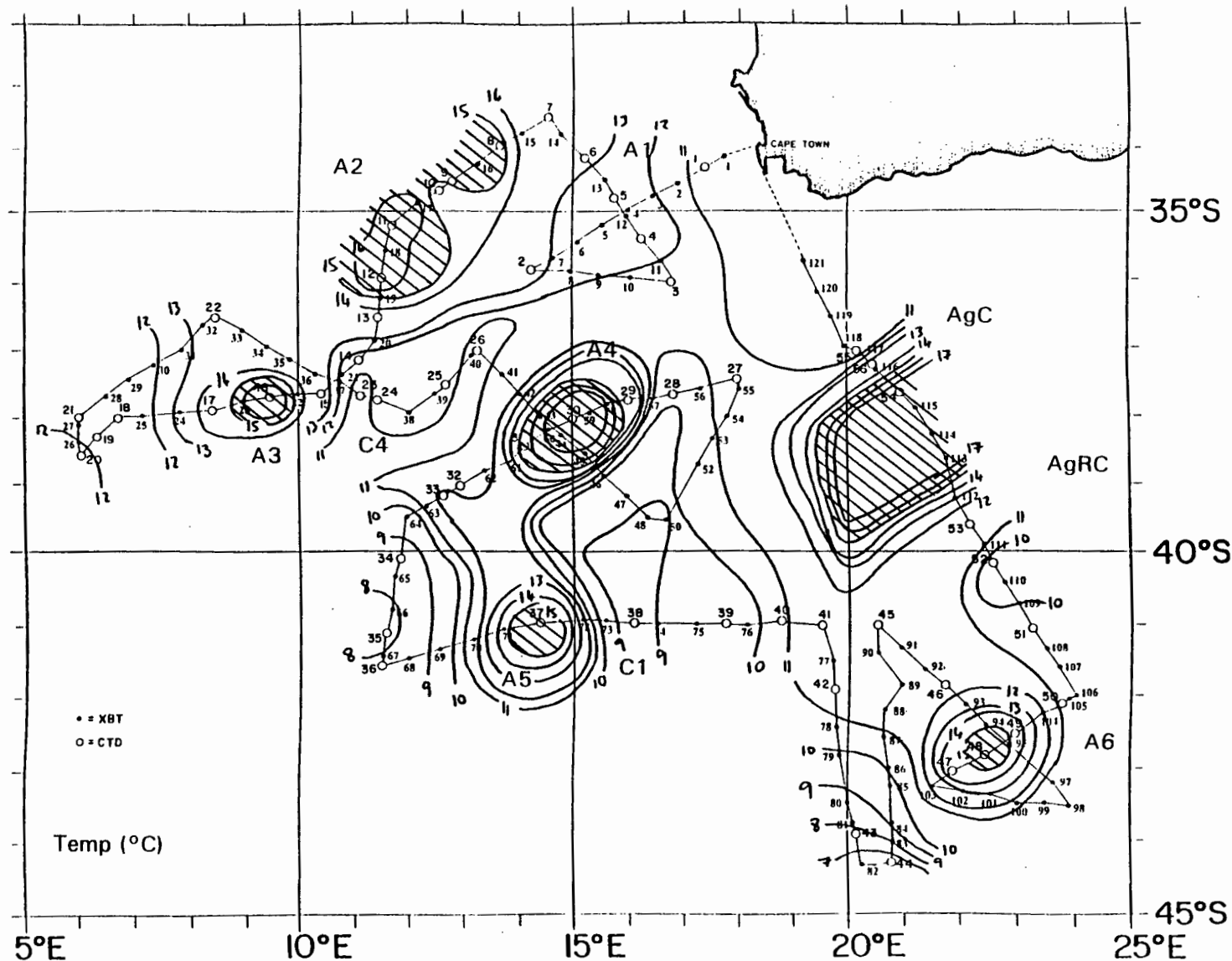


Figure 5.13: The potential temperature pattern at 200 db with an overlay of the SCARC cruise track. Temperatures $> 15^{\circ}\text{C}$ are shaded.

Thermohaline Pattern along Specific Density Surfaces

The thermohaline pattern is determined along core density surfaces in order to follow the geostrophic path of particular water masses within the Retroflection region (isentropic analysis). The results presented below outline the general thermohaline pattern. Identification of particular water masses along similar density surfaces are described in the **Water Mass Analyses**.

Surface Waters (Figures 5.15 and 5.16)

In order to trace the dominant surface waters (0 - 170 db) of the Retroflection the thermal pattern along the ($\text{Sigma-}\Theta = 25,8$) is chosen. The depth of this surface is presented in **Addendum 1**. A general thermohaline pattern emerges where warm, saline surface waters ($>18,0^\circ$; $>35,50$) enter the Retroflection along the near-shore edge of the Agulhas Current input (CTD_056 & CTD_055) (Figures 5.15 and 5.16). Waters exceeding $17,0^\circ\text{C}$ dominate much of the Retroflection region. Note the marked disjunct location of three zones of warm ($>17,0^\circ\text{C}$) surface waters. These three zones are comprised of Ring A2 and Eddies A3, A4 and A5 - a western warm zone; the Agulhas Retroflection - an eastern zone; and Eddy A6 - a southern zone. Notice the meridional connection of the cooler ($<17^\circ\text{C}$) surface waters in the south to the shelf waters in the north.

Waters with salinities exceeding 35,50 describe all the Agulhas rings and eddies at this density surface, except Ring A1, where anomalously fresh water ($<35,10$) overlies A1. Note the marked salinity front along the southwestern part of the SCARC grid, locating a northwest to southeast aligned "wall" of fresh Atlantic Water influence. A broad meridional band of fresh water ($<35,30$) separates the warm-core vortices shed to the west, from their source, the Agulhas Current.

Central Water (Figures 5.17 and 5.18)

The potential temperature of the central (thermocline) waters along the $\text{Sigma-}\Theta = 26,8$ is chosen to trace the Central Water of the Agulhas Retroflection, ranging in depth from 150 db south of the STC to a depth of 750 db within the Agulhas Current input (see **Addendum 1**). Water temperatures exceeding 10°C dominate the Retroflection region at this density surface (Figure 5.17), with cooler waters restricted to the shelf and southern regions of the SCARC grid. Interestingly, a body of marginally cooler water ($<10^\circ\text{C}$) is located between Rings A1, A2 and Eddy A4

(CTD_002 and CTD_026). There is strong connectedness between the Retroflection and Eddy A6 at this density surface, with evidence of a S-shaped cyclonic turn in the Return Current, around stations CTD_051 - CTD_052 (see Figure 5.1c).

Waters with salinities in excess of 34,80 dominate the Retroflection region at this density surface, with a strong connectedness between the Agulhas Current and its associated warm-core rings and eddies (Figure 5.18). Cooler, less saline waters are restricted to the southern regions of the *SCARC* grid.

Intermediate Water (Figures 5.19 - 5.23)

The intermediate waters of the Agulhas Retroflection comprise both Antarctic Intermediate Water (AAIW) and Deep North Indian Water (or Red Sea Water (RSW)). To facilitate the possible identification of these two waters masses, the thermal pattern along two specific density surfaces are analyzed.

The potential temperature along the $\text{Sigma-}I = 31,8$ density surface is chosen to trace the possible distribution of AAIW, ranging from depths of about 600 db (shelf and extreme southern stations) to 1140 db in the region of the Agulhas input (CTD_054) (see **Addendum 1**). A general pattern emerges with waters in excess of $4,5^{\circ}\text{C}$ located along the shelf regions as well as an invasion of warm water from the south along the western extension of the Retroflection (Figure 5.19). Interestingly, only Ring A1 and Eddy A3 exhibit this warmer water. Saline waters ($>34,30$) comprise the Agulhas Current and associated warm-core rings and eddies (except Eddy A5) at this density surface. The Agulhas Current and Eddies A4 and A6 seem to be contiguous along this density surface (Figure 5.20). An anomalously saline feature ($>34,30$) is located at a depth of about 700 db in the region of the Subantarctic filament (C4) (CTD_025 & CTD_033). The source of this saline water is possibly Ring A2 and Eddy A4 respectively, where Agulhas waters lie beneath (C4) at this density surface.

The potential temperature along the ($\text{Sigma-}I = 32,15$) density surface is chosen to trace the possible distribution of RSW remnants, ranging in depth from 1100 db (in the extreme southern and shelf stations; CTD_001 and CTD_055 are too shallow) to the bottom of the cast (1500 db) in the Agulhas Current (see **Addendum 1**). A general pattern emerges where waters warmer than $3,0^{\circ}\text{C}$ constitute much of the Retroflection region. Concentric isotherm circles characteristic of a vortex morphology are no longer evident at this density surface. The integrity of the cold filaments remain, with waters

colder than $3,0^{\circ}\text{C}$ tracing the location of the two dominant Subantarctic filaments (C1 and C4) (Figure 5.21).

The saline waters ($>34,55$) of the Agulhas Current enter the Retroflection from the northeast, plunging south to a latitude of about 44°S , to return north and then west as the Agulhas Return Current (Figure 5.22). A saline filament seems to extend from the Retroflection into the South Atlantic. However, the location of RSW as seen in the Θ/S plots of the CTD stations of the *SCARC* are not well represented by this saline "envelope" shaded in Figure 5.22. On closer examination of the Θ/S curves containing remnant RSW, an alternative density surface was chosen to best represent the core of the RSW during the *SCARC*. The density surface chosen is ($\text{Sigma-}t = 27,35$), determined primarily from the Agulhas input stations CTD_054 and CTD_056. This density surface was also identified by Gründlingh (1985) to best represent the core of the RSW remnants identified within the Agulhas Current at about 30°S (800 - 1100 db). The salinity pattern along the ($\text{Sigma-}t = 27,35$) density surface during the *SCARC* is presented in Figure 5.23, extending from 900 db in the shelf and southern regions, to 1200 db in the core of Agulhas Current Water (see **Addendum 1**). As expected, the "preferred" location of RSW is within the Agulhas Current itself and immediate warm-core features derived from the Current. Interestingly, RSW remnants are identified as far south as $44,3^{\circ}\text{S}$ (CTD_044) and as far west as $9,4^{\circ}\text{E}$ (CTD_016).

Deep Water

Since the *SCARC* hydrographic stations only extend to a common depth of 1500 db. Consequently, density surfaces deeper than 1500 db could not be analyzed, constituting the Deep and Bottom Waters of the Retroflection region. However, ten CTD casts executed during the *Discovery 165A*, extend to the ocean floor. Using these stations, the deeper water masses are identified in the **Water Mass Analyses**.

From the above analysis of the thermohaline pattern along specific density surfaces, the vertical extent of the mesoscale features of the Retroflection begin to emerge. The surface waters (mapped along $\text{Sigma-}\Theta = 25,8$) reveal similar trends to those described by the 0 db to 100 db in the previous section.

The Central (Thermocline) Waters of the Retroflection are traced along the $\text{Sigma-}\Theta = 26,8$ surface, revealing a dominance of water exceeding 10°C (and 34,80) within the Retroflection region. The increased connectedness of the Agulhas Current with its

vortices along this density surface is the result of the improved "tightness" of Θ/S space, characteristic of the Central Waters of the Agulhas Retroflection region (see Figure 2.6).

The Intermediate Waters of the Retroflection region are dominated by cold and fresh ($<4,5^{\circ}\text{C}$; $<34,4$) Antarctic Intermediate Water (AAIW). In order to trace this water, thermohaline characteristics are mapped along the $\text{Sigma-}I = 31,8$ density surface. As expected, the freshest (and coldest) AAIW invades the Retroflection from the south and west (Atlantic AAIW). In regions where the Agulhas Current and associated vortices are present, there is evidence of contamination of the fresh AAIW signal. This contamination may be a result of remnant RSW transported into the Retroflection region via the Agulhas Current and distributed west (and south) of the Retroflection through associated Agulhas vortices and filaments.

In order to trace the possible distribution of Red Sea Water (RSW) within the Retroflection region, the lower thermocline waters are traced along the $\text{Sigma-}I = 32,15$ density surface. The thermohaline characteristics at this depth reveal a pattern devoid of the concentric isolines indicative of Agulhas vortices, and thus this density surface lies at a depth below which most of the vortices can trap water. In addition, the thermohaline pattern revealed by this density surface poorly distinguishes the location of RSW identified in the Θ/S plots of the *SCARC* hydrographic data. Consequently, a slightly shallower density surface is used ($\text{Sigma-}t = 27,35$), which proves to better locate the possible flow path this water may take through the Retroflection region. True RSW remnants are identified within the core of the Agulhas Current, with contamination of these RSW remnants within the cores of the Agulhas vortices. This contamination of RSW by AAIW becomes increasingly evident with increasing distance westward from the Retroflection, thus highlighting the unique blend of water that results from the mixing of RSW and AAIW of opposing Θ/S characteristics.

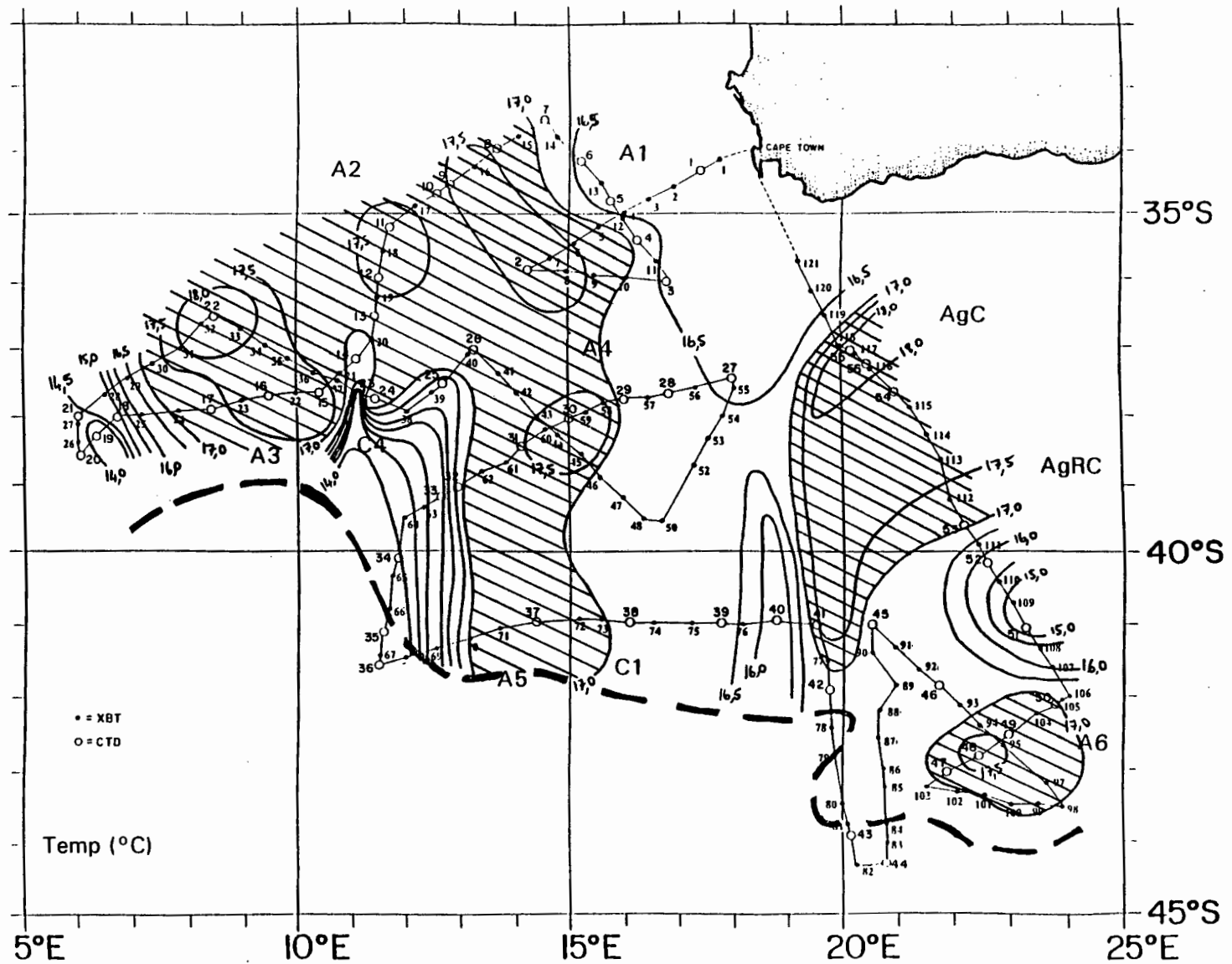


Figure 5.15: The potential temperature pattern along the $(\sigma_{\theta} = 25,80)$ density surface with an overlay of the SCARC cruise track. Temperatures $> 17^{\circ}\text{C}$ are shaded.

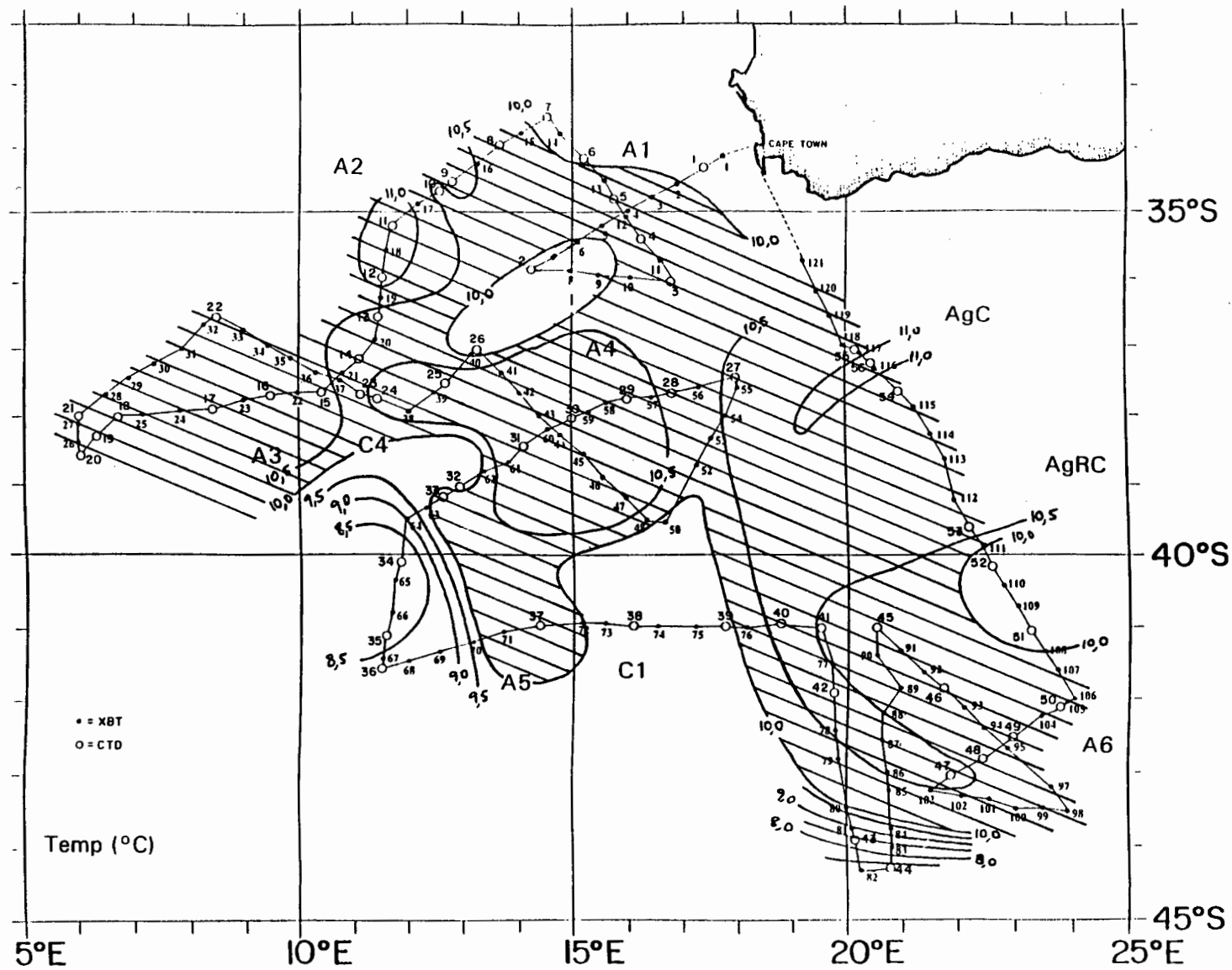


Figure 5.17: The potential temperature pattern along the ($\sigma_{\theta} = 26,80$) density surface with an overlay of the SCARC cruise track. Temperatures $> 10^{\circ}\text{C}$ are shaded.

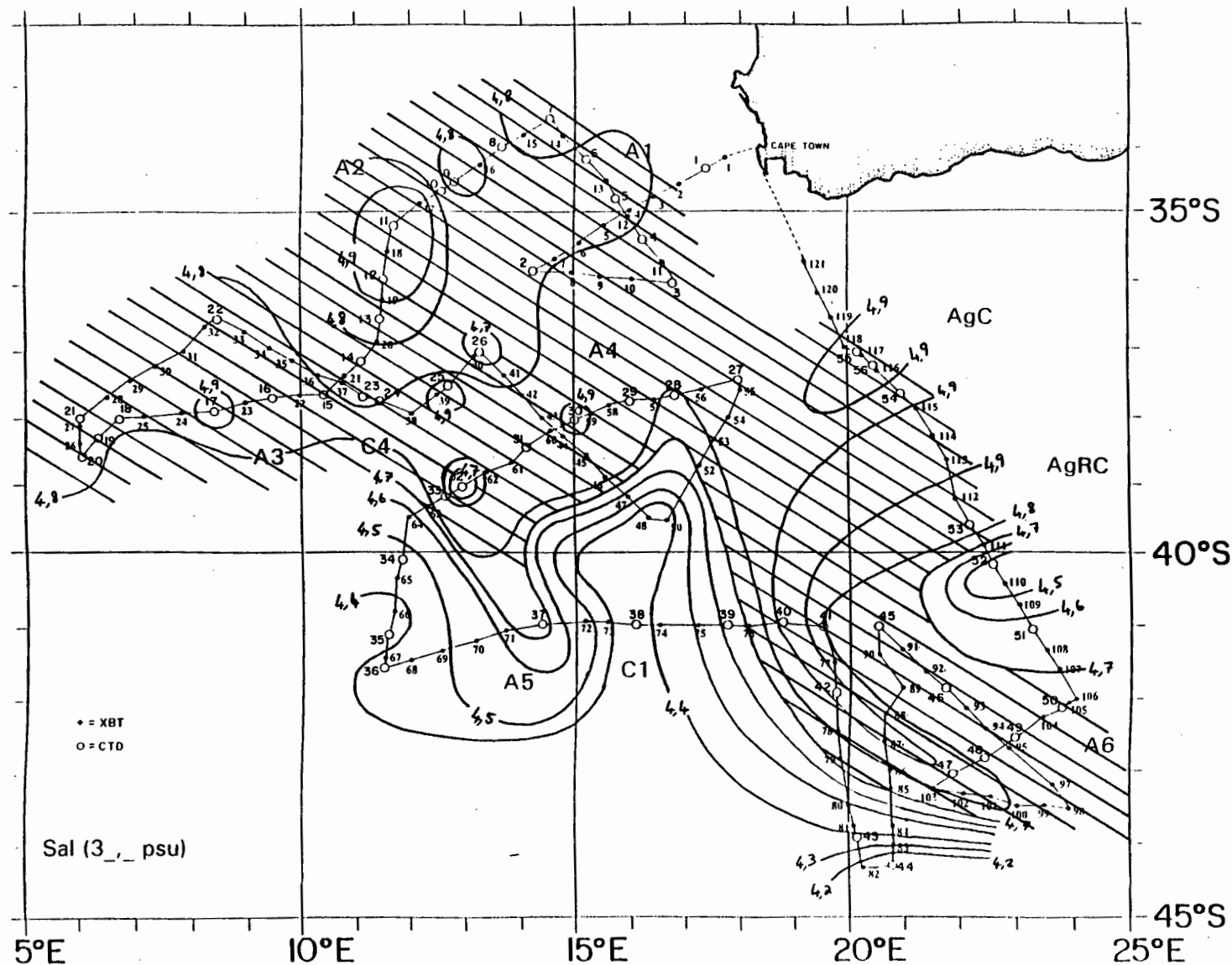


Figure 5.18: The salinity pattern along the ($\sigma_{\theta} = 26,80$) density surface with an overlay of the SCARC cruise track. Salinities $> 34,70$ are shaded.

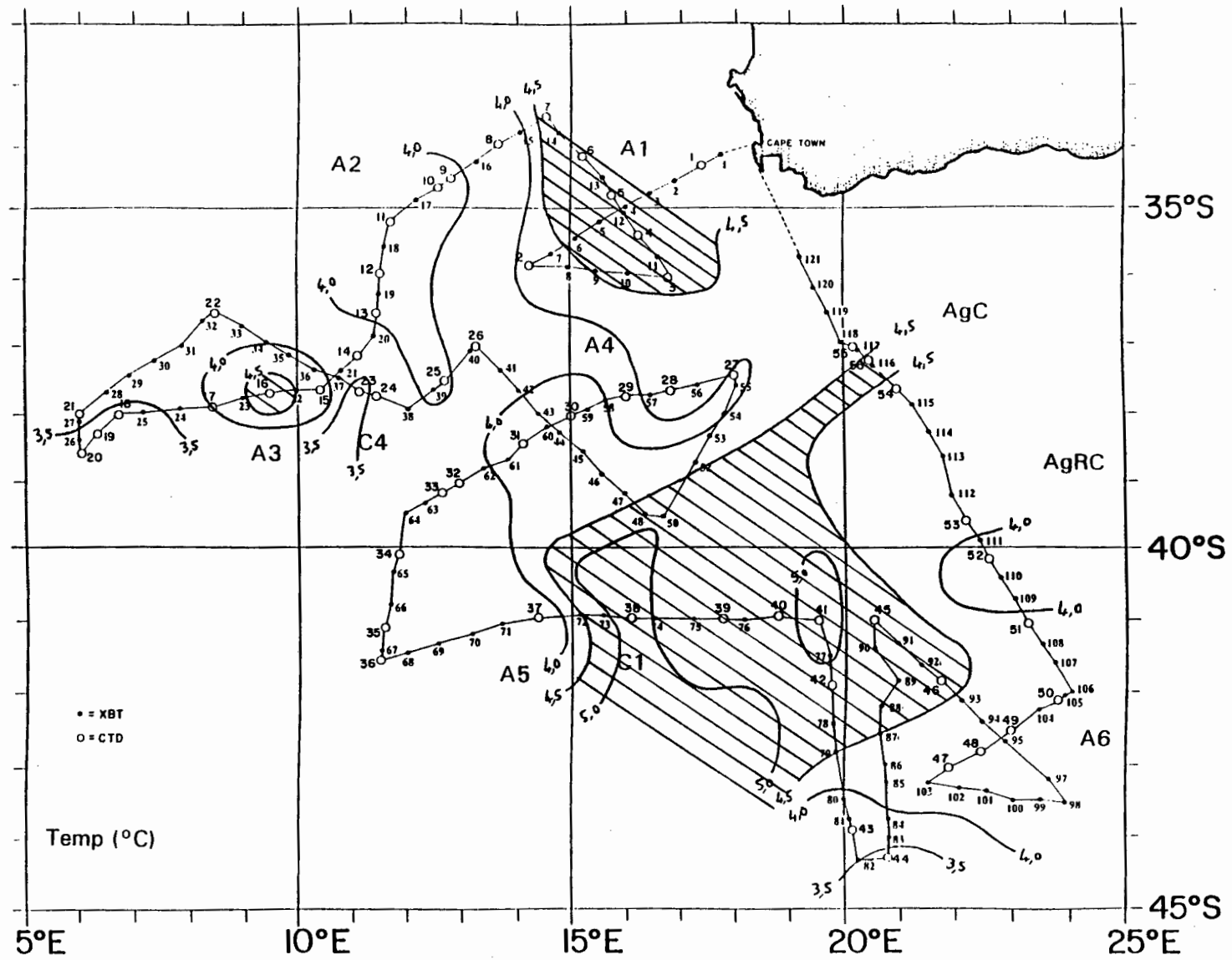


Figure 5.19: The potential temperature pattern along the $(\sigma_t = 31,80)$ density surface with an overlay of the SCARC cruise track. Temperatures $> 4,5^\circ\text{C}$ are shaded.

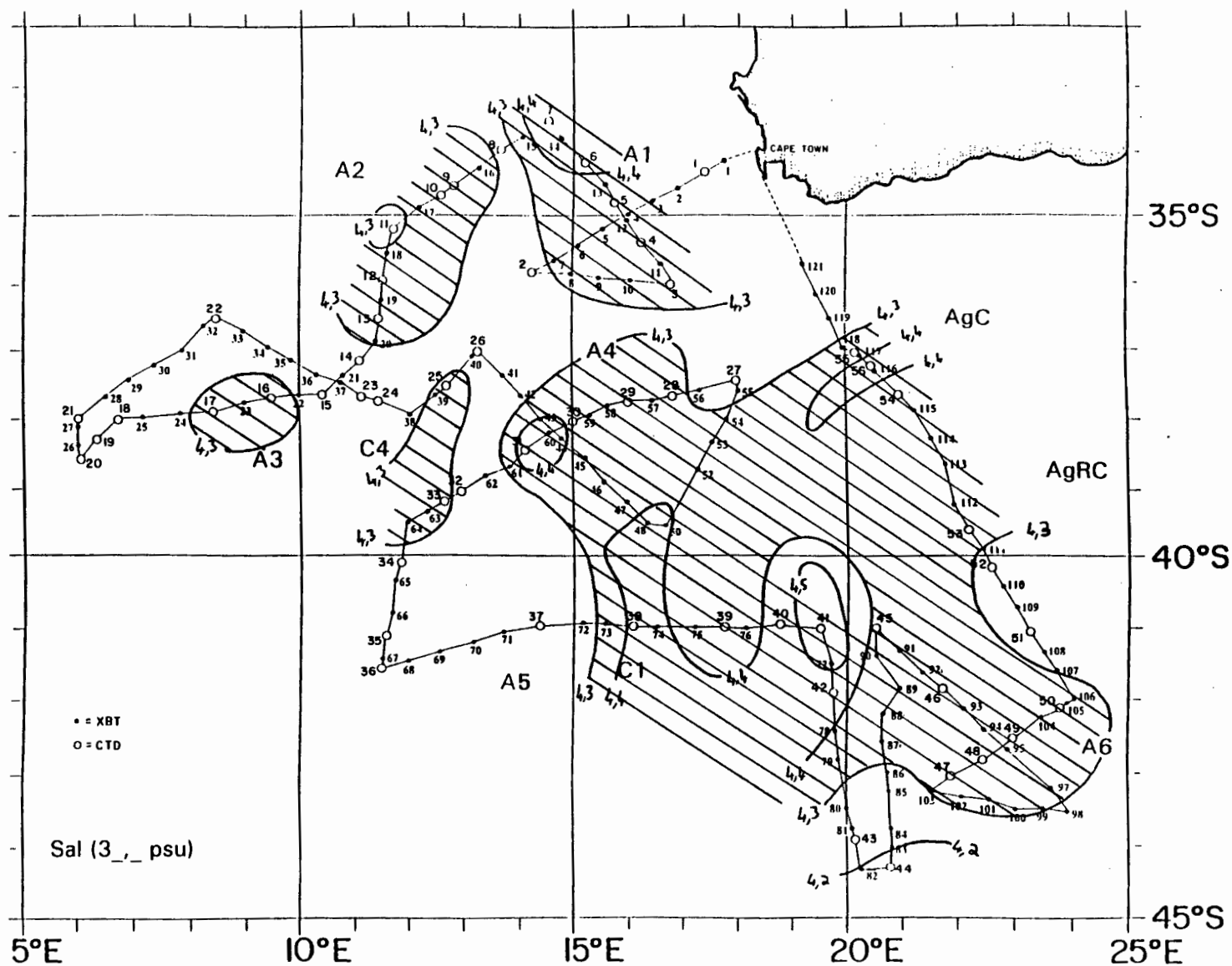


Figure 5.20: The salinity pattern along the ($\sigma_t = 31.80$) density surface with an overlay of the SCARC cruise track. Salinities > 34.30 are shaded.

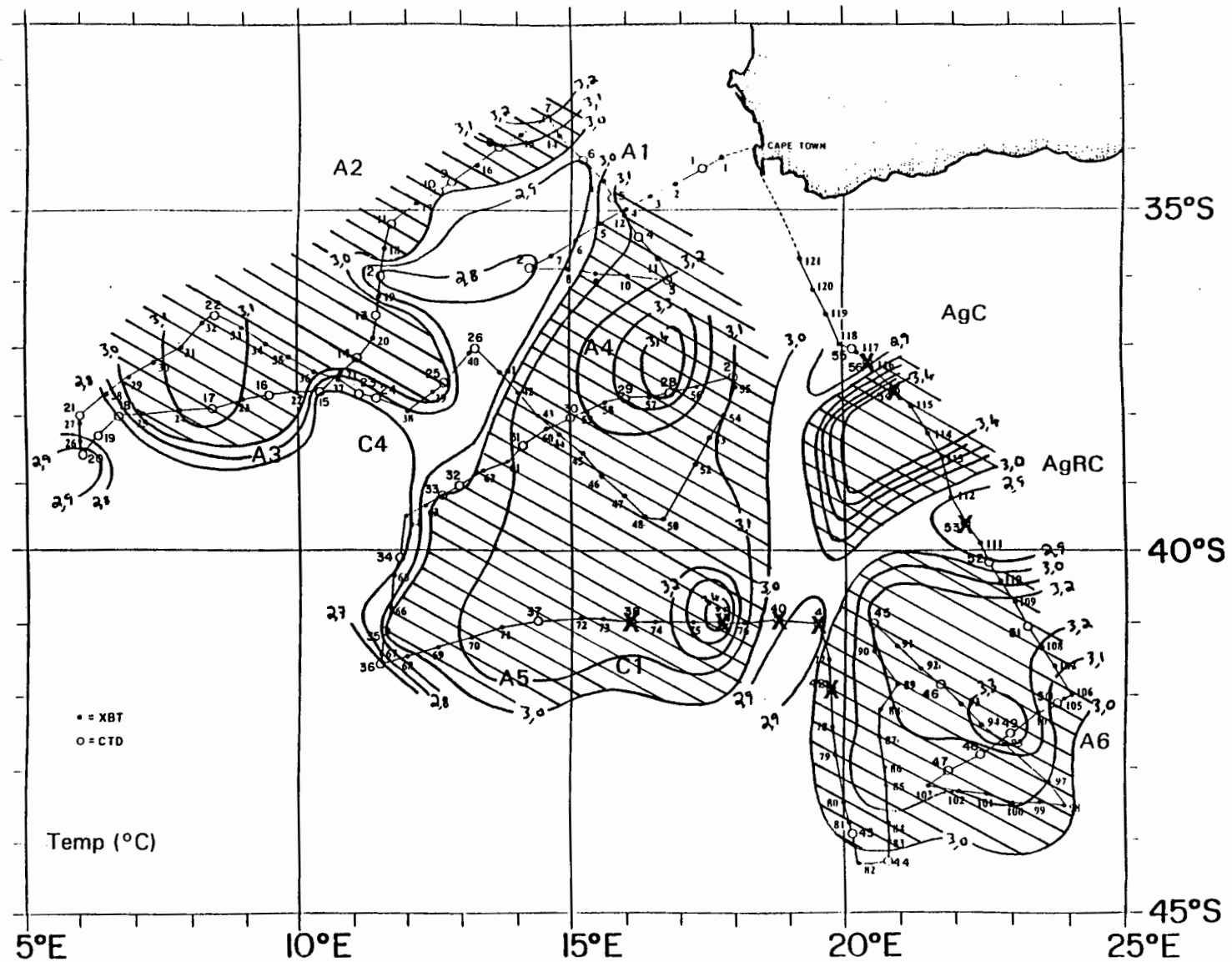


Figure 5.21: The potential temperature pattern along the ($\sigma_t = 32.15$) density surface with an overlay of the SCARC cruise track. Crosses indicate positive identification of Red Sea Water remnants in the Θ/S plots. Temperatures > 3°C are shaded.

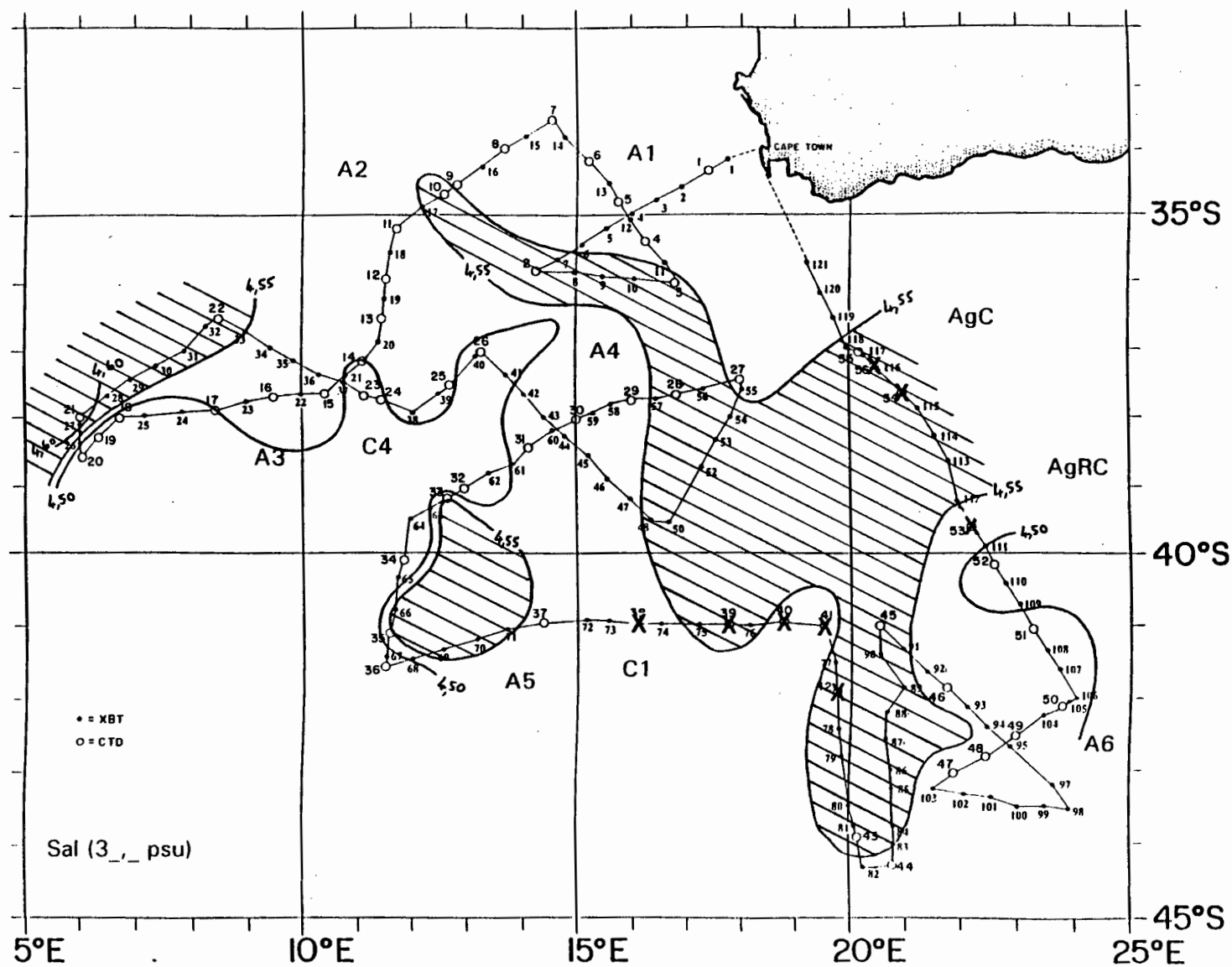


Figure 5.22: The salinity pattern along the $(\sigma_t = 32.15)$ density surface with an overlay of the SCARC cruise track. Crosses indicate positive identification of Red Sea Water remnants in the Θ/S plots. Salinities > 34.55 are shaded.

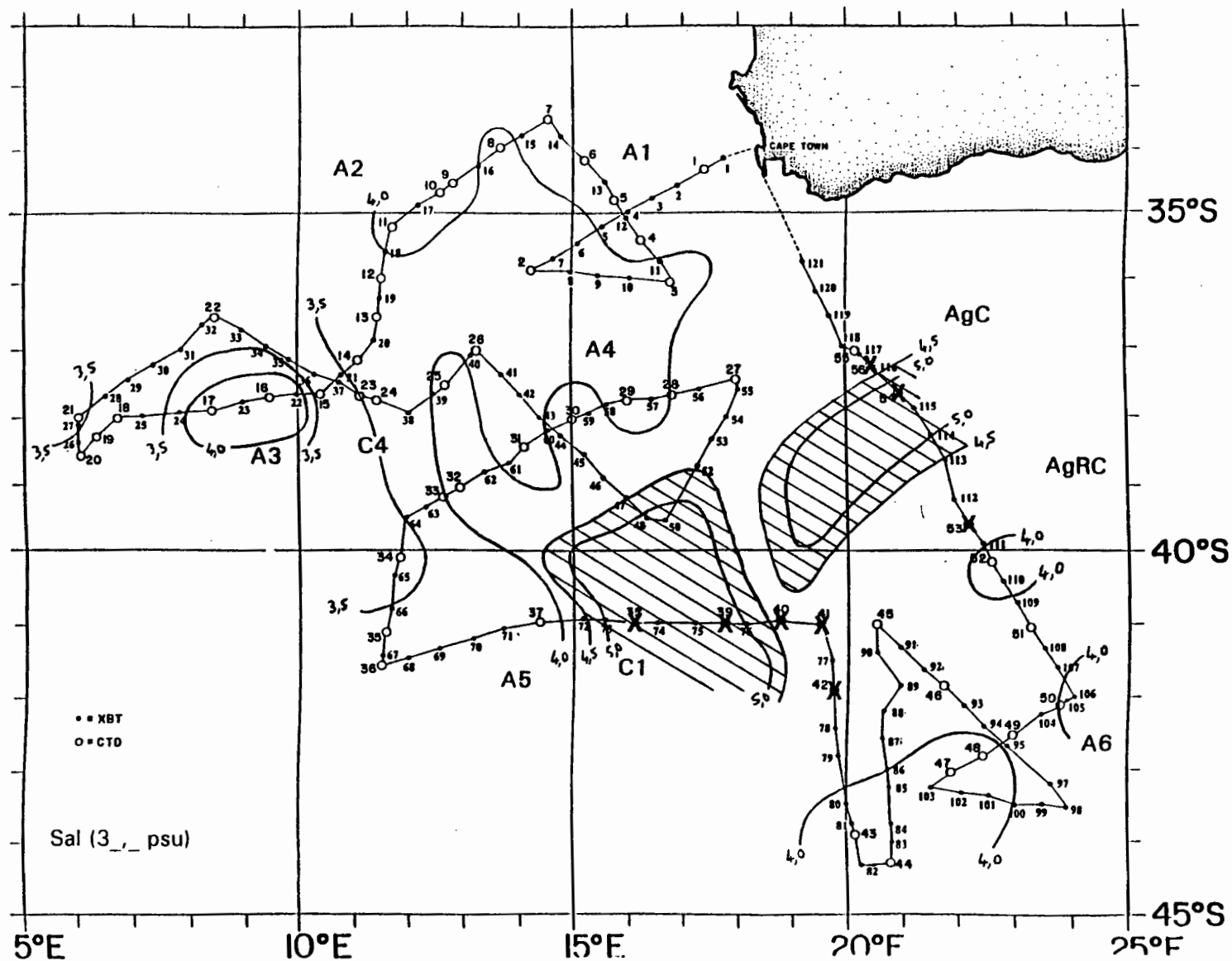


Figure 5.23: The salinity pattern along the ($\sigma_t = 27,35$) density surface with an overlay of the SCARC cruise track. Crosses indicate positive identification of Red Sea Water remnants in the Θ/S plots. Salinities $> 34,50$ are shaded.

5.2.2) Density Pattern

Density Pattern with Depth

The previous section analyzed the thermohaline characteristics within the Agulhas Retroflexion region along specific density surfaces. These individual density surfaces are chosen to trace the movement of particular core water masses, detailed in the **Data and Methods**. Contour plots of the depth of the following density surfaces are to be found in **Addendum 1**:

$\text{Sigma-}\Theta = 25,80$ (Surface Waters)

$\text{Sigma-}\Theta = 26,80$ (Central Waters)

$\text{Sigma-}I = 31,80$ (Antarctic Intermediate Waters)

$\text{Sigma-}I = 32,15$ (Red Sea Remnant Waters)

$\text{Sigma-}t = 27,35$ (Red Sea Remnant Waters)

A descriptive account of the pattern of these particular density surfaces is not given. Rather, the figures in **Addendum 1** are to be referred to in conjunction with the description of the thermohaline patterns revealed in **Section 2.1**.

Surface Mixed Layer Depth Pattern

From the thermohaline analyses above it is evident that the core of the Agulhas vortices generally exhibit anomalously saline waters as a result of salinity "boosting" at the surface. It is also shown that this saline surface water can be mixed to depths exceeding 100 db in most cases. A direct way to estimate the depth of the surface mix layer is to determine the pycnocline depth. To establish the pycnocline depth in an objective manner, the criterion by Priddle *et al.* (1986) was adopted, defining the pycnocline depth as described in the **Data and Methods**. Although this method boasts an objective approach, it suffers from sensitivity to small-scale variations in the potential density profile outlined in the **Data and Methods**. To overcome this, the mixed layer depth was defined as the depth at which a rate of change of density of $0,03 \text{ kg.m}^{-3}$ (per 1 db) is exceeded for at least 20 db (ie. the pycnocline must be at least 20 m thick). This proves to be a reasonable approach except in a few cases where the primary pycnocline is less than 20 m thick. Such is the case for station CTD_030, located in the centre of Eddy A4. This station exhibits a surface mixed layer extending to a depth of 185 db, with a pycnocline 15 m thick. Below the pycnocline the rate of change of the potential density decreased gradually with depth to reach an average of about $0,010 \text{ kg.m}^{-3}$ (per

1 db) at 600 db depth (see Figure 5.24). However, in most cases the primary pycnocline satisfied the above criteria. In some cases a shallow secondary pycnocline could be identified above the primary pycnocline, particularly in those stations occupying the southeastern quadrant of the *SCARC* grid. For example, station CTD_049 exhibits a warm surface cap, well mixed to 27 db. A primary pycnocline is located below this secondary pycnocline at a depth of 124 db (Figure 5.25). In such a case the depth of the secondary pycnocline was chosen to represent the depth of the mixed layer. The origin of this warm surface cap could be a consequence of "scavenging" of warm Agulhas water from the Retroflection by Eddy A6.

A plan view of the mixed layer depths observed in the *SCARC* is given in Figure 5.26. Surface mixed layers extending to depths exceeding 100 db (shaded) are restricted to the centre stations of Eddies A3, A4, A5 and A6. Interestingly, the two CTD stations in the extreme south (CTD_043 & CTD_044) exhibit mixed layers that exceed 100 db in depth, both capped with a thin surface layer (<5 m thick) of relatively warm, fresh water. The surface thermal core of the Agulhas input (CTD_056 & CTD_055) exhibit shallow well mixed layers (27 db and 17 db respectively) with the Return Current displaying a deeper mixed layer of about 46 db (CTD_053). Since the mixed layer depth of the waters of the Retroflection region can vary dramatically over a relatively short period owing to diurnal changes and synoptic weather events, no trends can be identified with confidence, other than the fact that the Agulhas vortices tend to exhibit relatively deep mixed layers within their core. These deep mixed layers are produced by rapid heat exchange with the atmosphere, driving deep convective overturning which progressively modifies the trapped water mass in the eddy core and through a net buoyancy loss, produces a surface thermostad. Consequently, the mixed layer depths increase rapidly on entering the core waters of the vortices sampled during the *SCARC*. The deepest surface mixed layer is located within Eddy A5, exhibiting an isothermal mixed layer extending to 158 db (CTD_037). The deepest isothermal mixed layer observed for an Agulhas ring is that of a "Winter Ring" in the South Atlantic which extended to a depth of 320 db (Duncombe Rae and Shillington, 1994). Although the surface mixed layers within warm-core Agulhas rings and eddies are relatively deep compared to the surrounding waters of the Retroflection, they generally have a shallower surface mixed layer than those observed in other current systems. For example, Kamenkovitch *et al.* (1986) describes a host of rings in other systems, some of which display surface mixed layers of up to 400 db deep. The distinguishing factor that produces this disparity is the fact that the waters of the Retroflection experience

cool, maritime air whilst those of, for example the Kuroshio and Gulf Stream systems, encounter much colder continental air, providing the thermal gradient necessary to drive deep convective overturning and mixing.

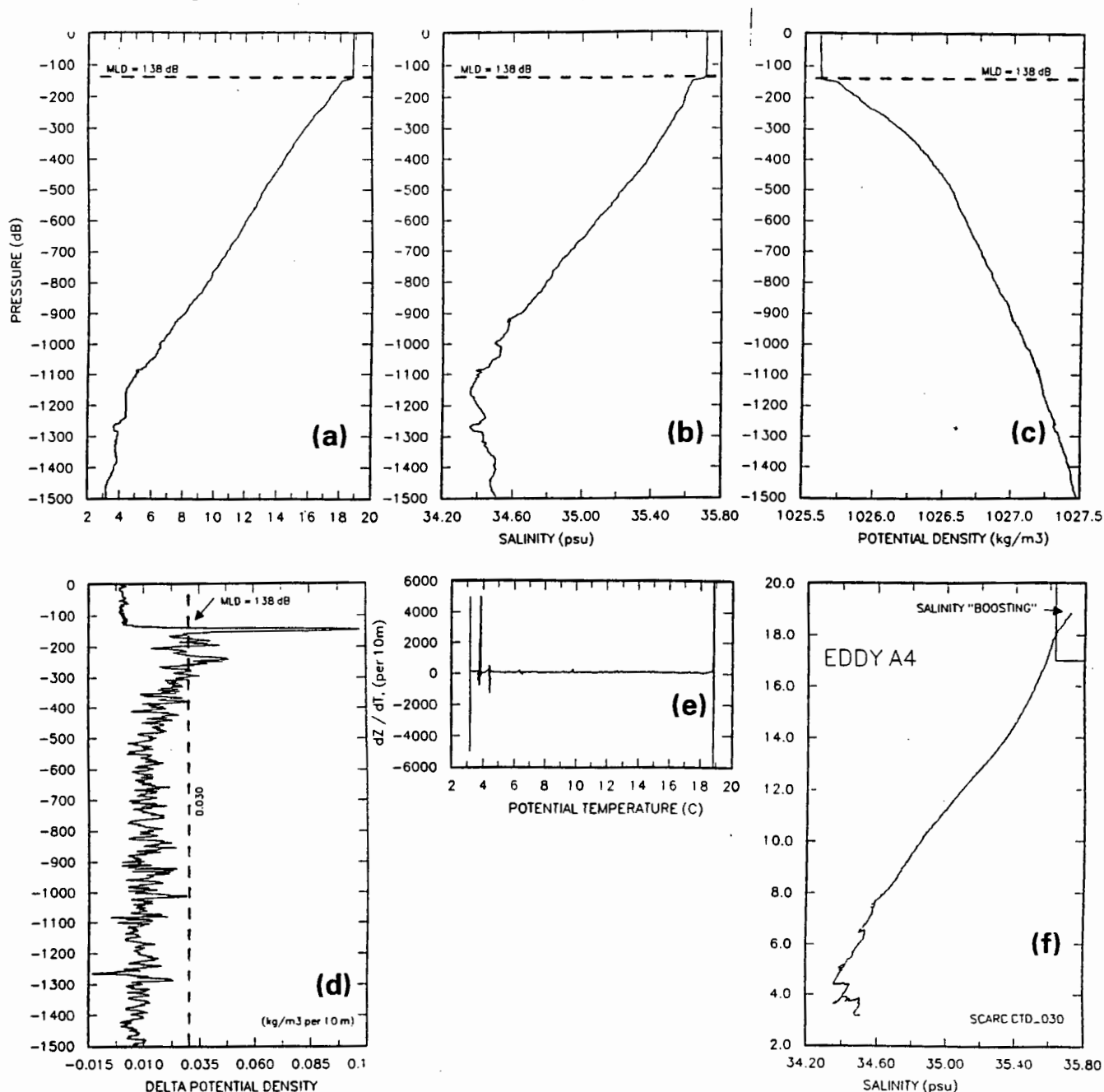


Figure 5.24: (a) Potential Temperature (b), Salinity (c), Potential Density (d) and Priddle's (1986) Mixed Layer Depth versus Pressure for Eddy A4 centre station (CTD 030). McCartney's (1977) $\delta z / \delta T$ versus Potential Temperature (e) and a Potential Temperature - Salinity (f) plot of CTD 030 is included. Notice how the Mixed Layer Depth (MLD) is so clearly defined by the Priddle (1986) criterion (d). No Mode Waters are identified in the $\delta z / \delta T$ plot (e). Peaks in the $\delta z / \delta T$ plot indicate the surface thermostad (18.9°C) of Eddy A4 and secondary stads in the Intermediate range (3° - 4°C).

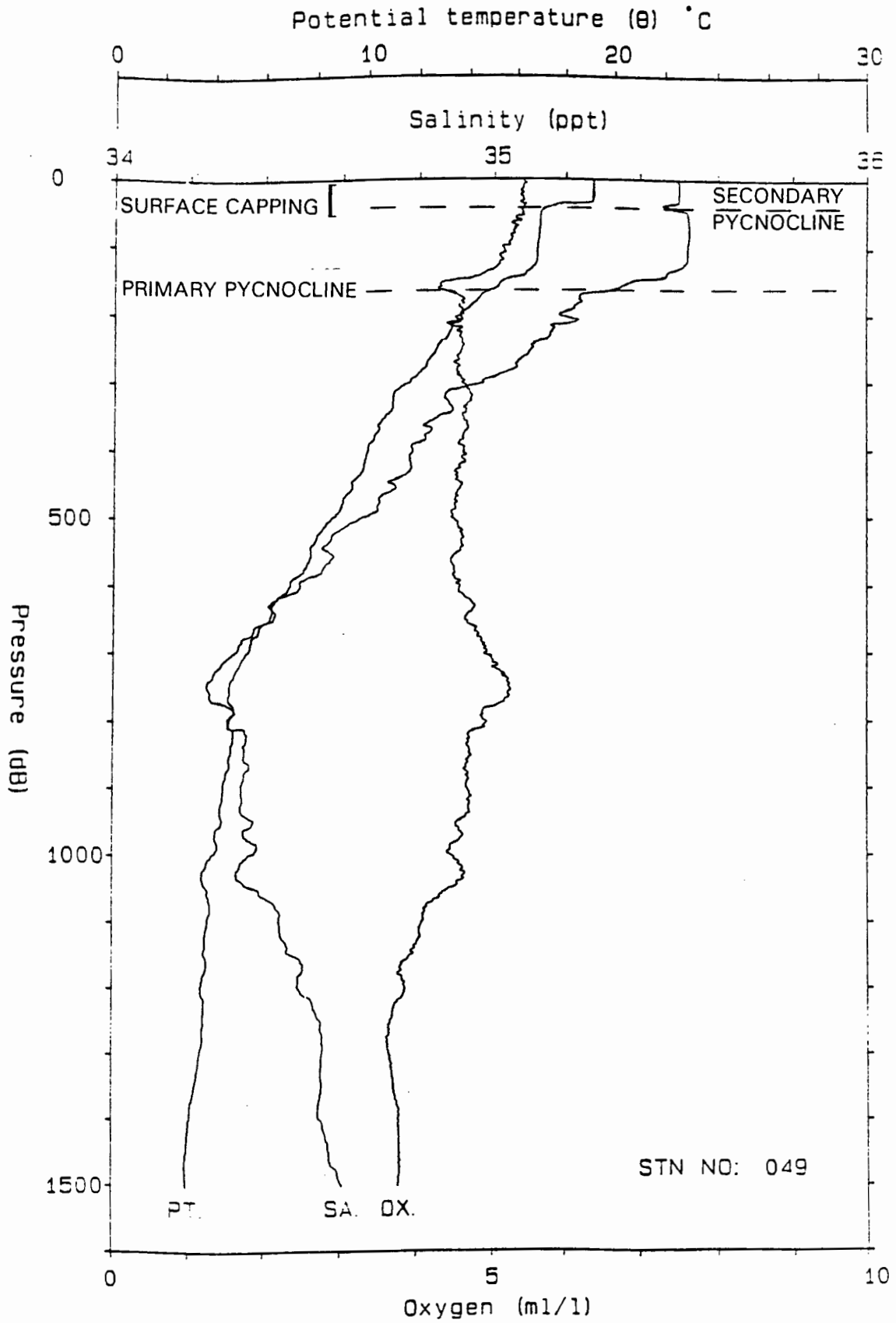


Figure 5.25: Potential Temperature, Salinity and Oxygen profiles of station CTD_049 showing a primary and secondary thermocline. Notice the surface capping caused from scavenging of warm surface water from the Agulhas Current into Eddy A6.

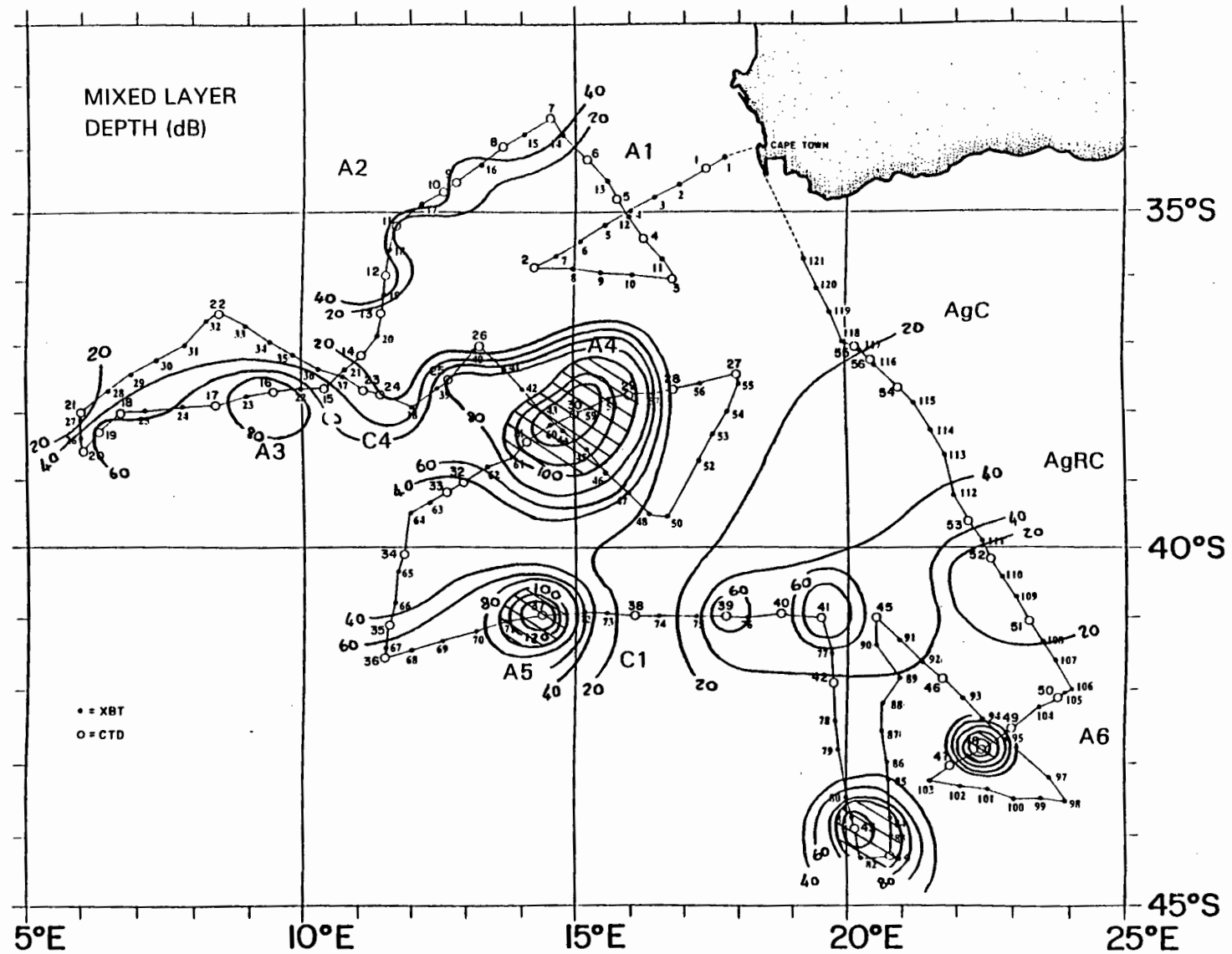


Figure 5.26: A contour plot of the mixed layer depth (MLD) in db with an overlay of the SCARC cruise track. The MLD was defined where the Priddle *et al.* (1986) criterion ($\delta\rho / \delta P > 0,03$) was satisfied for over 20 db.

Where:

ρ = potential density (kg.m^{-3})

P = pressure (db)

Mixed layer depths ≥ 100 db are shaded.

5.2.3) Structure of Temperature, Potential Temperature, Salinity and Potential Density with Depth

As part of the general hydrography of the Agulhas Retroflection region the following section briefly describes the mesoscale features as revealed by vertical property sections derived from the *SCARC* data. The relevant hydrographic sections are presented in **Addendum 2**.

a) The Agulhas Current

SCARC Section 16 (see **Addendum 2**)

Section 16 is the only hydrographic section of the *SCARC* that traverses the Agulhas Current input and Return Current. The thermal section, constructed from both XBT and CTD data, reveals the characteristically strongly sloped isotherms of the westward flowing Agulhas Current (CTD_055 to XBT_115), a width of 100 km (somewhat wider than that estimated further upstream by Gründlingh (1980) and Gordon *et al.* (1987)). The warm (saline) surface core of the Agulhas Current is located at the landward edge of the Current, comprising water warmer than 24°C (> 35,50). Interestingly, the most saline water constituting this section (35,60 - 35,62) is located along the southern edge of the Agulhas Current (CTD_054), from 90 to 220 db, indicative of the subsurface salinity maximum characteristic of Subtropical Surface Water (SSW). The majority of waters more saline than 35,63 are those within the modified cores of Ring A2 and Eddies A3, A4 and A5 (Figure 5.27).

The Agulhas Front, which bounds the southern margin of the Agulhas Return Current, is located at station CTD_053, expressing a surface temperature gradient of 0,104°C.km⁻¹ (comparable to the mean of 0,102°C.km⁻¹ estimated by Lutjeharms and Valentine (1984)). The vertical structure of this front was observed in the *Discovery 165A SeaSoar* data to undergo little change throughout the Retroflection region (Holford, 1990). The landward margin of the Return Current is more difficult to define since no distinct thermohaline boundary exists. Nevertheless, station XBT_113 is chosen to represent this boundary based on the rapid steepening of the 10°C isotherm, revealing the width of the Return Current to be in the region of 118 km. The dipping of the isotherms between station CTD_052 and CTD_051 could be the result of some small-scale eddy feature or perhaps the edge of the S-shaped meander of the Return Current further to the east.

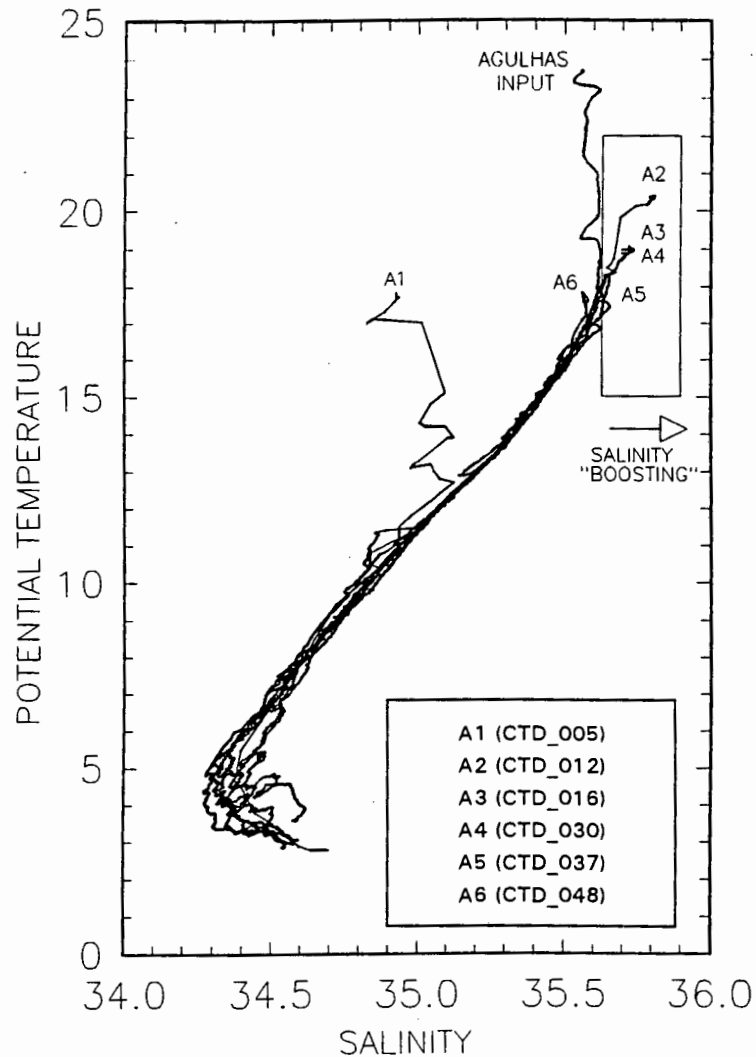


Figure 5.27: Multiple temperature - salinity (Θ/S) plot for the six ring / eddy centre stations, including Agulhas Current input station CTD_054.

Discovery 165A (SeaSoar data)

Fortunately the *Discovery 165A* cruise sampled the Retroflection region over a similar period (see Figure 5.28a). The temporal sampling differences between the two cruises was best over Eddy A4, a mere 4 to 10 days apart. The hydrographic sampling of the "southerly spill" of the Retroflection region ($40^{\circ} - 42^{\circ}\text{S}$; $17^{\circ} - 21^{\circ}\text{E}$) was 4 to 16 days apart, and that of the Agulhas Current input and Return Current some 20 to 23 days apart.

The *Discovery 165A SeaSoar* data are particularly useful in resolving the upper 350 db of the water column, thus enabling positive identification of the western extent of the

Retroflection (a region where the *SCARC* data are noticeably sparse). The *Discovery 165A* data reveal a further westward extension of the Retroflection to about 17°E, with a possible "southerly spill" of Agulhas Water at about 20°E (Figures 5.28a and 5.28b). For consistency, Figure 5.28a shows the plot of the 15°C intersection with the 200 db depth (a criterion used by Gründlingh (1983) to locate the dynamical core of the Agulhas Current) for both *SCARC* and *Discovery 165A* cruises. The size and location of the Retroflection, as defined by the 15°C / 200 db intersection in the *Discovery 165A* data, agrees surprisingly well with that revealed by the altimetrically derived 20 cm isoheight (A7). The Agulhas Retroflection is therefore located further west than previously assumed from the *SCARC* data. Interestingly, judging from the 15°C / 200 db intersection from the two cruises over the eastern quadrant of Eddy A4, A4 moved about 38 km west over a period of 7,3 days, equating to a translational velocity of about 6,0 cm.s⁻¹ (assuming the morphology of the eddy remained constant). This value is somewhat lower than the altimetric derived estimate of 9,0 cm.s⁻¹ from van Ballegooyen *et al.* (1994).

b) Ring A1

SCARC Sections 1 - 3 (see **Addendum 2**)

Hydrographic Sections 1 to 3 traverse Ring A1 in a star-shaped pattern, centered between XBT_003 & XBT_004 (Section 1) and XBT_013 (Section 3), where the 10°C isotherm is depressed to a maximum depth of 430 db and 454 db respectively. A rim of maximum sea surface temperature is identified, suggesting that A1 exhibits a true ring structure comprising an annulus of warm surface water. The 10°C isotherm field reveals Ring A1 as asymmetrical with a southeast to northwest diameter of 317 km and a northeast to southwest diameter of 258 km. The location and dimensions of A1 are comparable to that of the "Cape Town Eddy" (Gordon *et al.* (1987). However, the "Cape Town Eddy" is more symmetrical and intense, with the maximum depth of the 10°C extending to 770 db.

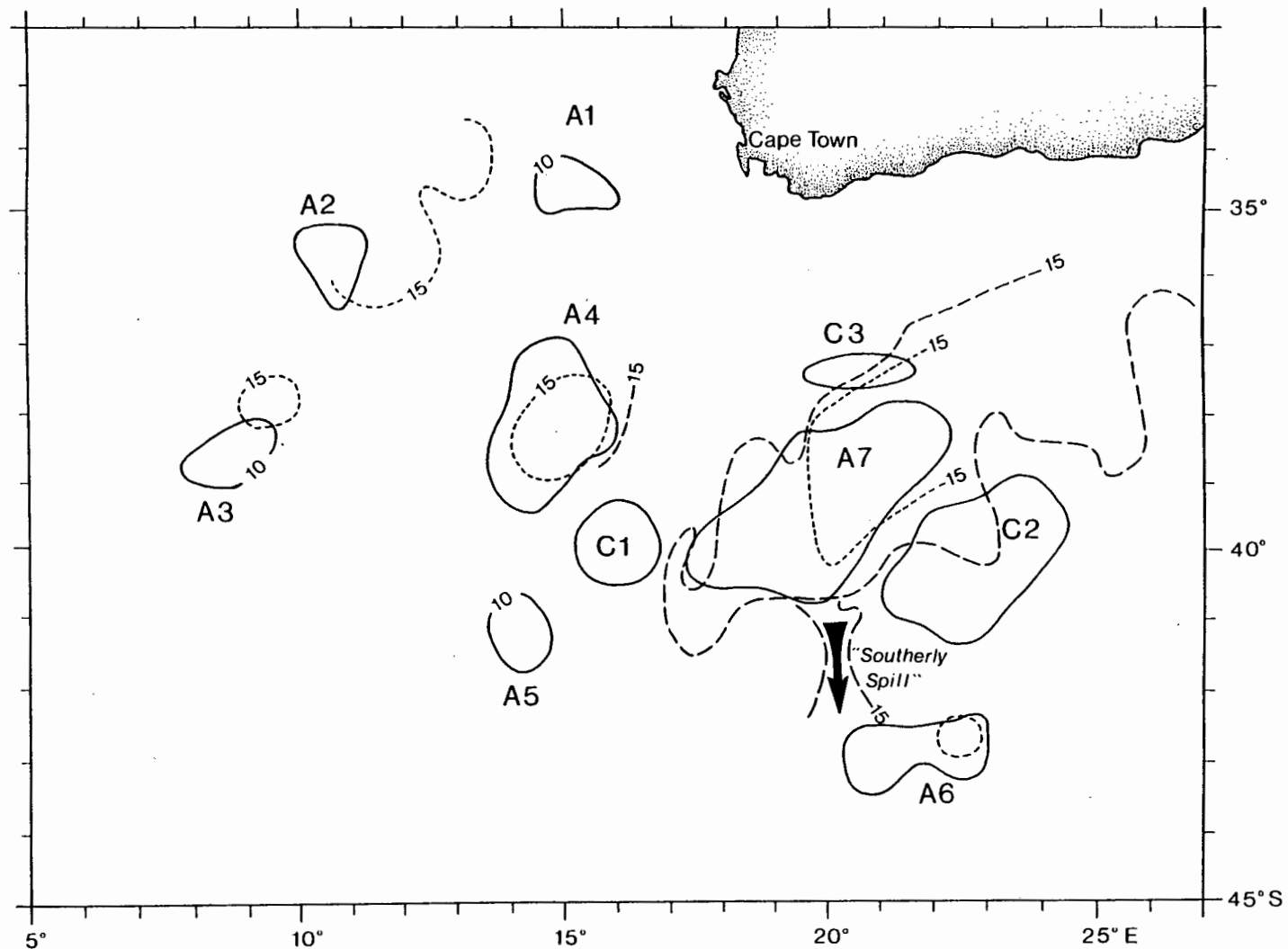


Figure 5.28a: A line drawing interpretation of the 15°C / 200 db intersection from both *SCARC* (dotted contours) and *Discovery 165A* data (dashed contours). Superimposed on this is the location of the hydrographic features as revealed by *Geosat* altimetry (from van Ballegooyen *et al.*, 1994). Indicated are the 20 cm isoheights (bold contours), except features A1, A3 and A5 where the 10 cm isoheight is portrayed. Notice the westward extension of the Agulhas Retroflection as revealed by the *Discovery 165A* data, in support of the altimetric evidence.

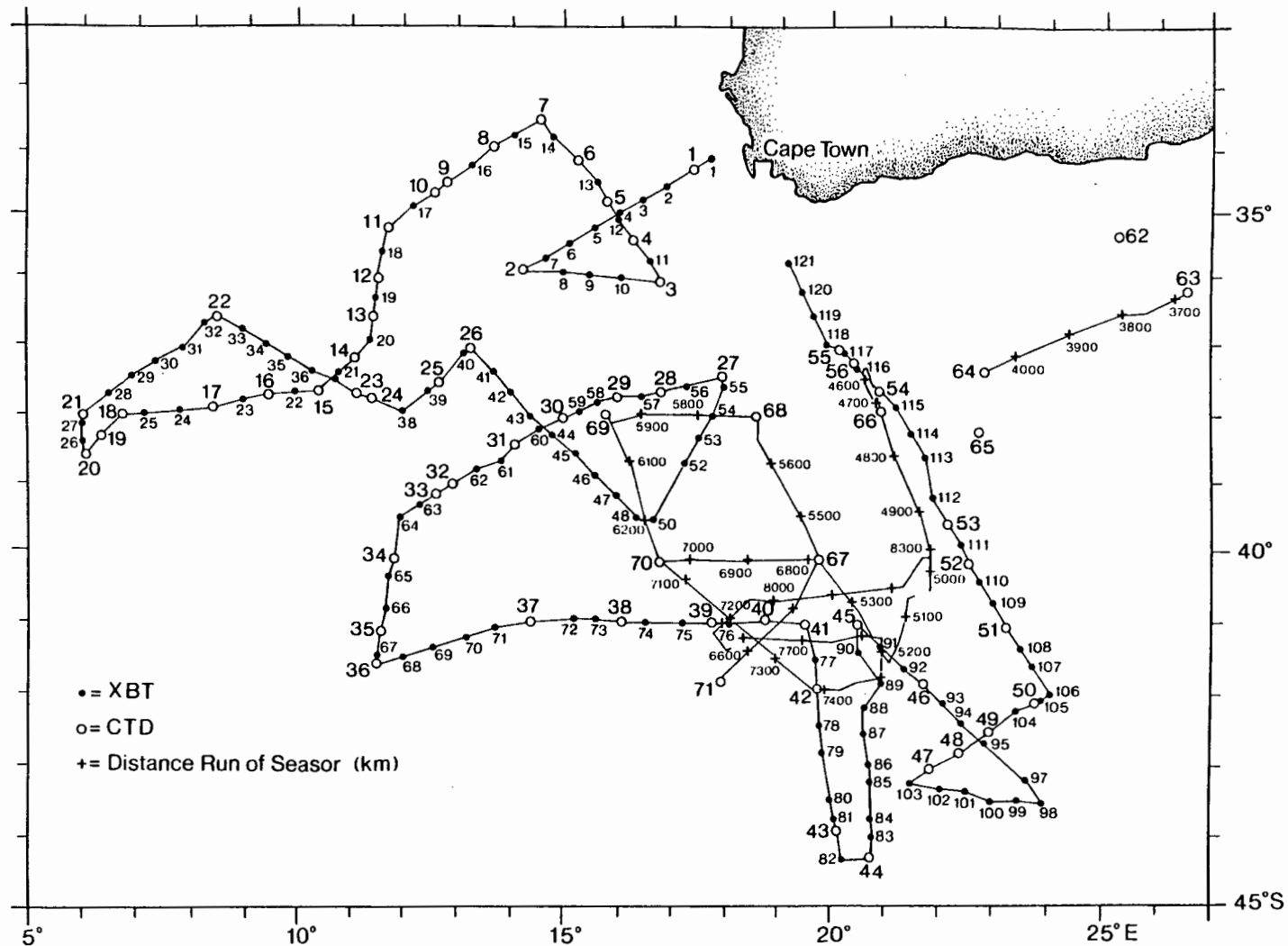


Figure 5.28b: The cruise tracks of both *SCARC* and *Discovery 165A* hydrographic voyages. Open circles denote CTD stations, solid circles indicate XBT stations. Crosses indicate the distance run (in km) by the *Discovery 165A SeaSoar*.

c) Ring A2

SCARC Section 4 (see **Addendum 2**)

Neither edges of A2 could be identified by the classic 10°C / 300 db intersection. The 10°C isotherm extends to a maximum depth of 684 db (CTD_012). The subsurface thermal structure of A2 indicates a rather skewed bowling of the isotherms, deepening sharply in the southwest and shallowing gently to the northeast. A slight uplifting of the isotherms between stations XBT_016 and XBT_017 reflects the "saddle-like" subsurface structure of A2 along its northeast to southwest axis. Although the 10°C isotherm never extends shallower than 300 db, the flattening off of the bowl-shaped isotherms along the northeastern (CTD_007) and southwestern (CTD_014) sectors indicates a northeast to southwest diameter of about 525 km. Assuming the above criteria, A2 is a remarkably large feature, of the order of the Agulhas Retroflection itself.

The location of the features described above are shown in the potential temperature, salinity and potential density sections (**Addendum 2**, Section 4). Interestingly, the salinity section clearly reveals the southeast to northwest aligned Subantarctic filament (C4 Minor) between A2 and A3, with low salinity (34,80) surface water (CTD_014).

d) Eddy A3

SCARC Sections 4 - 6 (see **Addendum 2**)

Eddy A3 exhibits a symmetrical bowl-shaped isothermal structure with the 10°C isotherm extending to a maximum depth of 637 db (CTD_016). Like A2, the background flow does not exhibit water cold enough to lift the 10°C isotherm above 300 db. Adopting the flattening off of the 10°C isotherm as the criterion for denoting the edge of the feature, stations XBT_021 and XBT_025 locate the eastern and western edges respectively, revealing a zonal diameter of 311 km. The centre of the eddy is characterized by a deep (125 db) isothermal layer of about 18,9°C.

Section 6 skims the northeastern edge of Eddy A3 (XBT_034 to CTD_023). The most notable feature of this hydrographic section is the dramatic uplifting of the 10°C to 240 db (XBT_033 to XBT_034). This may be interpreted as an extension of the cold Subantarctic filament (C4 minor) being drawn from the south around the eastern perimeter of A3, separating A3 from A2. Overlying this cold water intrusion is a

thermostad of 20,0°C water extending from the surface to 80 db. This surface stad may be an extension of the warm surface water located along the northwestern rim of Eddy A3 (hydrographic Section 5) "over-spilling" part of the Subantarctic filament (C4 minor). Stations CTD_023 to XBT_038 locate the base of the minor northwestern branch of Subantarctic filament (C4) (a width of about 71 km), separating A3 from A2. The actual width of this minor branch of filament (C4) is much narrower (± 35 km), since this section intersects the filament at an oblique angle. The major part of Subantarctic filament (C4) (aligned southwest to northeast) is traversed between stations XBT_040 and XBT_042, amounting to a width of about 76 km, separating the vortices to the west (A2 and A3) from Eddies A4 and A5.

The location of the features described above are shown in the potential temperature, salinity and potential density sections (**Addendum 2**, Sections 4 - 6). Incongruities between the location of the features (based on the temperature section) and the potential temperature, salinity and potential density fields are the result of software interpolation between poorly spaced CTD stations.

e) Eddy A4

SCARC Sections 7 - 9 (see **Addendum 2**)

Three hydrographic lines traverse Eddy A4 in a star-shaped pattern. Section 7 is characterized by bowling of the isotherms constituting Eddy A4. The maximum depth to which the 10°C isotherm is depressed is 756 db (XBT_044). Edge stations lie between XBT_041 & XBT_042 and XBT_046 & XBT_047, revealing a northwest to southeast diameter of 204 km (determined from the 10°C / 300 db intersection). A deep thermostad (19,1 - 19,0°C) extends from the surface to about 130 db in the centre of the eddy (XBT_043 - XBT_045). A relatively strong surface thermal front is evident along the northwestern edge at station XBT_042 (0,067°C.km⁻¹), intensified by the cold Subantarctic filament (C4) abutting the northwestern edge of Eddy A4. Also noticeable is the subsurface expression of Subantarctic filament (C1) along the eastern and southern edge of the eddy, uplifting the 10°C isotherm to within 190 db (XBT_048) of the surface.

Section 9 locates the centre of Eddy A4 at station CTD_030, with the 10°C isotherm dipping to a maximum depth of 770 db. The core of the eddy is characterized by a surface thermostad (18,8° - 17,9°C) extending to a maximum depth of 164 db. A

detailed analysis of the heat fluxes associated with the deepening and cooling of the well-mixed core of Eddy A4 is dealt with in **Chapter 7**. The edges of the eddy are characterized by an intensified thermocline and strong interleaving, particularly along the northeastern edge (CTD_028). Edge stations, as defined by the 10°C / 300 db intersection, are XBT_057 and XBT_063 (revealing a northeast to southwest diameter of 402 km). However, this is an overestimate of the actual eddy diameter since A4 is slightly skewed to the south. Considering the steep-sided bowl-like structure of the isotherms, a more conservative diameter of 276 km is attained (XBT_057 to XBT_062). Temperature profiles of the core of Eddy A4 (XBT_044 and CTD_030) exhibit a typical well-mixed layer ($19,1^{\circ}\text{C}$ and $18,8^{\circ}\text{C}$), extending from the surface to a depth of 130 db and 138 db respectively. Thereafter, the temperature decreases at a steady rate with depth (see Figure 5.29). A similar profile is also evident in the *Discovery 165A* station CTD_069 (51 km from SCARC station CTD_030; hydrographically sampled seven days earlier), with a surface mixed layer of about $18,7^{\circ}\text{C}$ extending to a depth of about 130 db.

So, in summary Eddy A4 is slightly elliptical, with a northwest to southeast diameter of 204 km and a northeast to southwest diameter of 276 km. The subsurface temperature signature of the eddy extends throughout the sample depth (1500 db), with the 10°C isotherm extending to a maximum depth of 770 db. A deep surface thermostad is identified in both northwest to southeast and northeast to southwest hydrographic transects. The maximum depth of the thermostad varies from 130 db to 164 db respectively, with the mean core temperatures of the mixed layer dropping from $19,16^{\circ}\text{C}$ to $19,00^{\circ}\text{C}$ over a period of two days (ie. equivalent to a deepening of the mixed layer at a rate of 17 m per day). This rate of deepening is substantially greater than the winter seasonal average of 1,4 - 1,9 m per day for warm-core rings from the East Australian Current (Mulhearn, 1983). Seasonal averaging tends to dissuade the importance of episodic events embedded within the seasonal climatology, such as accelerated mixed layer deepening during post-frontal climatic conditions. The consequences of enhanced mixing during post-frontal conditions will be dealt with in more detail in a case study presented in **Chapter 7**.

Eddy A4 can be compared to Gordon *et al.*'s (1987) "Retroflexion Eddy" since their "Retroflexion Eddy" was located in a similar region and was also found to be elliptical, with a major diameter of 340 km and a minor of 136 km (10°C / 300 db intersection). The depth of the 10°C isotherm within the "Retroflexion Eddy" extended

to a maximum depth of 767 db. The asymmetry of both Eddy A4 and the "Retroflexion Eddy" may be a function of them being hydrographically sampled relatively soon after being shed from the Agulhas Retroflexion, thus exhibiting an unstable asymmetrical configuration.

f) Eddy A5

SCARC Section 10 (see **Addendum 2**)

As was noted earlier, Eddy A5 is located deep within the Subantarctic, open to the north (centered on 42°S; 13°E - see Figures 5.1b and 5.1c). The zonal hydrographic section traversing Eddy A5 locates its centre between stations XBT_071 and CTD_037, with the 10°C isotherm dipping to a maximum depth of 540 db. The 10°C / 300 db intersection indicates a diameter of 145 km (edge stations XBT_070 and XBT_072). Since this eddy is located deep within the Subantarctic regime, the 10°C isotherm is drawn close to the surface, reaching depths shallower than 100 db along the edges of the eddy. Eddy A5 exhibits a surface mixed layer of about 17,5°C, extending to a depth of 158 db. Notice the intensification of the thermocline as a result of warm surface waters (>17°C; CTD_038) overlying the filamentous intrusion of Subantarctic Water along the eastern perimeter of Eddy A5. The origin of this warm surface water may be from over-spill of Agulhas surface water from the Retroflexion, possibly in the form of a cyclonic shear-edge plume extending from the southwestern extremity of the Retroflexion. The cyclonic shear-edge plume extending from the Retroflexion executes its cyclonic turn around stations XBT_075 and CTD_039, centered at (40,5°S; 17,5°E) (see Figure 5.1c).

g) Eddy A6

SCARC Sections 11 - 15 (see **Addendum 2**)

Five hydrographic lines traverse the region south of the Retroflexion. Eddy A6 is identified, exhibiting a double-lobe thermohaline structure. The western lobe (XBT_084 - XBT_087) is characterized by the 10°C isotherm extending to a maximum depth of 610 db. The extension of warm surface water (>15°C) to the north is indicative of the western margin of the "southward-spill" of Agulhas water, centered along a meridional axis between hydrographic Sections 11 and 12. The eastern lobe of Eddy A6 exhibits a surface thermostad (17,5° - 17,0°C) extending to a depth of 133

db. The 10°C isotherm extends to a maximum depth of about 500 db (CTD_048), 110 db shallower than that of the western lobe.

From the above description of the vertical thermohaline sections of the *SCARC* (and *Discovery 165A*) cruises, it is apparent that the morphology of each mesoscale feature within the Retroflexion region is different. The Agulhas Current input is approximately 100 km wide, with the surface (saline) core located at the landward edge of the Current. The *SeaSoar* data suggest that the westward extension of the Agulhas Retroflexion is located at about 17°E, with evidence of a possible "southerly spill" of Agulhas Water into Eddy A6 (20°E).

The six Agulhas vortices each display varying morphologies, ranging from near symmetrical to highly asymmetrical. Their diameters range from 143 - 525 km, with the maximum depression of the 10°C isotherm varying from 454 - 770 db. The diverse morphology of these six vortices encompass an extreme upper and lower range of characteristics for Agulhas vortices sampled in the Agulhas Retroflexion region. Deep isothermal surface layers characterize the core of these vortices, with typical temperatures of these thermostads ranging from 19,1 - 17,0°C. These thermostads extend from the surface to a maximum depth of between 125 - 164 db. The *SCARC* suite of vortices seem to identify the expected thermostad characteristics of Agulhas vortices within the immediate vicinity of the Agulhas Retroflexion. Five other Agulhas vortices (Gordon *et al.*'s (1987) "Cape Town Eddy" - 280 m; Gordon *et al.*'s (1987) "Retroflexion eddy" - 305 m; Bennett's (1988) "Cape Town eddy" - 195 db; McCartney and Woodgate-Jones' (1991) "Double thermostad eddy" - 200 m and Duncombe Rae *et al.*'s (1994) "Winter Ring" - 320 m) have been documented to exhibit near-isothermal surface mixed layers ($\pm 16^\circ\text{C}$) to similar and greater depths (195 - 320 m). In fact, there has been no publication to date suggesting that Agulhas vortices can develop surface thermostads deeper than that illustrated by Duncombe Rae *et al.*'s (1994) "Winter ring", even outside the Retroflexion region.

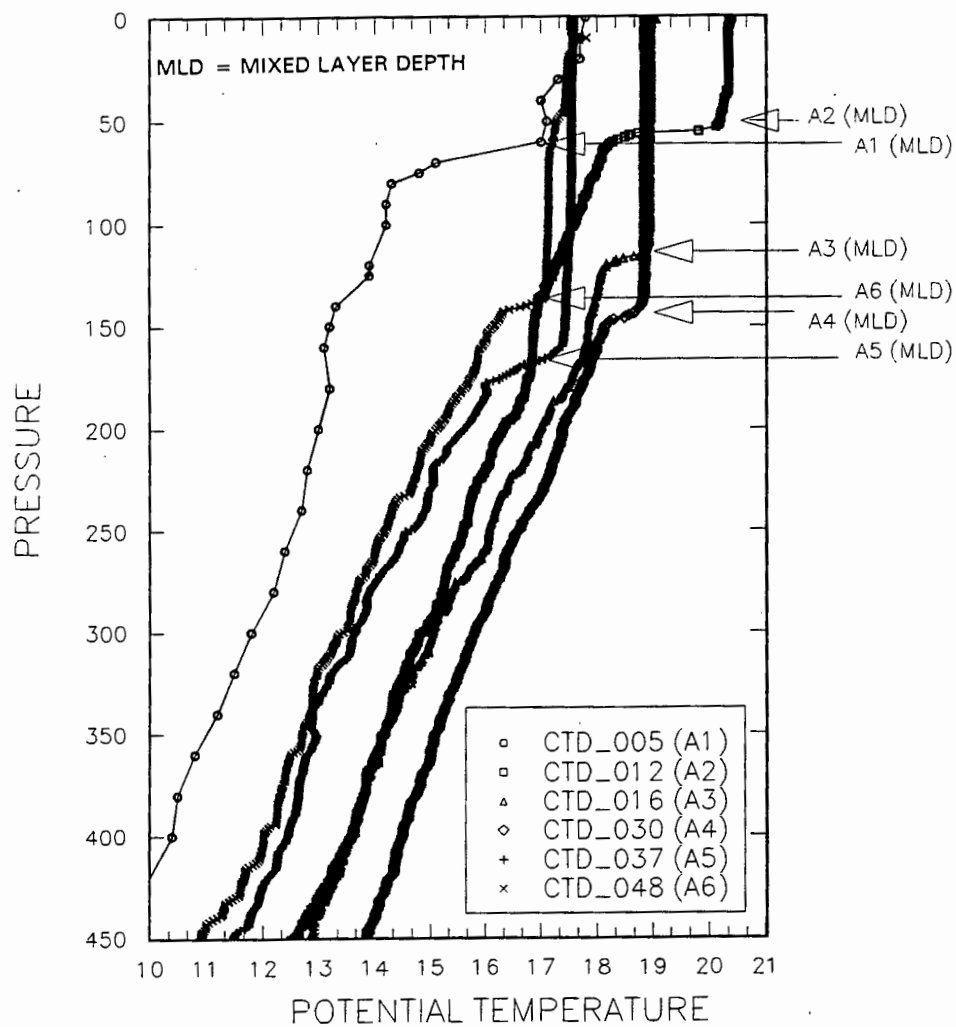


Figure 5.29: Temperature profiles at the centre of all six Agulhas rings and eddies sampled during the *SCARC* showing the deep mixed layers characteristic of Agulhas rings and eddies.

5.3) The dynamic structure of the mesoscale features of the Agulhas Retroflection region

5.3.1) Dynamic Topography

Dynamic Topography Pattern

The estimated geopotential anomalies of the sea surface relative to 1500 db and 1000 db during the *SCARC* are determined. Using the two-layered model (10°C isotherm) described in the **Data and Methods**, estimates of the geopotential anomalies for XBT stations are also included. The results of this analysis are listed in Table 4 below.

Table 4: Linear correlations (R^2 values) of the 8°, 10° and 12°C isotherms versus the geopotential anomalies calculated relative to 1500 db and 1000 db

	Isotherm	All Data	Excl. Bad Data	Excl. Marginal Data
Geopot₍₁₅₀₀₎ vs	8°C	0,891	0,931	0,946
	10°C	0,933	0,950	0,956
	12°C	0,903	0,904	-
Geopot₍₁₀₀₀₎ vs	8°C	0,910	0,929	0,940
	10°C	<u>0,949</u>	0,970	-
	12°C	0,928	0,932	-

The 10°C isotherm provides the best (linear) regression with the geopotential anomalies in the Retroflection region during the *SCARC*. Regression of the surface geopotential anomalies relative to 1000 db (Geopot₍₁₀₀₀₎) against the depth of the 10°C isotherm (h_{10}) in metres for all the data gives a best fit of ($r^2 = 0,949$), providing the following relationship:

$$\text{Geopot}_{(1000)} = 9,170 + 0,01021 \times h_{10}$$

The correlation of the Geopot₍₁₀₀₀₎ to Geopot₍₁₅₀₀₎ is good, implying that the Geopot₍₁₀₀₀₎ and Geopot₍₁₅₀₀₎ could be used interchangeably (ie. one needs only to determine the geopotential relative to 1000 db in order to get a good representation of the deeper flow). The correlation of the geopotential relative to 1000 db provides the best correlation when 'data points' < 200 db deep and two 'data points' at the inshore edge of the Agulhas Current are excluded. The second best correlation is obtained for

the geopotential relative to 1500 db versus the depth of the 10°C isotherm, when 'data points' <200 db and two stations at the edge of the Agulhas Current are excluded. This implies that shallow 'data points' (10°C <200 db) should be excluded. These generally occur at the Subtropical Convergence (STC) or in the cold filaments that extend northwards from the STC. Secondly, stations in high shear regions (eg. along the near-shore edge of the Agulhas Current) should also be excluded.

The estimated geopotential anomaly of the sea surface relative to 1000 db during the *SCARC* reveals an anomalously diverse eddy field (Figure 5.30). The greatest anomalies (140 - 170 dynamic cm) are associated with anti-cyclonic flow of Agulhas Water. The dynamic topography of all the warm-core rings and eddies of the *SCARC* are represented, with the greatest geopotential anomaly (> 160 dyn cm) associated with Ring A2 and Eddy A4. Evidence of the major Subantarctic filaments (C1 and C4) are observed where the $\text{Geopot}_{(1000)}$ exceeds 120 dyn cm. Caution is to be taken when interpreting the 'shallow data points' (10°C <200 m). This is generally the case where the $\text{Geopot}_{(1000)}$ is less than 110 dyn cm. Notice the location of a possible "southward-spill" of Agulhas Water from the southern terminus of the Agulhas Retroflection into Eddy A6, denoted by the question-mark (Figure 5.30). The local dynamic depression (<100 dyn cm; CTD_039) represents the centre around which the shear-edge plume from the southwestern terminus of the Retroflection executes a cyclonic turn (see Figure 5.1c). The estimated geopotential anomaly of the sea surface relative to 1500 db reveals a similar pattern to that relative to 1000 db (Figure 5.31).

Use of the 10°C Isotherm

From the previous section it is clear that the depth of the 10°C isotherm provides the best linear correlation to the dynamic height in the Agulhas Retroflection region during the *SCARC*. Since the average depth of the 10°C isotherm outside the influence of the Agulhas Current (and associated vortices) is about 300 db ($\text{Geopot}_{(1500)} = 156$ dyn cm), the intersection of the 10°C isotherm with the 300 db depth provides a useful criterion to define the horizontal dimensions of the Agulhas rings and eddies. Van Ballegooyen *et al.* (1994) used the intersection of the 10°C with the 300 db depth to define the horizontal dimensions of the same rings and eddies in their comparison with satellite derived dynamic height anomalies over the Agulhas Retroflection region. Similarly, Olson and Evans (1986) employed the two-layer model to their data over the Retroflection, using a 300 m reference depth of the 10°C isotherm, which translated to a reference (or background) dynamic height (geopotential anomaly) of 153 dyn cm. This

result compares rather favorably with a dynamic height of 156 dyn cm during the *SCARC*.

A plot of the depth of the 10°C isotherm (Figure 5.32) reveals a similar pattern to that of the estimated geopotential anomalies (Figures 5.30 and 5.31). All the dominant mesoscale features are evident, with the depression of the 10°C isotherm below 300 db inferring warm-core anti-cyclonic flow. Where the 10°C isotherm is shallower than the 300 db background flow, intrusions of cold Subantarctic Water are expected (except in the case where hydrographic stations are located over the continental shelf). A three-dimensional plot of the depth of the 10°C isotherm over the two hydrographic crossings of Eddy A4 (Figure 5.33) illustrates the depression of the 10°C isotherm associated with the warm-core vortex. The orientation of this 3-D view is such that one is viewing the eddy from the southeast, looking north. Notice that the 10°C isotherm extends to a depth exceeding 700 db. The flat plane (indicating no data) lies at the depth of the background flow (300 db). Evidence of the cold filaments encompassing the western and southeastern perimeter of Eddy A4 are observed (Subantarctic filaments C4 and C1 respectively), with the shoaling of the 10°C isotherm to within 190 db of the surface.

In summary, a two layer model (Olson, 1980; Olson *et al.*, 1985; Olson and Evans, 1986; Bennett, 1988) is used to describe the circulation within the Agulhas Retroflection region during the *SCARC*. From this model linear regressions of the geopotential anomalies (relative to 1000 db and 1500 db) against the depth of the 8°C, 10°C and 12°C isotherms are estimated. The regression of surface geopotential anomaly (relative to 1000 db) with the depth of the 10°C isotherm is identified to give the best (linear) fit. This result is consistent with the Olson and Evans (1986) analysis of the *Knorr* (ARC) data over the Agulhas Retroflection region. Furthermore, it is found that the geopotential anomalies relative to 1000 db provide an adequate representation of the deeper flow. Surface geopotential anomalies (relative to 1000 db) exceeding 140 dyn cm are associated with anti-cyclonic flow of Agulhas Water, and identify the dynamic topography of all six warm-core vortices within the Retroflection region. Geopotential anomalies less than 120 dyn cm identify all the cold-core cyclonic mesoscale features within the Retroflection region. These cyclonic features are generally of Subantarctic origin. A geopotential anomaly of 156 dyn cm (about 300 db) is identified to represent the background (or reference) dynamic height of the Retroflection region.

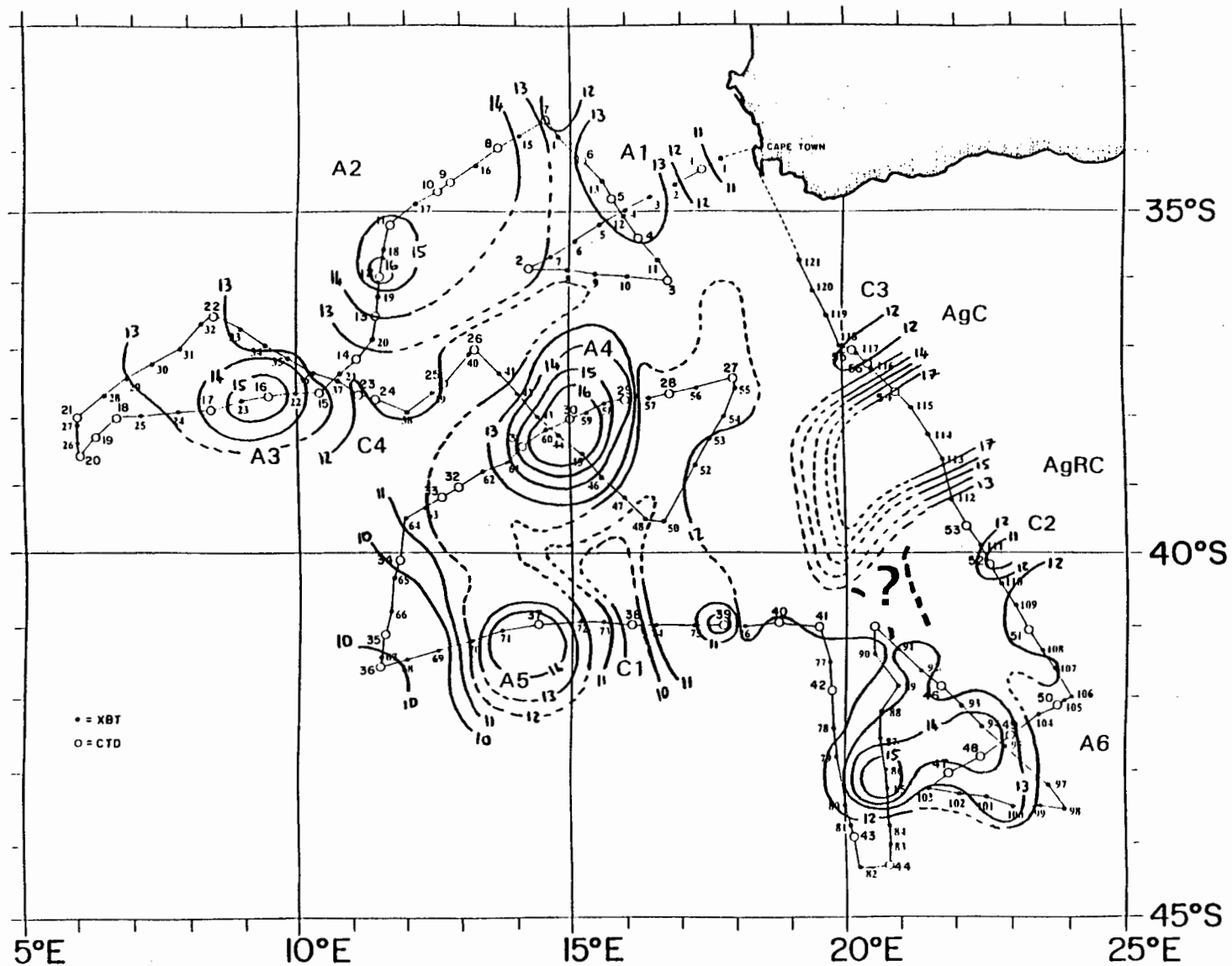


Figure 5.30: A contour plot of the estimated geopotential anomaly (in dynamic cm x 10) relative to 1000 db during the SCARC, with an overlay of the SCARC cruise track. A1 to A6 denote the anti-cyclonic mesoscale features, A7 the Retroflection, and C1 to C4 the cyclonic features. AgC and AgRC indicate the Agulhas Current and Return Current respectively.

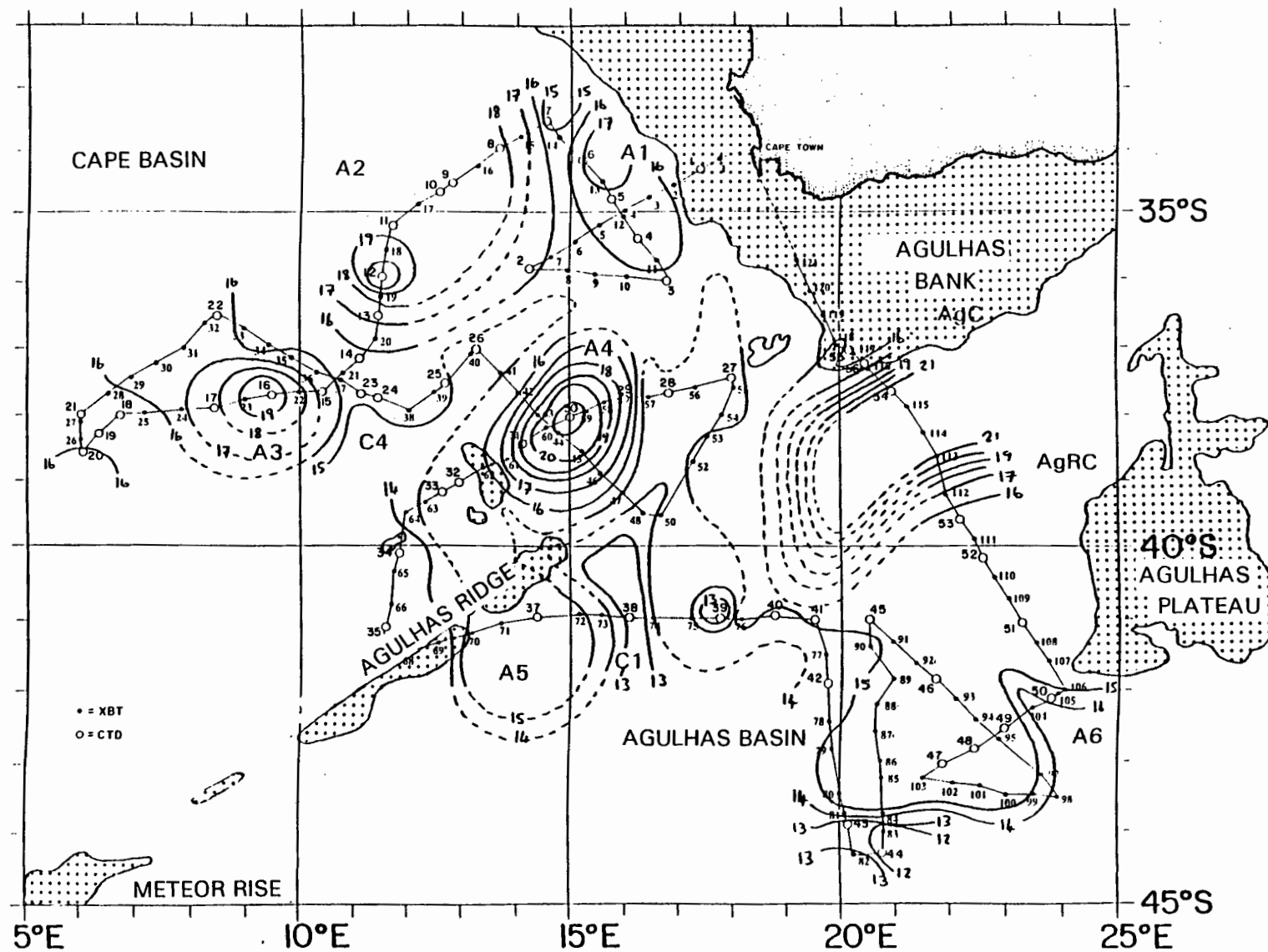


Figure 5.31: A contour plot of the estimated geopotential anomaly (in dynamic cm x 10) relative to 1500 db during the *SCARC* with an overlay of the *SCARC* cruise track. A1 to A6 denote the anti-cyclonic mesoscale features, A7 the Retroflection, and C1 to C4 the cyclonic features. AgC and AgRC indicate the Agulhas Current and Return Current respectively. The main bathymetry (< 3000 db) is shaded.

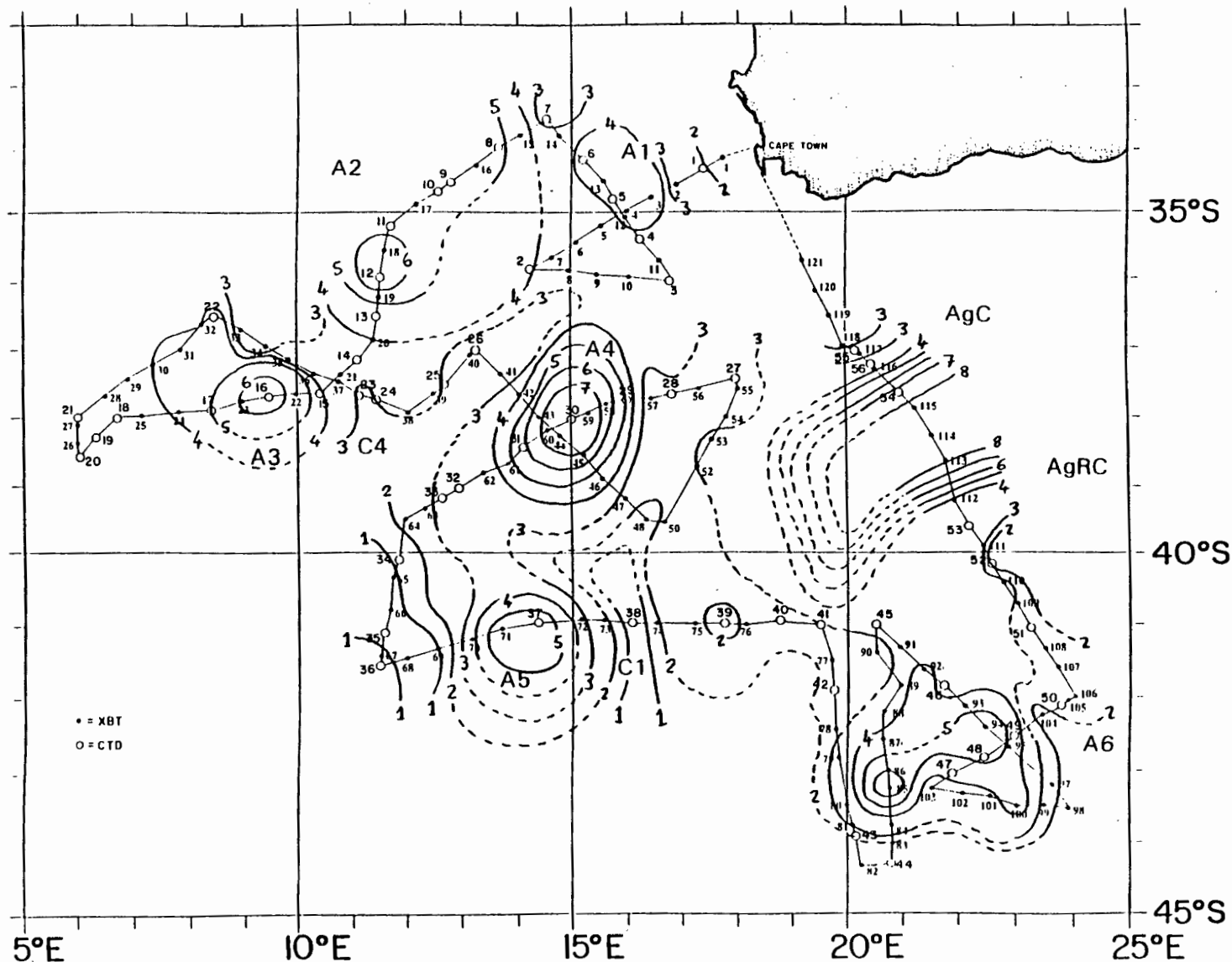


Figure 5.32: A contour plot of the depth of the 10°C isotherm (x 100 db) with an overlay of the SCARC cruise track. A1 to A6 denote the anti-cyclonic mesoscale features, A7 the Retroflexion, and C1 to C4 the cyclonic features. AgC and AgRC indicate the Agulhas Current and Return Current respectively.

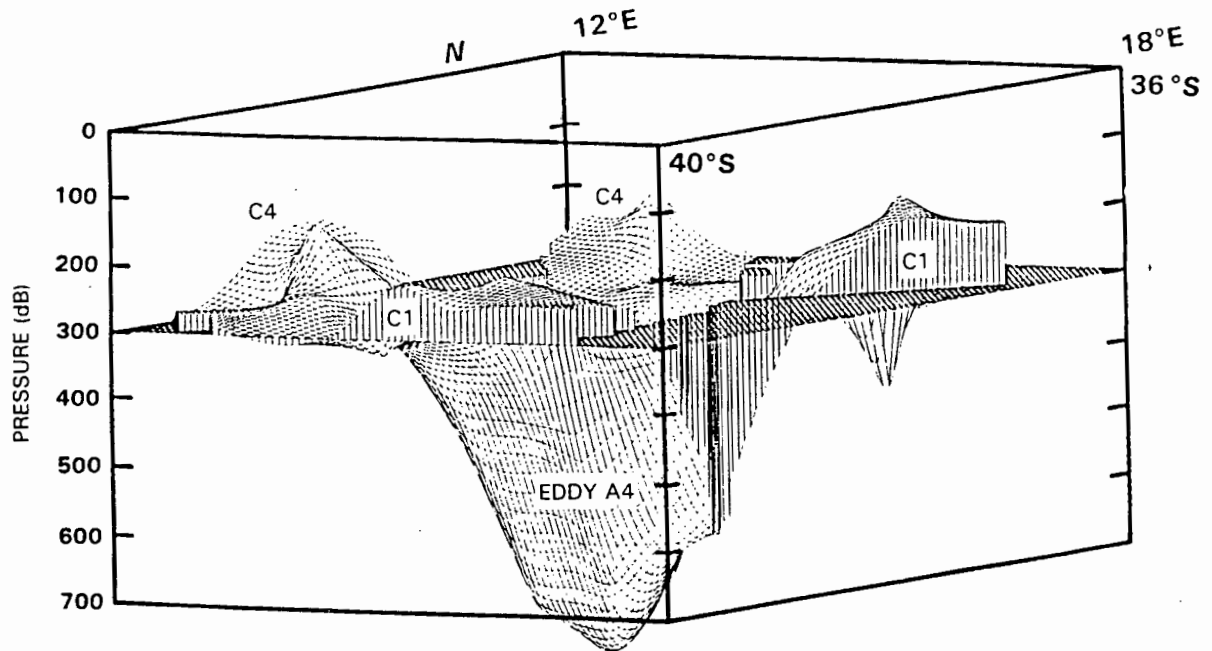


Figure 5.33: A three dimensional contour plot of the depth of the 10°C isotherm for the *SCARC* Eddy A4. The flat plane is located at a depth of 300 db. The matrix below the 300 db plane denotes the core of Eddy A4. The dotted contour denotes the 10°C / 600 db intersection. The 'topography' above the 300 db plane denotes the Subantarctic filaments which have been drawn around the western and eastern perimeter of the eddy, namely C4 and C1 respectively.

5.3.2) Geostrophic Velocity

Geostrophic Velocity Pattern

Surface geostrophic current velocities relative to the 1500 db level during the *SCARC* (Figure 5.34a) and those determined from the electromagnetic (EM) log of the *Discovery 165A* cruise (Figure 5.34b) show the general surface currents of the Agulhas Retroflection region in February - March 1987. Combining the *SCARC* geostrophic surface current vectors as well as the EM log vectors clearly shows the magnitude and direction of the surface circulation associated with the diverse hydrography of the Retroflection region (Figure 5.34c). The Agulhas Retroflection and its attendant anti-cyclonic warm-core rings and eddies are evident. Unfortunately there is a noticeable absence of hydrographic data further upstream of the Retroflection region. The EM log data of the *Discovery 165A* cruise fortuitously covers the "spatial gap" in the *SCARC* data where the western extreme of the Retroflection is located, and provides hydrographic evidence of the Agulhas Return Current extending northwards, after initiating a S-shaped meander as the current encounters the Agulhas Plateau (see Figures 5.1b and 5.1c).

The maximum geostrophic velocities of the Agulhas vortices encountered during the *SCARC* reach up to 44% of the maximum geostrophic surface velocity of the Agulhas Current inflow (a slightly greater percentage is obtained using the EM log data of the *Discovery 165A* cruise, with the maximum rim velocity of Eddy A4 being about 61% of the Agulhas Current surface velocity inflow). The highest surface geostrophic velocities for the *SCARC* data are that of the Agulhas input ($113,59 \text{ cm.s}^{-1}$), whilst a surface velocity of $191,80 \text{ cm.s}^{-1}$ is estimated from the EM log of the *Discovery 165A* for the same inflow region some 21 days earlier; a significant difference of $78,21 \text{ cm.s}^{-1}$. The surface velocity over the eastern sector of Eddy A4, a mere six days apart, reveals a maximum surface rim velocity of $51,16 \text{ cm.s}^{-1}$ and $117,27 \text{ cm.s}^{-1}$ for the *SCARC* and the *Discovery 165A* EM log estimates respectively. This compares rather poorly and draws caution when comparing the *SCARC* geostrophic velocities to measured EM log velocities, highlighting the importance of the barotropic contribution to the total flow. Assuming the surface *Discovery 165A* EM Log velocities of the mesoscale features of the Retroflection region accurately depict the total measured surface velocities, and the *SCARC* geostrophic surface velocities are representative of the baroclinic velocities of the same features (referenced to 1500 db), a barotropic component of about 56% and 40% of the total surface flow is estimated for the Agulhas input and vortices respectively.

The geostrophic maximum rim velocities for the six warm-core rings and eddies of the *SCARC* survey vary in magnitude from about 14 to 51 cm.s^{-1} . This range is comparable to that of the eddy in the Subtropical Convergence (Duncan, 1968), the "Cape Town Eddy" (Olson and Evans, 1986) and the Agulhas eddies encountered in the South Atlantic (Gordon and Haxby, 1990; McCartney and Woodgate-Jones, 1991; Duncombe Rae *et al.*, 1992; Duncombe Rae and Shillington, 1994). Table 5 below lists the range of maximum geostrophic surface velocities (referenced to 1500 db) for the host of mesoscale features sampled during the *SCARC*. Average velocities from the *Discovery 165A* data are included, highlighting the large discrepancy between the geostrophically derived *SCARC* surface velocities and those derived from the *Discovery 165A* Electromagnetic (EM) Log.

Table 5: Peak geostrophic surface velocities of the mesoscale features sampled during the *SCARC* and corresponding surface velocities derived from the *Discovery 165A* Electromagnetic Log where available.

Feature	Peak Geostrophic Velocity (cm.s^{-1})	EM Log Velocity (cm.s^{-1})
Ring A1	14,46 - 22,72	-
Ring A2	36,30 - 45,67	-
Eddy A3	22,58 - 32,92 ^a	-
Eddy A4	34,29 - 51,16	117,27
Eddy A5	18,82 - 35,84 ^b	-
Eddy A6	19,81 - 31,82	-
AgC Input	70,28 ^a - 113,59	191,80
AgC Return	33,35 ^c	219,20
^a Geostrophic Velocity Referenced to 1000 db ^b May be an overestimate due to a possible contribution from Subantarctic filament (C1) ^c May be an underestimate due to poor CTD station spacing		

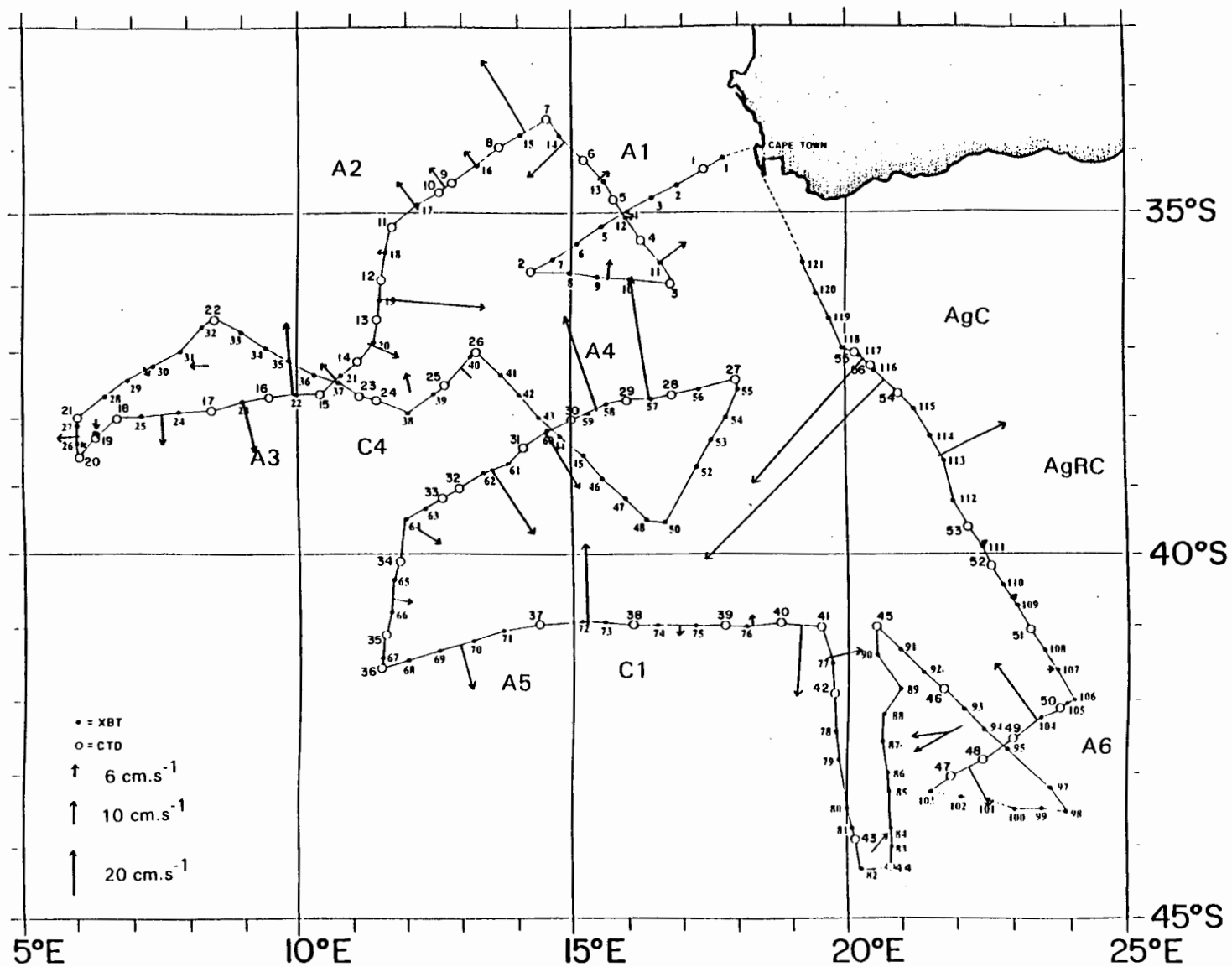


Figure 5.34a: The geostrophic surface velocity pattern of the SCARC referenced to 1500 db with an overlay of the SCARC cruise track.

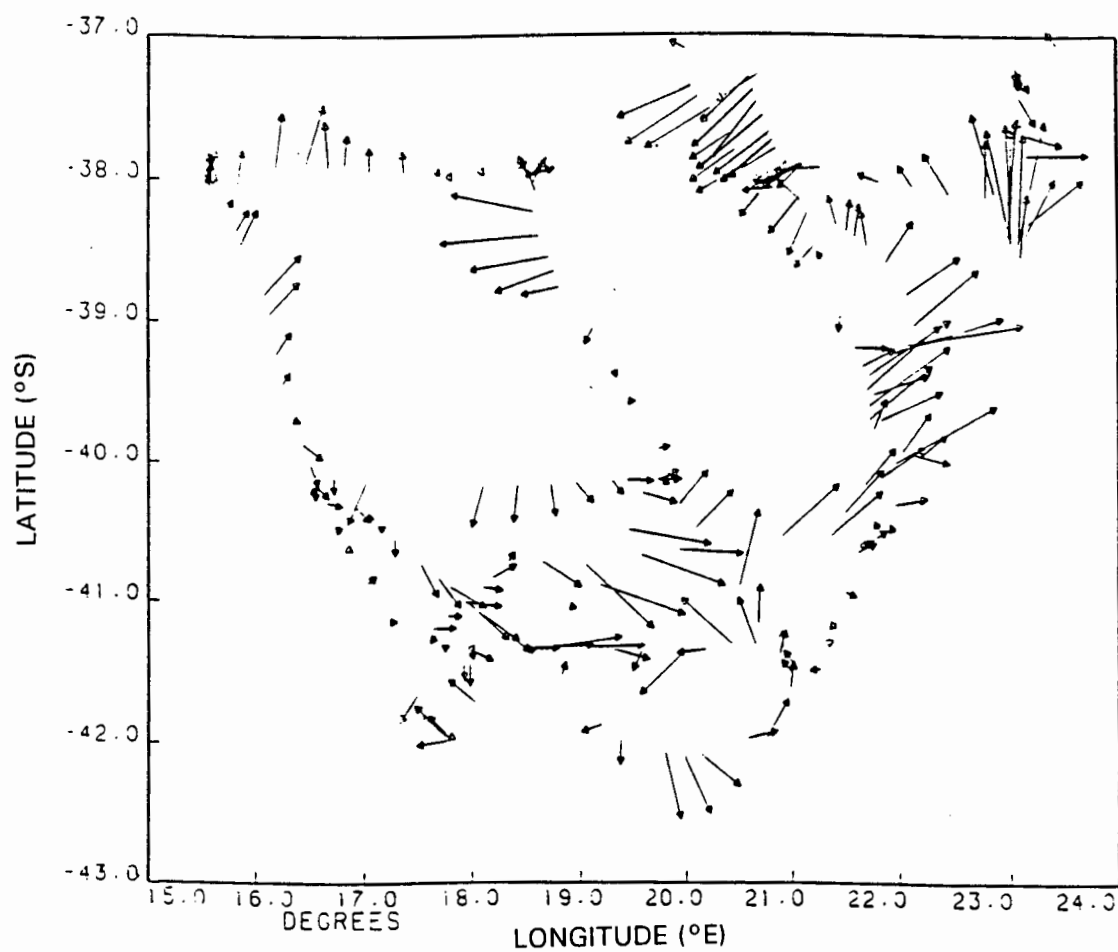


Figure 5.34b: The *Discovery 165A* surface currents derived from electromagnetic (EM) log (from Read *et al.*, 1987).

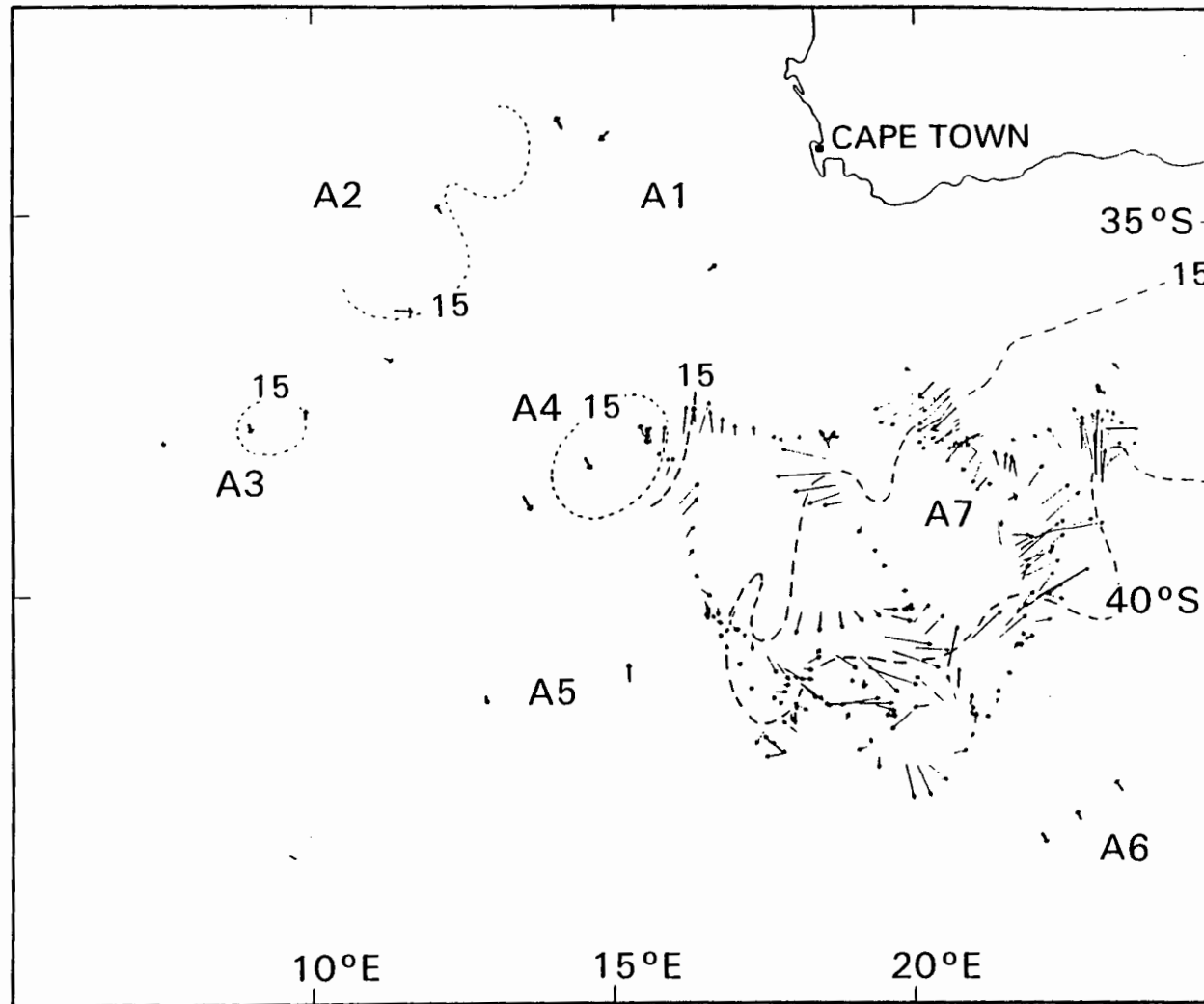


Figure 5.34c: The surface velocity pattern of the *SCARC* ($D_{\text{ref}} = 1500$ db) and *Discovery 165A* (EM log) combined, with the 15°C / 200 db intersection from both *SCARC* and *Discovery 165A* data. The *SCARC* surface velocities have been adjusted to include a 44% (and 60%) baroclinic increase in the surface flow for the Agulhas input (and vortices).

Geostrophic Velocity Structure

The geostrophic velocity structure is derived at 10 db intervals, over the entire depth of the CTD casts (referenced to 1500 db). Geostrophic velocities calculated from the *SCARC* data are generally low, with peak surface velocities of 113,59 and 51,16 cm.s^{-1} for the Agulhas Current input and the Agulhas vortices respectively. Peak rim geostrophic velocities for the six Agulhas rings and eddies sampled in the *SCARC* drop to below 5,0 cm.s^{-1} at depths exceeding 970 db (5,0 cm.s^{-1} is equivalent to about 15% of the mean peak surface velocity for the six vortices). This depth is somewhat shallower than that of 1100 db estimated by McCartney and Woodgate-Jones (1991) for their single eddy sampled in the South Atlantic (referenced to 4000 db).

The Agulhas Current

SCARC Section 16 (see **Addendum 2**)

The geostrophic velocity relative to 1500 db shows an average surface flow of 91 cm.s^{-1} between CTD_054 and CTD_055, spanning the Agulhas inflow. A peak surface velocity of 113 cm.s^{-1} is estimated for the Agulhas Current between CTD_054 - CTD_056 (see Figure 5.34a). Geostrophic velocities between CTD_056 and CTD_055 (over the shelf) are referenced to 1000 db. Caution must therefore be taken when comparing the geostrophic velocities between these two stations with those calculated for other stations in the section. Nevertheless, there seems to be evidence of a weak current reversal (maximum geostrophic velocity of 2 cm.s^{-1}) between CTD_056 and CTD_055 over the shelf below 600 db depth. This reversal may be the result of boundary frictional shear over the shelf.

The geostrophic velocity calculated over the Agulhas Return Current seems to indicate a broad, slower flowing Return Current (CTD_053 - CTD_054), with a maximum surface geostrophic velocity of 33 cm.s^{-1} . However, the spatial sample resolution over the Return Current is poor, with only a single set of CTD stations spanning the Return Current. Overlaying the *Discovery 165A* surface current data onto the *SCARC* data indicates a more defined Return Current between XBT_111 and XBT_113 (see Figure 5.34c), with surface velocities in excess of 200 cm.s^{-1} . The small sub-surface reversal of flow below 74 db (CTD_052 - CTD_053) is difficult to explain but seems to be associated with a poorly defined anti-cyclonic feature between CTD_051 and CTD_052. It may be "overspill" from the seaward edge of the Return Current or a

slight meander of the Current. The *Geosat* and *NOAA AVHRR* data seem to favour the S-shaped meander possibility, coinciding with the cyclonic feature named C2 (see Figure 5.28a).

Ring A1

SCARC Sections 1 - 3 (see **Addendum 2**)

Maximum surface geostrophic velocities ($14,6 - 22,7 \text{ cm.s}^{-1}$) are located along the perimeter of the ring. Interestingly, a slight subsurface reversal in the geostrophic flow (referenced to 1500 db) is evident between station pairs CTD_004 & CTD_005 and CTD_005 & CTD_006, the likes of which are difficult to explain.

Ring A2

SCARC Section 4 (see **Addendum 2**)

The geostrophic velocity structure of Section 4 reveals a peak geostrophic current of $36,30 \text{ cm.s}^{-1}$ over the northeastern perimeter of Ring A2 and a peak of $45,67 \text{ cm.s}^{-1}$ over the southwestern perimeter. The deep-reaching anti-cyclonic flow associated with A2 extends to the reference depth of 1500 db, with no indication of a subsurface reversal in the flow. Station pair CTD_014 & CTD_015 exhibit a peak surface velocity of $9,37 \text{ cm.s}^{-1}$ to the northwest, associated with the flow of Subantarctic water (C4 minor) entrained around the northeastern perimeter of Eddy A3.

Eddy A3

SCARC Sections 4 - 6 (see **Addendum 2**)

The anti-cyclonic nature of Eddy A3 between CTD_015 and CTD_018 is evident, with peak geostrophic surface velocities of $32,92 \text{ cm.s}^{-1}$ and $22,58 \text{ cm.s}^{-1}$ between station pairs CTD_015 & CTD_016 and CTD_016 & CTD_017 respectively. Positive geostrophic velocities (northwestward) are evident between stations CTD_018 and CTD_020, hinting at the possibility of another anti-cyclonic eddy to the southwest. Unfortunately, evidence of such a feature in the T.I.R imagery could not be identified, owing to extensive cloud cover over the region. No such feature was observed in the *Geosat* analysis presented by van Ballegooyen *et al.* (1994).

Eddy A4

SCARC Sections 7 - 9 (see **Addendum 2**)

Section 9 provides the only satisfactory CTD line traversing Eddy A4, clearly revealing its anti-cyclonic rotation. The first sector of the line (CTD_027 - CTD_030) displays north to northwest surface geostrophic velocities, increasing dramatically on entering the perimeter of the eddy (CTD_028 & CTD_029; $50,33 \text{ cm.s}^{-1}$), diminishing somewhat on nearing the centre of the eddy (CTD_029 & CTD_030; $43,25 \text{ cm.s}^{-1}$). The second sector of this line, moving southwestward from the center of A4, illustrates the expected. Geostrophic surface velocities increase from $27,15 \text{ cm.s}^{-1}$ to $34,29 \text{ cm.s}^{-1}$ on nearing the southwestern perimeter of A4. A weak reversal in the surface flow ($2,21 \text{ cm.s}^{-1}$) is evident at station pair CTD_032 & CTD_033 along the southwestern edge of A4. Peak geostrophic velocities associated with Eddy A4 are located along the perimeter of the eddy, ranging from $34,29 - 50,33 \text{ cm.s}^{-1}$ (similar to those estimated for Gordon *et al.*'s (1987) "Retroflection Eddy").

Eddy A5

SCARC Section 10 (see **Addendum 2**)

Section 10 traverses Eddy A5, the Subantarctic filament (C1) and the shear-edge plume extending from the southwestern terminus of the Agulhas Retroflection. The CTD station spacing is particularly poor over Eddy A5 and Subantarctic filament (C1). Nevertheless, peak surface geostrophic velocities for Eddy A5 range between $18,82 - 35,84 \text{ cm.s}^{-1}$. The former estimate may be an underestimate since the station spacing is poor and the latter may be an overestimate since there may be an additional contribution to the flow from the northward extension of filament (C1). Station pair CTD_040 & CTD_041 locate the southward surface flow (velocity core of $33,87 \text{ cm.s}^{-1}$ at 60 db) of the shear-edge plume from the southwestern terminus of the Agulhas Retroflection.

Eddy A6

SCARC Sections 11 - 15 (see **Addendum 2**)

Sections 11 - 14 are comprised of poor CTD station spacing and thus reveal little in the geostrophic velocity structure of the region. Section 15 provides the most

comprehensive hydrographic line over Eddy A6, albeit only across the eastern lobe. The anticyclonic nature of A6 is evident, displaying maximum geostrophic velocities between 19,81 - 31,82 cm.s⁻¹.

In summary, the maximum surface geostrophic velocities (relative to 1500 db) of the six Agulhas vortices reach up to 45% of the Agulhas Current inflow. A comparison of the geostrophically derived surface velocities from the *SCARC* data with those derived from the *Discovery 165A* (EM Log) data suggest that a further 56% (and 40%) of the surface flow for the Agulhas input (and vortices) can be attributed to a barotropic component. This result identifies an inherent underestimate of the surface velocity derived from geostrophic computations alone.

Peak geostrophic surface velocities are located at the perimeter of the six Agulhas vortices and compare well with those estimated for other Agulhas vortices (compare the peak surface geostrophic velocities for the six vortices listed in Table 5 with those for other vortices summarized in Table 2). The vertical structure of the geostrophically derived velocities of the mesoscale features of the Retroflexion region indicate that few of these features exhibit any subsurface reversal in flow. A possible exception is the near-shore region of the Agulhas Current input, where there is evidence of a weak reversal of flow over the shelf at depths exceeding 600 db, attributed to possible boundary frictional shear over the shelf. The peak rim velocities of these vortices drop to less than 15% of their mean peak surface velocities at depths exceeding 970 db, some 130 shallower than that estimated by McCartney and Woodgate-Jones (1991) for their Agulhas eddy in the South Atlantic. This result has important implications for the possible depth to which these vortices may trap water, and is the topic of the following section.

5.3.3) Geostrophic Volume Flux

Geostrophic Volume Flux Pattern

The total volume flux estimates for the *SCARC* data relative to the 1500 db level are calculated from 28 CTD station pairs to generate a general flux pattern over the Agulhas Retroflexion during February - March 1987. A schematic representation of this pattern (Figure 5.35) provides total flux values, aided by the dynamic topography (Figure 5.31) and complimented with *Discovery 165A SeaSoar* data where possible. The solid proportional arrows illustrate the calculated total volume fluxes between

SCARC station pairs. The open arrows infer the flow field associated with the various mesoscale features of the Retroflexion region. All the total volume (and heat) flux values are likely to be an overestimate of the total fluxes associated with the particular features since these values are integrated over the entire sample depth of 1500 db.

Illustrations of the total volume (and heat) fluxes over the individual hydrographic sections are given in **Addendum 2**.

The Geostrophic Volume Flux of the Agulhas Current (see **Addendum 2**, Section 16)

The volume flux of the Agulhas input yields a total flux (relative to 1500 db) of 47,06 Sv (CTD_054 & CTD_056) and 4,46 Sv across the neighboring station pair (CTD_056 & CTD_055), clearly revealing the near-shore boundary of the Agulhas Current in the vicinity of station CTD_056. Combining the two station pairs amounts to a total volume flux of 51,52 Sv for the Agulhas Current input to the Retroflexion. This is substantially lower than the average of 70,00 Sv estimated by Gründlingh (1980) and Gordon *et al.* (1987) for the same latitude. The relatively low volume flux and low peak surface velocities ($113,59 \text{ cm.s}^{-1}$) across the Agulhas input region may be attributed to the poor station spacing across the input region. From the thermal structure of the input region, the Agulhas Current extends some 36 km wider to station XBT_115. Assuming a further 20% contribution to the volume flux of the Agulhas Current input between stations CTD_054 - XBT_115, an estimated total volume flux of 61,82 Sv is attained.

The Agulhas Return Current is even more poorly sampled by the SCARC CTD stations. As was mention earlier, the edges of the Return Current are defined by stations CTD_053 - XBT_113. Unfortunately, the only CTD station pair covering the Return Current is CTD_053 & CTD_054, some 246 km apart. This station pair not only covers the Return Current but also extends some way into the westward flowing Agulhas Current. The resultant total volume flux between stations CTD_053 & CTD_054 is 45,68 Sv eastward. Once again, this seriously underestimates the total volume flux of the Return Current since it includes a significant contribution of westward Agulhas Current flow. Correcting for a 10,30 Sv westward volume transport contribution from the Agulhas Current (which is included in the CTD_053 & CTD_054 station pair), a resultant estimate of the volume flux of the Return Current increases to a maximum of about 55,98 Sv. This rough estimate of the total volume flux contribution to the Return Current produces a miss-match of 5,84 Sv between inflow

and outflow. The imbalance (9,3% of the Agulhas Current input) could be attributed to a number of things. Firstly, this 9,3% imbalance is well within the error of the rather subjective estimation of the boundaries defining the southwestward flowing Agulhas Current input and northeastward flowing Return Current. Secondly, further errors may be introduced in the actual geostrophic calculations, since the velocity profile of the Agulhas Current may differ markedly from that of the Return Current, producing total volume transports that are incomparable. Indeed Holford (1990), in calculating the volume transports across various sections of the Agulhas Current using the *Discovery 165A SeaSoar* data, also highlights the fact that the Agulhas Current should not be treated as a steady stream with constant volume fluxes. However, realizing the many errors inherent in trying to calculate and compare volume fluxes of the Agulhas system, perhaps the possibility of a 5,84 Sv loss from the system should be entertained. This water could be lost in a number of ways. Growth of the Retroflection, shedding of rings and eddies, development of shear-edge features and loss of water to the Atlantic in the form of Agulhas filaments could all easily "consume" the 5,84 Sv. Work by Gordon *et al.* (1987) revealed a miss-match of 16 Sv between inflow and outflow of the Agulhas System in November - December 1983, and attribute this miss-match to either a westward growth of the Retroflection or a loss of water to the Atlantic.

If an Agulhas Current input to the Retroflection region of 61,82 Sv is considered to complete the entire circuit, with a small input - output imbalance, what is the most plausible mechanism accounting for this miss-match? The small loss of 5,84 Sv may be accounted for by the southerly leakage from the southern edge of the Agulhas Retroflection. This water may be introduced into Eddy A6, refueling the anti-cyclonic feature with Agulhas water. Such a phenomenon is not unique and has been observed to have occurred in the same region during the *SAAMES-I* cruise (Rigg *et al.*, 1992) in April - May 1991.

The total volume flux along the hydrographic line south of the Return Current is negligible, amounting to a general eastward flux of 3,39 Sv between stations CTD_050 - CTD_052 over a distance of 241 km. The CTD station spacing is too coarse and does not represent the volume fluxes that must be related to the small-scale cyclonic feature evident (C2) in the CTD & XBT vertical sections, centered on station CTD_051. Interestingly, the subsurface reversal of flow between stations CTD_052 - CTD_053 reveals a total volume flux of 2,00 Sv in an easterly direction with a negligible opposing surface volume flux (< 80 db) of 0,08 Sv.

In summary, the total volume flux values above are treated in such a way as to provide a general impression of the flow field of the Retroflection region. An attempt is made to balance the volume fluxes and treat the area as a closed "input - output" system, and to entertain possible scenarios explaining the miss-match. However, treatment of the Retroflection region as a so-called "black-box" is fraught with problems, owing to the varied spatial resolution of the hydrographic CTD stations and the extremely diverse eddy field encountered during the sampling period.

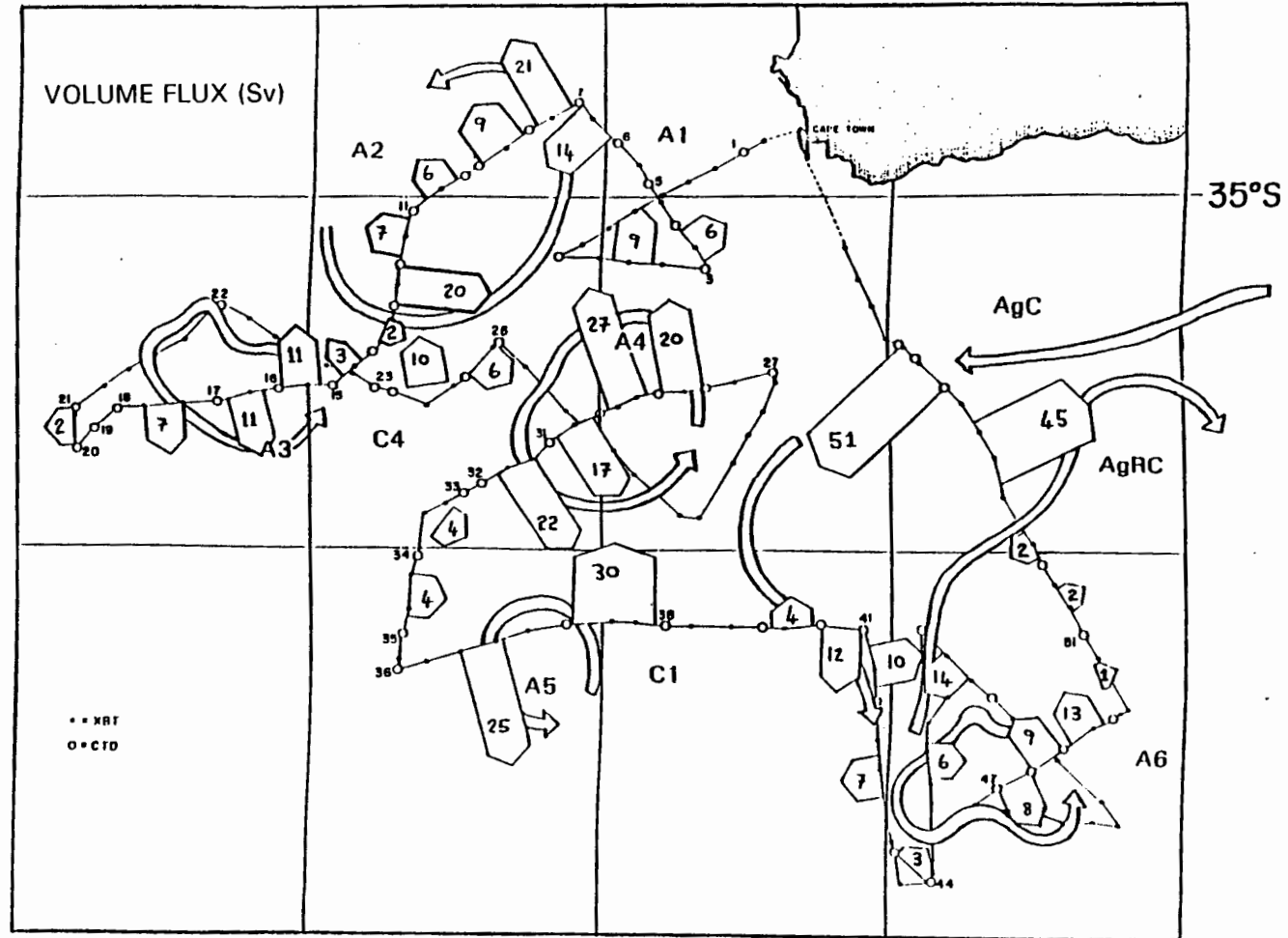


Figure 5.35: The geostrophic volume pattern of the SCARC referenced to 1500 db with an overlay of the SCARC cruise track.

The Geostrophic Volume Flux of the Agulhas Rings and Eddies (see **Addendum 2**, Sections 1 - 15)

Before discussing the results of this analysis a distinction between a volume *flux* and a volume *transport* is made. For the purposes of this thesis a *flux* refers to the normal volume flow of water between two fixed (eulerian) points, whilst that of volume *transport* refers to the volume of water trapped within a feature, and moving at the translational velocity of the feature.

The basic geostrophic volume *flux* associated with Rings A1 and A2 are about 21,4% (11,04 Sv) and 63,8% (32,89 Sv) of the total Agulhas Current volume input respectively. Ring A1 compares fairly well with the net volume flux of 14 Sv for the "Cape Town Eddy" (Gordon, 1985). However, Ring A2 exhibits an anomalously high geostrophic volume flux due to its horizontal diameter extending a tremendous 547 km (CTD_007 - CTD_014). The volume flux associated with Eddy A3 is about 17,57 Sv (34,1% of the total Agulhas Current volume input), comparable to the 19,1 Sv for the McCartney and Woodgate-Jones' (1991) eddy in the South Atlantic. Note that the total volume fluxes derived from station pairs (CTD_018 - CTD_020) and (CTD_020 & CTD_021) seem to indicate that perhaps yet another anti-cyclonic feature is present to the southwest of station CTD_020. The volume flux associated with Eddy A4 is about 43,81 Sv (85,0% of the total Agulhas Current volume flux input), a function of its high rotational velocity rather than its volume. This compares well with the 40 Sv of the "Retroflexion Eddy" (Gordon *et al.*, 1987). The basic volume flux associated with Eddy A5 is difficult to determine because of the exceedingly poor spatial resolution of the CTD stations. However, station pair (CTD_036 & CTD_037) is chosen to represent the total volume flux of Eddy A5 since station pair (CTD_037 & CTD_038) includes the northward flux constituting the wedge of Subantarctic water (C1) along the eastern edge of Eddy A5. The total volume flux associated with Eddy A5 is about 25,71 Sv (49% of the total Agulhas Current volume input). Eddy A6 poses much the same problem in determining the basic volume flux because of the poor spatial resolution of the hydrographic stations. Furthermore, both the *SCARC* and *Discovery 165A* data indicate a "southward spill" of Agulhas water from the southern edge of the Retroflexion (41,5°S; 20°E) into the vicinity of Eddy A6. Whether Eddy A6 is connected to the Agulhas Return Current during the period of hydrographic sampling is difficult to determine. Nevertheless, there is evidence of southerly spill of Agulhas water in the vicinity of Eddy A6. Eddy A6 seems to have a double lobe-like structure,

flattened meridionally. Station pairs CTD_047 & CTD_048 and CTD_048 & CTD_049 are chosen to represent the total volume flux of Eddy A6, revealing a volume flux of 8,89 Sv (17% of the total Agulhas Current volume transport input).

Volume Transport of the Agulhas Rings and Eddies

As was noted above, the volume *transport* of a ring or eddy is considered to be the transport of water trapped within the vortex of the feature. For the purposes of this thesis no specific dynamical model is used. A comparison of ring and eddy volumes is determined using three methods, namely:

- i) The general kinematic concept of "volume trapping" by Flierl (1981)
- ii) The volume of water warmer than 10°C (and 6°C)
- iii) The volume of water where the Salt Anomaly (SA) $\geq 0,0$ relative to the Agulhas Current input

The results of these three methods are presented below.

i) Eddy Volume (and transport) - Flierl's (1981) Parameter (ϵ)

This parameter is simply the ratio of the maximum azimuthal speed at the depth in question to that of the translation speed of the vortex - Flierl's (ϵ) parameter. Trapping only occurs where $\epsilon > 1,0$ (ie. water is lost from the vortex when the translational speed exceeds the azimuthal speed for that depth). Details concerning the geometry of the trapped region and the extent of the induced disturbance is not discussed here; for this the reader is referred to the paper by Flierl (1981). To obtain the volume transport associated with the vortices, the altimetrically derived translational velocities of the Agulhas vortices are used (Table 5), moving the feature a distance of 1x its diameter. The trapped region is assumed to be parabolic in shape and symmetrical. Estimates from this analysis are summarized in Table 6.

Table 6: *In situ* volume and volume transport associated with the rings and eddies of the SCARC using the Flierl (1981) Parameter (ϵ)

Feature	Depth (db) of ($\epsilon=1$)	Flierl's Trapped Volume ($\times 10^{13} \text{ m}^3$)	Volume Transport (Sv) *
Ring A1	970	-	-
Ring A2	1000	-	-
Eddy A3	910	3,942	4,747
Eddy A4	1080	7,287	15,822
Eddy A5	1210	3,022	4,434
Eddy A6	1010	3,057	5,946
* Calculated assuming the altimetrically derived translational velocity (Table 3)			

These volumes and volume *transports* are considered to be the *in situ* values determined at the point where they were hydrographically sampled. Estimates for Rings A1 and A2 are not determined since the morphology of their "trapped region" is complicated and poorly described by the parabolic function. Notice that the volume *transport* (and volume) associated with the various vortices are far lower than those determined from the geostrophically derived volume *fluxes* relative to 1500 db, yet are comparable to the similarly derived $3,6 \times 10^{13} \text{ m}^3$ for the slow moving eddy (McCartney and Woodgate-Jones, 1991) in the South Atlantic. Should a ring or eddy shed from the Retroflection trap Indian Ocean Water over the entire sample depth (1500 db), much of the Indian Ocean Water will be left behind at the point of origin as the vortex begins to move relative to its surroundings, since the translation speeds for recently shed rings and eddies are faster (ie. which means smaller values for ϵ ; therefore less trapping).

In order to compare these volume transport results with those documented in the literature, Eddy A4 has been assumed to best represent a "typical" eddy that is shed from the Retroflection, entering the South Atlantic. Two scenarios are presented. Assuming five such eddies enter the Atlantic from the Retroflection per annum (a low value supported by estimates from Gordon and Haxby, 1990), an estimated 11,55 Sv will enter the South Atlantic per annum. This forecast agrees well with those determined from the *FRAM* model (10 Sv; *FRAM* Group, 1991) and those by Gordon *et al.* (1992) for Agulhas eddies and plumes (3 - 20 Sv). McCartney and Woodgate-Jones

(1991) estimate a reduced volume flux of about 2,0 - 5,5 Sv per annum, correcting for the "Flierl trapping". However, this may be an underestimate since their eddy was well within the South Atlantic when it was hydrographically sampled and may have "lost" much of its trapping ability as its azimuthal velocity decays. The lower estimate (2,0 Sv) is definitely an underestimate since it is an artefact of an unreasonably high translational velocity (10 cm.s^{-1}), so far from the Retroflection. A second scenario assumes eight such eddies enter the Atlantic per annum (eg. Feron *et al.*, 1992), which equates to a fantastic 18,48 Sv entering the South Atlantic in the form of Agulhas eddies per annum. If 8 such eddies are assumed to enter the South Atlantic per annum, the near-surface volume transport estimate of 15 Sv (Hastenrath, 1982; Gordon and Piola, 1983) to balance the global heat and salt budgets for the World is easily satisfied.

In summary, application of the "Flierl trapping" method provides a useful technique for determining the theoretical depth to which a particular vortex can trap water. Although this method relies heavily on the assumptions used in the calculation of the geostrophic (and translational) velocities, it nevertheless does suggest the varied ability of rings and eddies in trapping water within their vortices, depending on their unique dynamics. Interestingly, this method overestimates the trapped volume of water of a ring or eddy if Subantarctic Water is drawn along the eastern perimeter of the feature, strongly skewing the shape of the trapped region. This is clearly observed in Eddies A4 and A5 (see Figure 5.36).

Volume-trapping results presented above all seem to indicate that the *SCARC* rings and eddies may trap water from the surface to depths well within the Intermediate Water range (1200 db). Further evidence presented in the **Water Mass Analyses** supports this result.

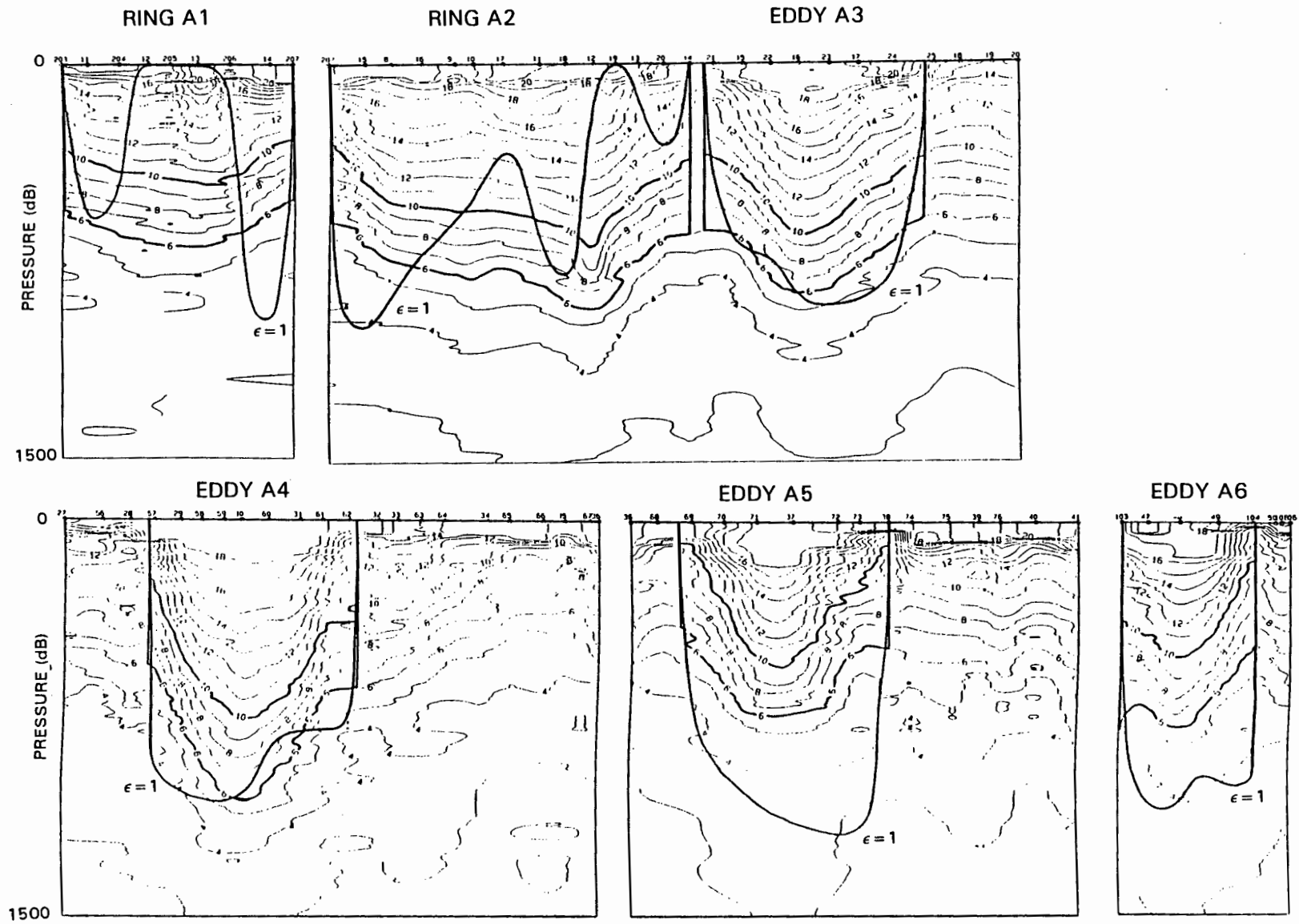


Figure 5.36: Vertical sections of the volumes associated with the six SCARC Agulhas rings and eddies. Volumes encompassed by the Flierl (1981) $\epsilon \geq 1$ parameter, temperatures $\geq 10^\circ\text{C}$ and $\geq 6^\circ\text{C}$ are depicted.

ii) Eddy Volume (and transport) - Water warmer than 10°C (and 6°C)

The volume of water located within a ring and eddy with a temperature exceeding 10°C is calculated (assuming a symmetrical parabolic structure). Estimates from this analysis are summarized in Table 7 below.

Table 7: *In situ* volume and volume transport of water warmer than 10°C and 6°C associated with the rings and eddies of the SCARC

Feature	>10°C Water (x 10 ¹³ m ³)	>6°C Water (x 10 ¹³ m ³)	Vol. T _{Sv} * (10°C)	Vol. T _{Sv} * (6°C)
A1	-	-	-	-
A2	-	-	-	-
A3	2,759	3,725	3,323	4,486
A4	5,195	7,051	11,280	15,309
A5	1,373	2,425	2,015	3,558
A6	1,574	2,343	3,061	4,557
* Calculated assuming the altimetrically derived translational velocity (Table 3)				

The above results suggest that Eddy A4 contains the greatest volume of water of all the rings and eddies sampled during the SCARC (again, the volume of Rings A1 and A2 are not estimated due to irregularities in the topography of the isotherms). Notice how the depth of the 10°C isotherm seems to underestimate the depth to which water is trapped within a ring or eddy (as compared to the "Flierl trapping" parameter - Table 6). Trapping of water within a ring or eddy is a dynamic phenomenon, and one which seems to be poorly represented by the volume of water warmer than 10°C. On closer inspection of Figure 5.36, the 6°C isotherm seems to better represent the trapped region (if the Flierl (1981) method is assumed correct). However, even the 6°C isotherm underestimates the extent of trapping, particularly in the smaller eddies in the vicinity of the Subtropical Convergence, where "Flierl trapping" extends to waters colder than 4°C.

iii) Eddy Volume (and transport) - Salinity Anomaly (SA) $\geq 0,0$

A third method is implemented whereby the volume of water comprising the vortex is considered to be the volume of "pure" Agulhas Water (ie. where the Salt Anomaly (SA) $\geq 0,0$ - using Agulhas input station CTD_054 as the reference station). This method proves to be too sensitive, producing vertically disjunct stads of Agulhas Water separated by weakly negative salt anomalies (SA's), often centered on potential density surfaces ranging from 26,0 - 26,1 kg.m^{-3} (Thermocline Waters) (Figure 5.37). These fresh layers between the saline stads are not the consequence of anomalously saline water in the Agulhas reference station. This result suggests that either lateral mixing between the saline core waters of Agulhas vortices with their fresher surroundings occurs preferentially at thermocline depths, or it is simply an artefact of the narrow Θ/S characteristics of the Thermocline Waters of the Retroflection region. The latter explanation is most likely. Since this result may be greatly influenced by the accuracy to which the salt can be measured, the SA $\geq 0,05$ is also plotted on Figure 5.37, revealing a more conservative and hence underestimate of the volume of Agulhas Water contained within the rings and eddies. Essentially this provides an estimate of the volume of Agulhas Water of anomalously high salinity (relative to the reference station CTD_054), which is primarily a function of evaporation. Surprisingly, these saline stads (SA $\geq 0,05$) are not only restricted to the surface waters, but can be also located at greater depths in the rings and eddies. No actual volumes of the SA $\geq 0,0$ are calculated due to the asymmetry of the anomalously saline stads. Nevertheless, Figure 5.37 yields some interesting results. Ring A1 reveals a rather small stad of (SA) $\geq 0,0$ at a depth of about 400 db (CTD_004). The larger double stad of (SA) $\geq 0,0$ located at CTD_007 results from Ring A2 (or possibly some other ring further to the northwest). Ring A2 exhibits a rather interesting morphology of (SA) $\geq 0,0$, severely skewed to the southwest (CTD_010 to CTD_013). This result is consistent with the skewed thermal (and salinity) section. Eddies A3 and A4 display similar (SA $\geq 0,0$) vertical structure, with distinct interleaving of fresh SA's within the thermocline waters. The hydrographic section of Eddy A5 reveals extensive fresh-water contamination of the core of A5, suggesting that A5 has mixed extensively with the fresher Subantarctic waters within which it is embedded. Interestingly, the SA $\geq 0,0$ distribution to the west of A5 (CTD_038 to CTD_041) reveals an extensive "tongue" of saline water centered along a potential density surface of about 27,1 - 27,2 kg.m^{-3} . This subsurface intrusion of anomalously saline water is the result of a southwesterly extension of the shear-edge plume extending from the terminus of the Agulhas Retroflection. Notice that this

anomalously saline "tongue" extends as far westward as station CTD_038, plunging beneath the anomalously fresh Subantarctic filament (C1). Eddy A6 exhibits a mean SA of -0,032 from the surface to a depth of about 700 db (corresponding to a potential density surface of $27,0 \text{ kg.m}^{-3}$). At greater depths, SA's become remarkably fresher (mean SA = -0,135). Notice that A6 displays a single small stad of saline water (SA $\geq 0,0$), implying that the eddy consists of pure Agulhas water. This result reinforces the possibility that A6 was connected to the Agulhas Current at the time that it was hydrographically sampled, or had been recently "refueled" by the Agulhas Current.

In summary, a distinction between a volume *flux* and a volume *transport* is made. A *flux* refers to the normal flow of water between two fixed points. A volume flux of 61,82 Sv (and 55,98 Sv) is estimated for the Agulhas Current input and Return Current respectively, with a inflow - outflow miss-match of 5,84 Sv. It is suggested that the loss of 5,84 Sv could be easily accounted for by the southerly leakage of Agulhas Water from the terminus of the Agulhas Retroflection, thus introducing this water into Eddy A6. Volume flux estimates for the six Agulhas vortices range from 8,89 - 43,81 Sv (17% - 85% of the Agulhas input respectively). A more useful quantity to know is the actual volume *transport* associated with each mesoscale feature. This quantity is a measure of the volume of water trapped within a feature, moving at the translational velocity of the feature. With this in mind, volume *transport* estimates are made using three methods. The results of the three methods vary markedly, revealing volume transport estimates of individual vortices ranging from 2 - 15 Sv. The Flierl (1981) volume trapping method is the most favoured of the three methods, since it takes into account the unique dynamics of the individual vortices. Applying the Flierl (1981) volume trapping method to the six Agulhas vortices yields results that suggest that an interbasin volume transport requirement of 15 Sv (Hastenrath, 1982; Gordon and Piola, 1983) can be easily achieved via such vortices. In addition, trapping within individual vortices can occur from the surface to depths well within the Lower Thermocline and Intermediate Water range (910 - 1210 db). This result hints at the possibility that some Agulhas vortices may trap remnant RSW within their vortices and distribute this water well into the South Atlantic.

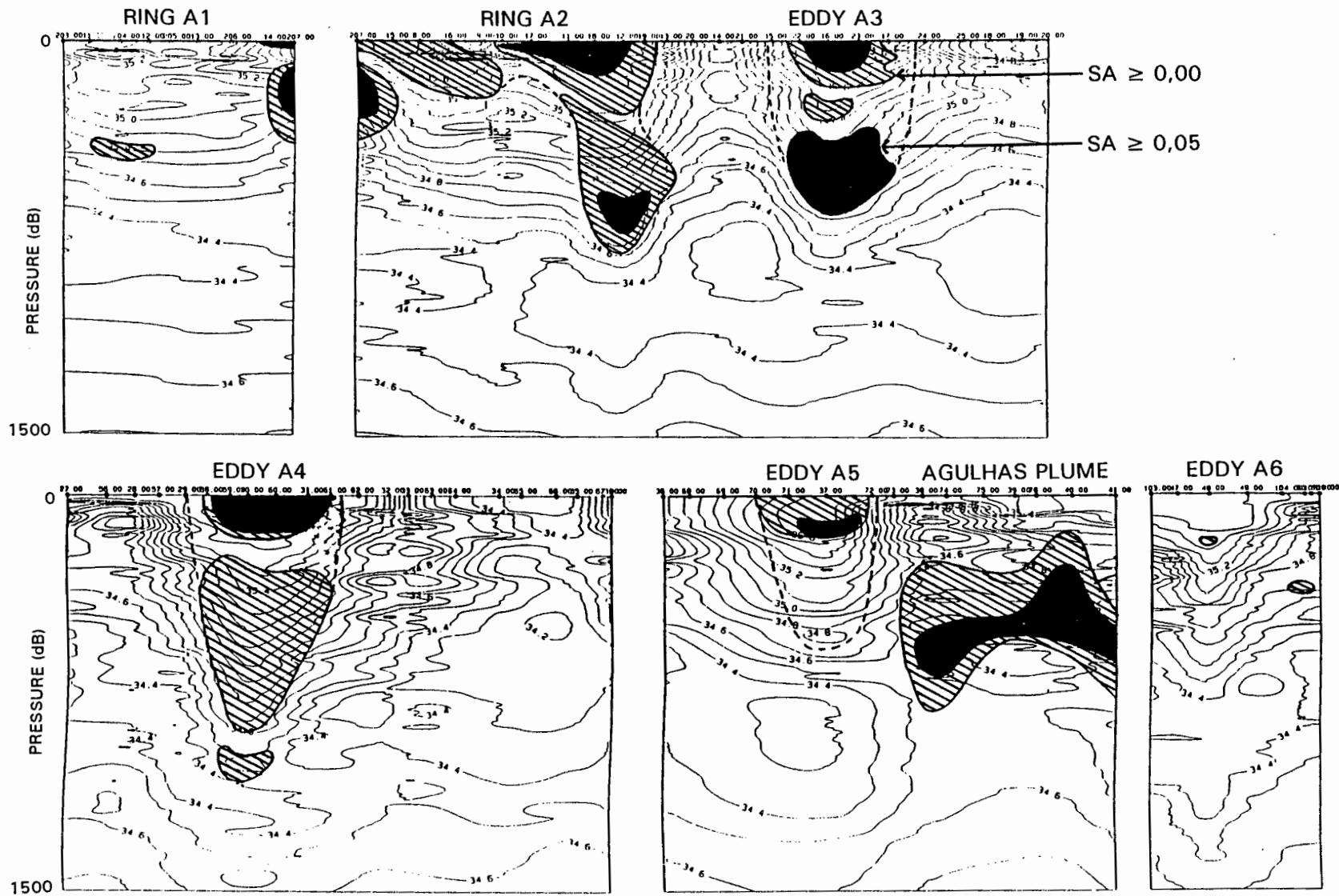


Figure 5.37: Vertical sections of the positive salt anomaly (SA) volumes associated with the six SCARC Agulhas rings and eddies are depicted, superimposed on the vertical potential density field. $SA \geq 0.00$ and $SA \geq 0.05$ are shaded.

5.3.4) Geostrophic Heat Fluxes

Geostrophic Heat Flux Pattern

The geostrophic heat fluxes for the *SCARC* referenced to 1500 db reveal similar trends to those of the volume fluxes of the Retroflexion region, the results of which are presented below (see **Addendum 2** for heat and volume flux figures).

The Geostrophic Heat Flux of the Agulhas Current (see **Addendum 2**, Section 16)

The Agulhas input yields a total heat flux of $2438,31 \times 10^{12}$ Watts (CTD_054 & CTD_056) and $294,45 \times 10^{12}$ Watts across the neighboring station pair CTD_056 & CTD_055. Combining the two station pairs amounts to a total heat flux of $2732,76 \times 10^{12}$ Watts for the Agulhas Current input to the Retroflexion. Assuming a further 20% contribution to the heat flux (outlined earlier), an estimated total heat flux of $3279,31 \times 10^{12}$ Watts is attained for the Agulhas input. The Agulhas Return Current reveals a heat flux of $2286,62 \times 10^{12}$ Watts (CTD_053 & CTD_054) eastward. Correcting for a $546,55 \times 10^{12}$ Watts westward heat flux contribution from the Agulhas Current (included in the CTD_053 and CTD_054 station pair), a resultant estimate of the total heat flux of the Return Current increases to a maximum of about $2833,17 \times 10^{12}$ Watts, producing an input - output miss-match of $446,13 \times 10^{12}$ Watts between inflow and outflow. This imbalance (13,6% of the Agulhas Current input) is greater than the estimated 9,3% for the volume flux, hinting that a substantial contribution of the heat "lost" from the system is lost not only to mixing out of the system but also to heat loss to the atmosphere.

The Geostrophic Heat Flux of the Agulhas vortices (see **Addendum 2**, Sections 1 - 15)

The basic geostrophic heat fluxes associated with Rings A1 and A2 are about 17,2% ($470,28 \times 10^{12}$ Watts) and 60,5% ($1655,35 \times 10^{12}$ Watts) of the total Agulhas Current heat input respectively. The heat flux associated with Eddy A3 is about $930,42 \times 10^{12}$ Watts (34,0% of the total Agulhas Current heat input). The heat flux associated with Eddy A4 is about $2168,00 \times 10^{12}$ Watts (79,3% of the total Agulhas Current heat input). Again, the basic heat flux associated with Eddy A5 is difficult to determine because of the poor spatial resolution of the CTD stations. However, station pair (CTD_036 - CTD_037) is chosen to represent the total heat flux of Eddy A5 since station pair (CTD_037 & CTD_038) includes the northward transport of a wedge of cold Subantarctic water (C1) along the eastern edge of Eddy A5. The total heat flux

associated with Eddy A5 is therefore estimated to be about $1044,85 \times 10^{12}$ Watts (38,2% of the total Agulhas Current heat input). Eddy A6 poses the same problem in determining the basic heat flux because of the poor spatial resolution of the hydrographic stations. Eddy A6, with its meridionally aligned double-lobe structure, reveals a heat flux of $409,86 \times 10^{12}$ Watts (14,9% of the total Agulhas Current heat input, using station pairs CTD_047 & CTD_048 and CTD_048 & CTD_049).

Heat (and Salt) Transport of Agulhas rings and eddies - Flierl's Parameter (ϵ)

Consider the Flierl (1981) volumes listed in Table 6 to approximate the volume of water transported within the individual vortices. The heat (and salt) content of each vortex can therefore be calculated. However, oceanographers are interested in the anomalous heat (and salt) transported via Agulhas rings and eddies, rather than the bulk quantities contained within their vortices. Since one of the main objectives of this thesis is concerned with the modification of the Agulhas waters through the Retroflection, all heat (and salt) anomalies are referenced relative to the Agulhas input (CTD_054). Consequently, heat (and salt) anomalies calculated within the vortices of the SCARC yield low values, the results of which are insignificant. For example, the heat (and salt) anomalies calculated for Eddy A4 yield surprisingly low values of $4,818 \times 10^8$ J and $2,887 \times 10^{-15}$ kg respectively (referenced to the Agulhas input), highlighting that although atmospheric modification of the surface waters of an Agulhas eddy is important, the anomalous quantities (referenced to the Agulhas input) become insignificant when integrated over the entire column of water trapped within the vortex.

Heat (and salt) anomalies for Agulhas rings and eddies should rather be referenced according to the water which would replace the volume of the vortex should it be removed. Two possibilities exist. Either the heat (and salt) anomalies of water of the eddy should be referenced to the immediate background water of the southeast Atlantic (as was done by van Ballegooyen *et al.*, 1994) or, the anomalies should be referenced to North Atlantic Deep Water (assuming the Gordon (1986) concept of a global "Thermohaline Conveyor Belt" is true, the anomalous salt (and heat) within the thermocline waters of Agulhas rings and eddies are in a sense, compensatory flow to the production of NADW in the northern North Atlantic). Naturally, heat (and salt) anomalies referenced to NADW will be huge. The more realistic situation would be a combination of the two, a ratio that is not fully understood (yet).

Consider the first possibility. In order to calculate the heat (and salt) anomalies referenced to the southeast Atlantic, a representative hydrographic station is required. To isolate such a station is extremely difficult owing to the unique "cocktail" of mixing that occurs in the Retroflection region. According to the Flierl (1981) Parameter (ϵ), much of the Agulhas water initially trapped with an Agulhas eddy would be expected to be left behind in the Retroflection region immediately after the vortex is shed and moves off from the Retroflection. Consequently, one would expect much contamination of the Retroflection region with Agulhas water. This is indeed the case, as it is difficult to determine a satisfactory reference station outside the influence of the Agulhas. However, van Ballegooyen *et al.* (1994) calculate heat and salt anomalies for Eddies A3, A4, A5 and A6, referenced to southeast Atlantic Thermocline Water (stations CTD_014, CTD_026 and CTD_027). Anomalies for A1 and A2 are not calculated, owing to the same morphological complications mentioned earlier. The results of their analysis are listed in Table 8 below.

Table 8: Volume, heat and salt anomalies in the Agulhas rings and eddies sampled during the SCARC (from van Ballegooyen *et al.*, 1994).

Eddy identification	A3	A4 ^a	A5	A6
Radius of eddy	160	140	95	125
Volume > 10°C, 10 ¹² m ³	33.8	33.0	11.2	16.5
Volume > 8°C, 10 ¹² m ³	43.1	39.4	15.3	24.5
Heat anomaly in eddy ^b , 10 ²⁰ J	1.50	2.36	0.73	1.06
Salt anomaly in eddy ^b , 10 ¹² kg	8.74	13.10	4.35	4.59
Volume flux of > 10°C water per eddy, Sv	1.07	1.05	0.36	0.52
Volume flux of > 8°C water per eddy, Sv	1.37	1.25	0.49	0.78
Heat flux per eddy ^b , 10 ⁻³ PW	4.8	7.5	2.3	3.4

^aHydrographic coverage is sufficient to ensure robust estimates.

^bCalculated relative to southeast Atlantic thermocline water (stations 14, 26, and 27)

Assuming the above results and an "injection rate" of six Agulhas eddies per annum into the southeast Atlantic via the Agulhas Retroflection region, van Ballegooyen *et al.* (1994) estimate a heat and salt flux into the South Atlantic of approximately 0,045 PW and 78×10^{12} kg per annum, respectively. This estimate compares rather well to those eddy heat fluxes predicted by the FRAM output (an order of magnitude smaller than the mean heat flux of 0.51 PW (Thompson, *personal communication*; see Stevens and Thompson, 1994; Thompson *et al.*, 1995)).

In summary, the geostrophic heat flux estimates yield similar trends to those of the volume fluxes presented earlier. A geostrophic heat flux of the Agulhas input (referenced to 1500 db) of about 3279×10^{12} Watts is estimated, with an input - output deficit of about $446,13 \times 10^{12}$ Watts (13,6% of the Agulhas Current input). This imbalance is 4,3% greater than that revealed by the volume flux estimates, and hints at a substantial heat loss from the system not only through mixing but also through heat loss to the atmosphere. The heat flux associated with the six vortices of the SCARC varies dramatically, ranging from about 15% - 79% of that of the Agulhas input.

5.4) Conclusions on the general hydrography and dynamics of the Agulhas Retroflection region

The first aim of this thesis is to describe the general hydrography of a number of Agulhas vortices present in the Retroflection region at one time, thus providing the detail necessary to define the range of attributes that can be expected of such features. Sections 5.1 to 5.3 set about to fulfill this aim. Section 5.1 describes the general hydrography of the Agulhas Retroflection region as observed by satellite. Satellite altimetry (and to a lesser extent thermal infrared imagery) identify all the mesoscale hydrographic features within the Retroflection region. In particular, the altimetric data provides valuable insight to the formation, lifetime and decay of the six Agulhas vortices identified in the SCARC hydrographic data. Section 5.2 is concerned with the general hydrography and dynamics as revealed by the SCARC (and *Discovery 165A*) data. The morphology of each feature is found to be different, ranging from near-symmetrical to highly asymmetrical. The diameters of the six vortices vary from 143 km to 525 km, whilst the depth of the 10°C isotherm varies from 454 db to 770 db. Although each vortex is shown to exhibit unique thermohaline characteristics, they also display similar characteristics. Most noticeable in this regard is the salinity boosting

(>35,60) evident within their surface mixed layers, extending to depths in excess of 100 db in most cases.

The vertical extent of the vortices become apparent when the thermohaline pattern is traced along specific density surfaces. Contamination of Antarctic Intermediate Water (AAIW) by Red Sea Water (RSW) is observed. RSW is identified to enter the Retroflexion region via the Agulhas Current input, distributed west and south of the Retroflexion through associated Agulhas vortices. Such a process is observed to produce a unique blend of AAIW / RSW within the Retroflexion region.

Section 5.3 examines the dynamic structure of the Agulhas Retroflexion region. A two-layer model is successfully used to describe the geostrophic circulation within the Retroflexion region. Peak geostrophic velocities are identified along the perimeter of all six vortices. These velocities range from 13% - 45% of the Agulhas Current input. Having determined the geostrophic velocity profile of each vortex and knowing their individual translational velocity (as revealed by satellite altimetric tracking), an estimate of the volume trapped within each vortex is determined using Flierl's (1981) parameter. The Agulhas vortices are found to be capable of trapping water within the Intermediate Water range (910 - 1210 db). A volume transport contribution of between 11,55 - 18,48 Sv is estimated, should 5 to 8 Agulhas vortices enter the South Atlantic per annum. A summary of the characteristics of the major mesoscale features identified in this chapter are listed in Table 9 below.

Table 9: A summary of some hydrographic parameters measured for the rings and eddies of the SCARC. The maximum diameter ($\text{Diameter}_{(\text{MAX})}$) of the vortices are defined by the 300 db / 10°C intersection. The maximum depth of the 10°C isotherm ($\text{Depth}_{(10^{\circ}\text{C})}$) is given in decibars (db) for the core of each feature, with δDepth the difference between the depth of the 10°C isotherm at the centre and at the edge of the ring. $\text{Velocity}_{(\text{T})}$ and $\text{Velocity}_{(\text{R})}$ refer to the translational and maximum azimuthal velocities respectively. The surface pycnocline depth is defined by exceeding the Priddle *et al.* (1986) criterion for at least 20 db. Volume flux estimates are relative to 1500 db and volume trapped estimates are calculated using Flierl's (1981) parameter. Volume transport estimates are based on the Flierl (1981) volume estimates and the translational velocity derived from *Geosat* altimetric tracking results. Similarly, volume trapped and volume transport estimates are listed for waters $> 10^{\circ}\text{C}$ within the core of each vortex.

FEATURE INPUT	A1	A2	A3	A4	A5	A6	AgC
DIAMETER_(MAX) (km)	317	525	311	276	145	143	100
DEPTH_(10°C) (db)	454	684	637	770	540	610	> 760
δDEPTH (db)	134	364	327	490	450	410	> 510
VELOCITY_(T) (cm.s^{-1})	4,7	6,0	4,0	9,0	3,7	5,4	6,4
VELOCITY_(R) (cm.s^{-1})	22,7	45,6	32,9	50,3	35,8	31,8	113,5
SURFACE PYCNOCLINE DEPTH (db)	30	50	100	125	150	125	29
VOLUME FLUX ($\times 10^6 \text{m}^3.\text{s}^{-1}$)	11,0	32,8	17,5	43,8	25,71	8,89	61,8
VOLUME TRAPPED_(FLIERL) ($\times 10^{13} \text{m}^3$)	-	-	3,94	7,28	3,02	3,05	-
VOLUME TRANSPORT_(FLIERL) ($\times 10^6 \text{m}^3.\text{s}^{-1}$)	-	-	4,74	15,82	4,43	5,94	-
VOLUME TRAPPED_(>10°C) ($\times 10^{13} \text{m}^3$)	-	-	2,75	5,19	1,37	1,57	-
VOLUME TRANSPORT_(>10°C) ($\times 10^6 \text{m}^3.\text{s}^{-1}$)	-	-	3,32	11,28	2,01	3,06	-

CHAPTER 6

RESULTS AND DISCUSSION ON THE WATER MASSES OF THE AGULHAS RETROFLECTION REGION

6.1) Introduction to the Water Masses of the Agulhas Retroflection Region

From the literature review and the results presented in the previous sections it is apparent that the individual mesoscale features identified in the Retroflection region each exhibit unique thermochemical characteristics. These characteristics are a product of their source and subsequent modification by the surroundings in which they are imbedded. It is the primary aim of this chapter (and the second major objective of this thesis) to identify the water masses that constitute the mesoscale features of the Agulhas Retroflection region. Particular detail is given to the property extrema that distinguish each water mass.

The water masses observed during the *SCARC* embrace a wide variety of Surface, Central and Intermediate Waters. Unfortunately the CTD stations only extend to a maximum depth of 1500 db, thus hampering identification of the deeper water masses. Multiple potential temperature - salinity - oxygen ($\theta/S/O_2$) plots of the 56 CTD stations executed during the *SCARC* reveal a remarkably diverse salinity and oxygen range for nearly every isotherm (Figures 6.1 and 6.2). The Agulhas input stations (CTD_054 & CTD_056) are located on the high salinity side of the θ/S curve at all temperatures below 18°C, where the salinity of the Retroflection water is more saline by about 0,01. The most saline waters ($\geq 35,63$) are located in the core surface waters of the Agulhas vortices (except A1) (Figures 6.3 and 6.1), indicative of a Modified type of Subtropical Surface Water (MSSW) caused by salinity boosting through evaporative processes. The Agulhas input station (CTD_056) exhibits a saline variety of Tropical Surface Water ($T \geq 23^\circ$; $S \geq 35,42$), locating the surface core of the Agulhas Current. Station CTD_054 (Agulhas Current reference station for heat and salt anomalies of this thesis) exhibits more saline surface waters ($\delta S = 0,14$) than CTD_056, located within the dynamical core of the Agulhas Current input. The near-linear part of the θ/S curve (Figure 6.1) identifies the Central Waters of the Retroflection region, with the more saline waters characteristic of an Agulhas influence. Low salinity deviations from the linearity of the SICW part of the θ/S curve

are attributed to a South Atlantic. Further reduced salinities are characteristic of a Subantarctic Water influence. Extreme Subantarctic characteristics are identified by a salinity minimum in the Surface and Thermocline waters, deviating strongly from the linearity of the Central Waters of the Retroflection region.

The Intermediate Waters of the Retroflection region range in temperature from 3° - 6° , and are located below the linear component of the SICW (6° - 14°C). The salinity range within the Intermediate Waters is large ($\delta S = 0,46$), indicating a fresh water influence from the Atlantic and a high salinity influence from the RSW remnants of the Indian Ocean. No identification of the deeper waters masses of the Agulhas Retroflection can be made from the *SCARC* data.

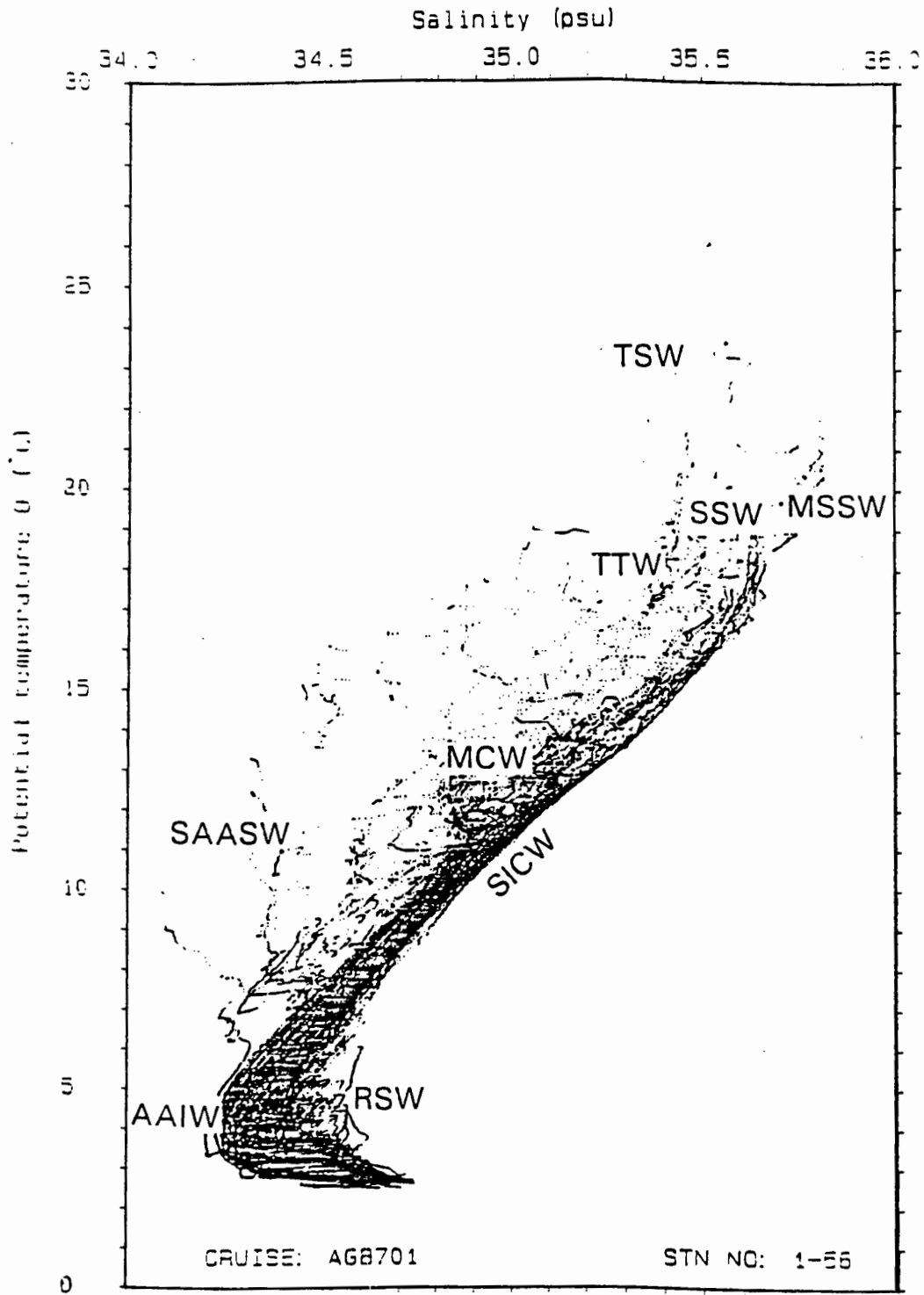


Figure 6.1: Multiple potential temperature - salinity (θ/S) plot of all 56 SCARC CTD stations. Superimposed on this plot is a idealized graphical representation of the θ/S space occupied by the water masses of the Agulhas Retroflexion region during the SCARC. The labeling of the water masses are as follows:

Tropical Surface Water (TSW), Subtropical Surface Water (SSW), Modified Subtropical Surface Water (MSSW), Tropical Thermocline Water (TTW), South Indian Central Water (SICW), Modified Central Water (MCW), Subantarctic Surface Water (SAASW), Antarctic Intermediate Water (AAIW), Red Sea Water remnants (RSW), North Atlantic Deep Water (NADW), Indian Deep Water (IDW) and Antarctic Bottom Water (AABW).

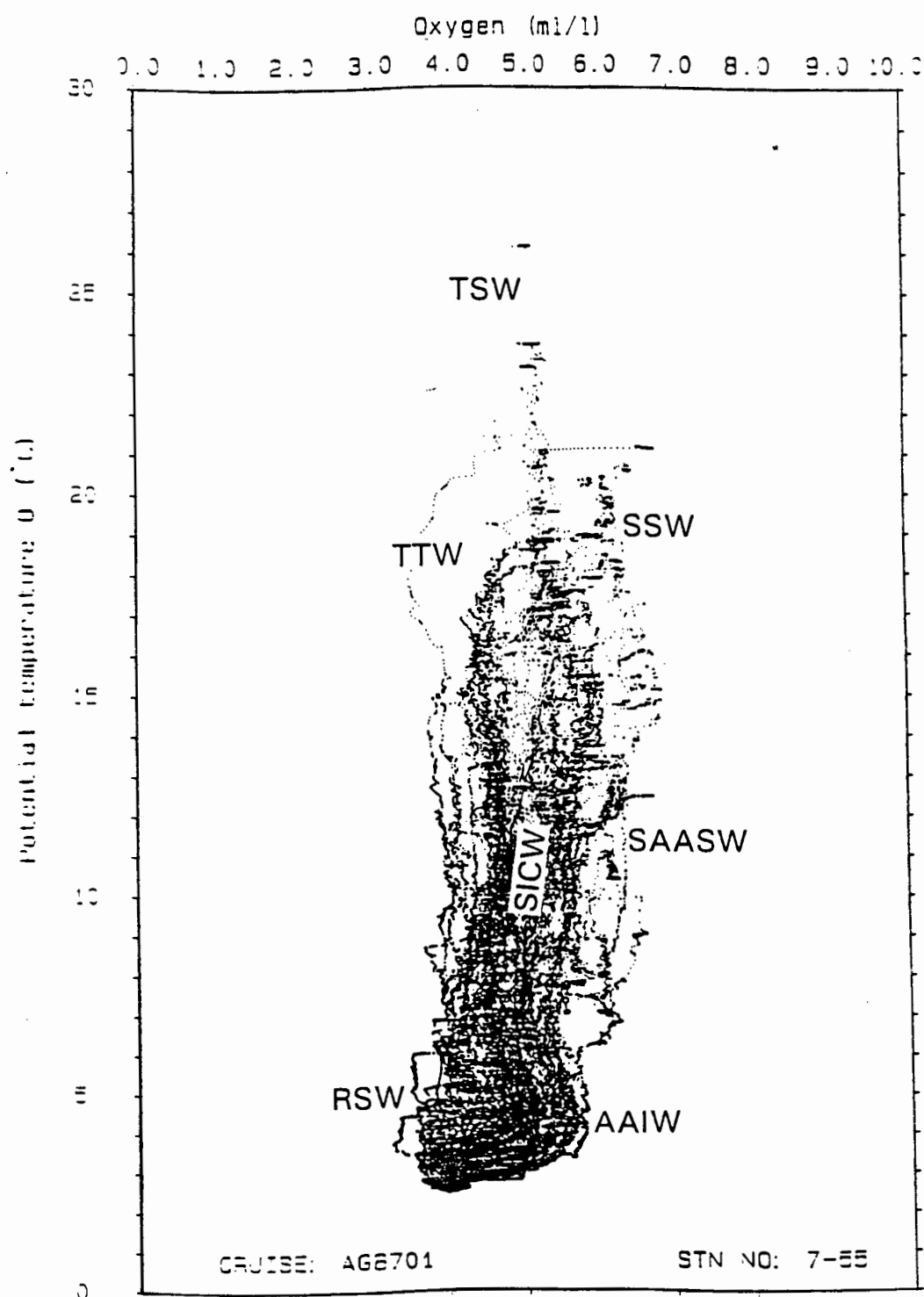


Figure 6.2: A multiple potential temperature - oxygen (Θ/O_2) plot of the 56 CTD stations of the SCARC. Superimposed on this plot is the labeling of the various water masses, namely:

Tropical Surface Water (TSW), Subtropical Surface Water (SSW), Tropical Thermocline Water (TTW), South Indian Central Water (SICW), Subantarctic Surface Water (SAASW), Red Sea Water remnants (RSW) and Antarctic Intermediate Water (AAIW).

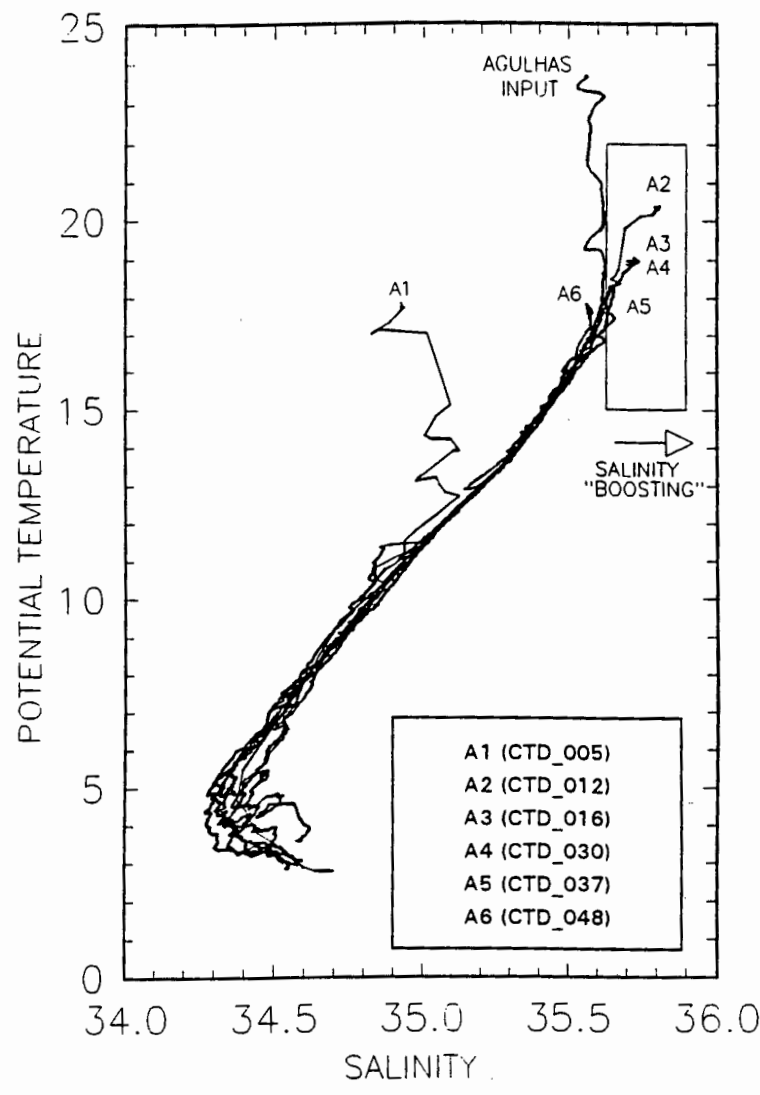


Figure 6.3: Multiple potential temperature - salinity (Θ/S) plot of the *SCARC* ring and eddy centre stations together with the Agulhas reference station CTD_054.

6.2) Intercomparisons between other data sets

a) Agulhas Current input intercomparisons

Before undertaking a detailed potential temperature - salinity - oxygen ($\Theta/S/O_2$) analysis of the *SCARC* data, this data set is compared to other data sets collected in the region. The Θ/S curves of two Agulhas input stations (CTD_054 and CTD_056) are compared to two Agulhas input stations of the *Robert Conrad 17* (February - March 1974), *Knorr (ARC)* (November - December 1983), and *Thomas Washington* (February - March 1985) cruises. Bottle data from the *Robert Conrad 17* (Jacobs and Georgi, 1977), 10 db continuous CTD data from the *Thomas Washington* (courtesy of Dr. John Toole, Woods Hole Oceanographic Institution), 1 db resolution CTD from the *Knorr (ARC)* and 50 db resolution CTD data from the *SCARC* are used. The location of seven of the eight hydrographic stations are within 90 km of each other, each sampling the Agulhas Current input (see Figure 6.4). A multiple plot of these eight Agulhas input stations is presented in Figure 6.5. All eight stations occupy a rather tight Θ/S space, particularly in the linear part of the curve which constitutes the Central Waters of the Retroflexion region. The most noticeable feature of this Θ/S plot is the remarkably fresh Tropical Thermocline and Antarctic Intermediate Waters of the *Robert Conrad 17*. Notice that the Agulhas input stations of the *SCARC* fall well within the extremes of the Θ/S "envelope", yet display rather saline Surface and Intermediate Waters. A distinct Red Sea Water signal is evident in both *SCARC* (CTD_054 & CTD_056), *Knorr (ARC)* (CTD_050) and *Thomas Washington* (CTD_296) hydrographic stations. The multiple potential temperature - oxygen (Θ/O_2) curves for the same eight stations (Figure 6.6) reveal similar trends to those identified in the Θ/S plot (Figure 6.5).

The Agulhas input stations of the *SCARC* seem to follow the general trend set by the three other cruises mentioned above. Although the comparison is rather crude, it does indicate that the *SCARC* data occupy the expected Θ/S space. However, this analysis only considered the two Agulhas input stations. How do the *SCARC* data compare to that of the *Discovery 165A* data? The *Discovery 165A* cruise fortuitously sampled the waters of the Retroflexion during the same period as the *SCARC*. The results of this analysis follow.

SCARC INTERCOMPARISONS CONRAD, ARC, THOMAS WASHINGTON & SCARC

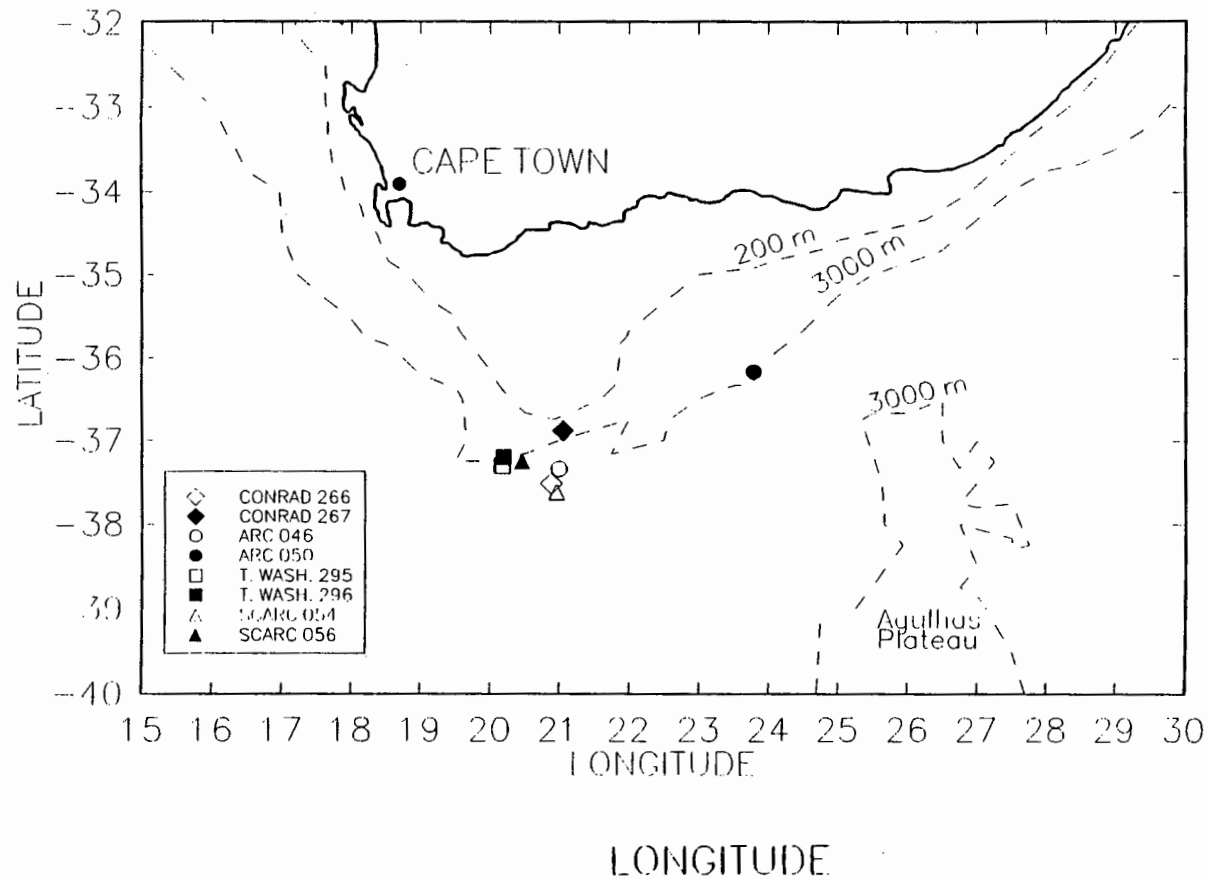


Figure 6.4: A plot of the location of two Agulhas Current input stations from each of the following cruises: *Robert Conrad* 17 (1974), *ARC* (1983), *Thomas Washington* (1985) and the *SCARC* (1987). Contours of the 200 m and 3000 m isobaths are indicated.

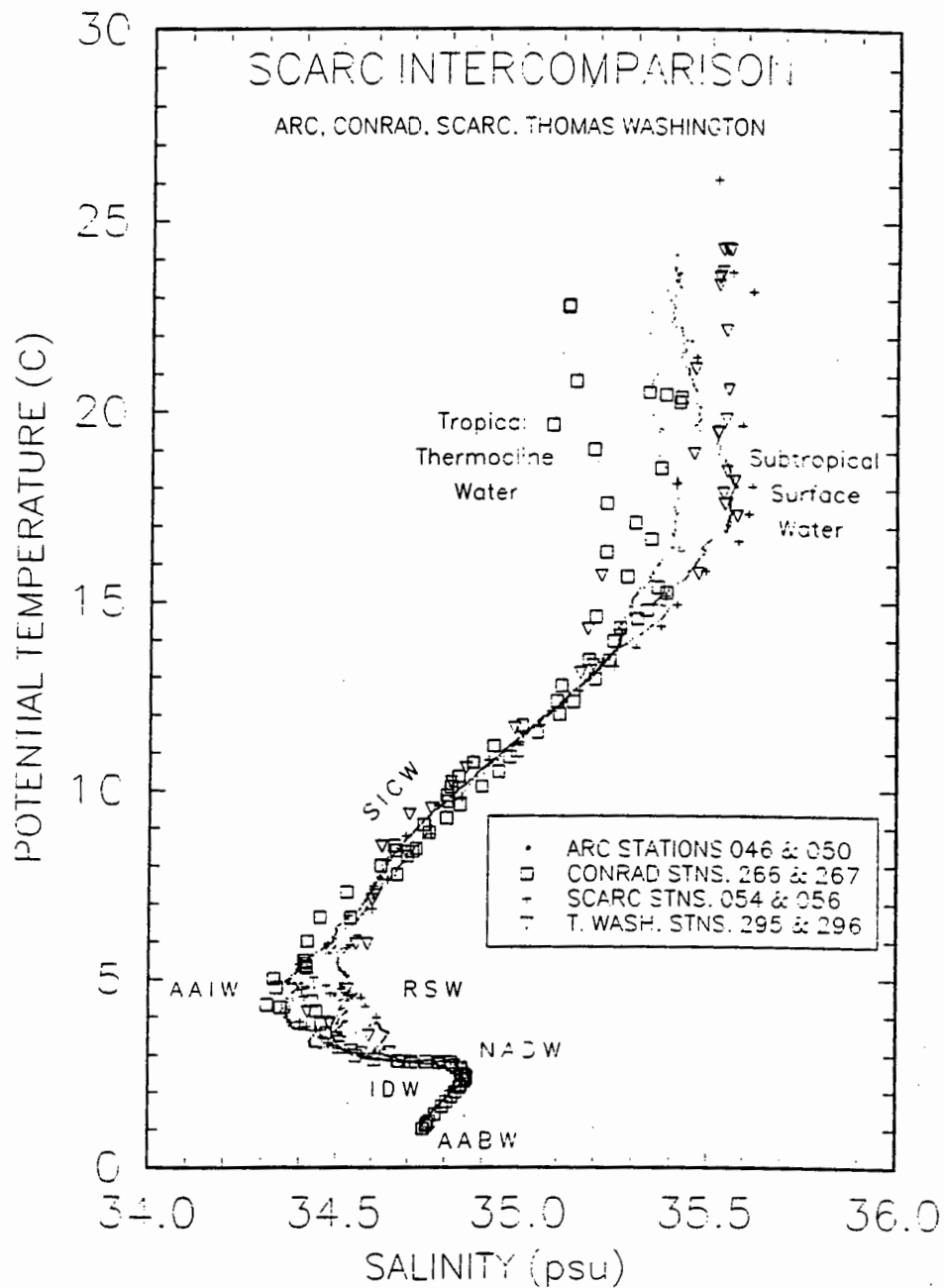


Figure 6.5: A multiple potential temperature - salinity (Θ/S) plot of the eight Agulhas input stations from the following cruises: *Robert Conrad 17* (1974), *ARC* (1983), *Thomas Washington* (1985) and the *SCARC* (1987). South Indian Central Water (SICW), Antarctic Intermediate Water (AAIW), Red Sea Water remnants (RSW), North Atlantic Deep Water (NADW), Indian Deep Water (IDW) and Antarctic Bottom Water (AABW) are identified.

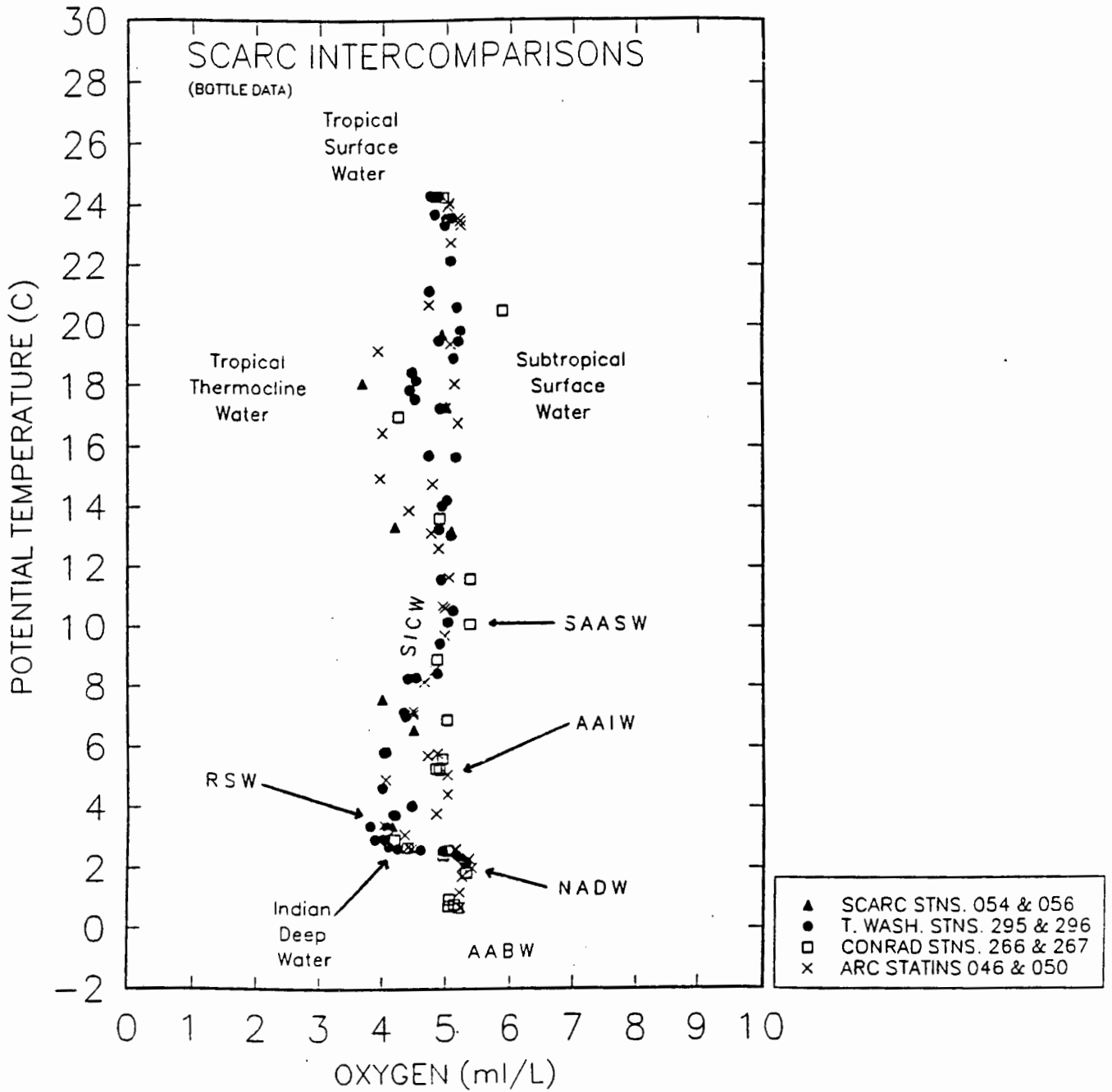


Figure 6.6: A multiple potential temperature - oxygen (Θ/O_2) plot of the eight Agulhas input stations from the following cruises: *Robert Conrad 17* (1974), *ARC* (1983), *Thomas Washington* (1985) and the *SCARC* (1987). South Indian Central Water (SICW), Antarctic Intermediate Water (AAIW), Red Sea Water remnants (RSW), North Atlantic Deep Water (NADW), Indian Deep Water (IDW) and Antarctic Bottom Water (AABW) are identified.

b) SCARC - Discovery 165A Intercomparisons

The *Discovery 165A* cruise (28 February - 25 March) was primarily designed to recover ten moorings deployed two years previously in the Agulhas Current and Retroflection region. Fortunately, a CTD cast was done in the vicinity of each mooring, and *SeaSoar* sections were run between moorings. For listings of this CTD data and contoured sections of potential temperature, salinity, density, chlorophyll-*a* and geostrophic shear the reader is referred to the *I.O.S* data report by Read *et al.* (1987).

Multiple Θ/S and Θ/O_2 plots from the ten CTD casts of the *Discovery 165A* cruise are presented in Figures 6.7 and 6.8 respectively (with kind permission from Dr. Raymond Pollard and Dr. Jane Read, Institute of Oceanographic Sciences). The *Discovery 165A* data reveal some interesting trends. As expected, the lower Deep and Bottom Waters of the Θ/S curve exhibit the tightest fit. The greatest variation of salinity for a particular isotherm is found in the Surface, upper Central and lower Intermediate Waters. A detailed discussion of specific water masses identified in the *Discovery 165A* data is reserved for **Section 6.3**.

Since much of this thesis relies rather heavily on the station that best represents the Agulhas input, a Θ/S plot of the two possible SCARC stations (CTD_054 & CTD_056) are plotted against two Agulhas input stations (CTD_464 & CTD_466) from the *Discovery 165A* data. The resultant Θ/S curves are shown in Figure 6.9, illustrating the remarkably warm ($>25^\circ\text{C}$) Tropical Surface Waters and fresh ($<35,40$) Tropical Thermocline Waters of SCARC station CTD_056, compared to the other three input stations. Station CTD_056 is located within the near-shore surface core of the Agulhas Current, and is therefore not a suitable reference station for calculating the heat and salt anomalies of the SCARC. CTD_054 better represents the Agulhas input as judged by the *Discovery 165A* stations, with its Surface and Central Waters suitably located within the general Θ/S space. However, CTD_054 does exhibit a substantial Red Sea Water (RSW) signal in the Intermediate levels. Caution should therefore be taken when interpreting the salt anomalies in the region of this RSW signal (potential density = $27,30 \text{ kg.m}^{-3}$) in **Chapter 7** that follows later.

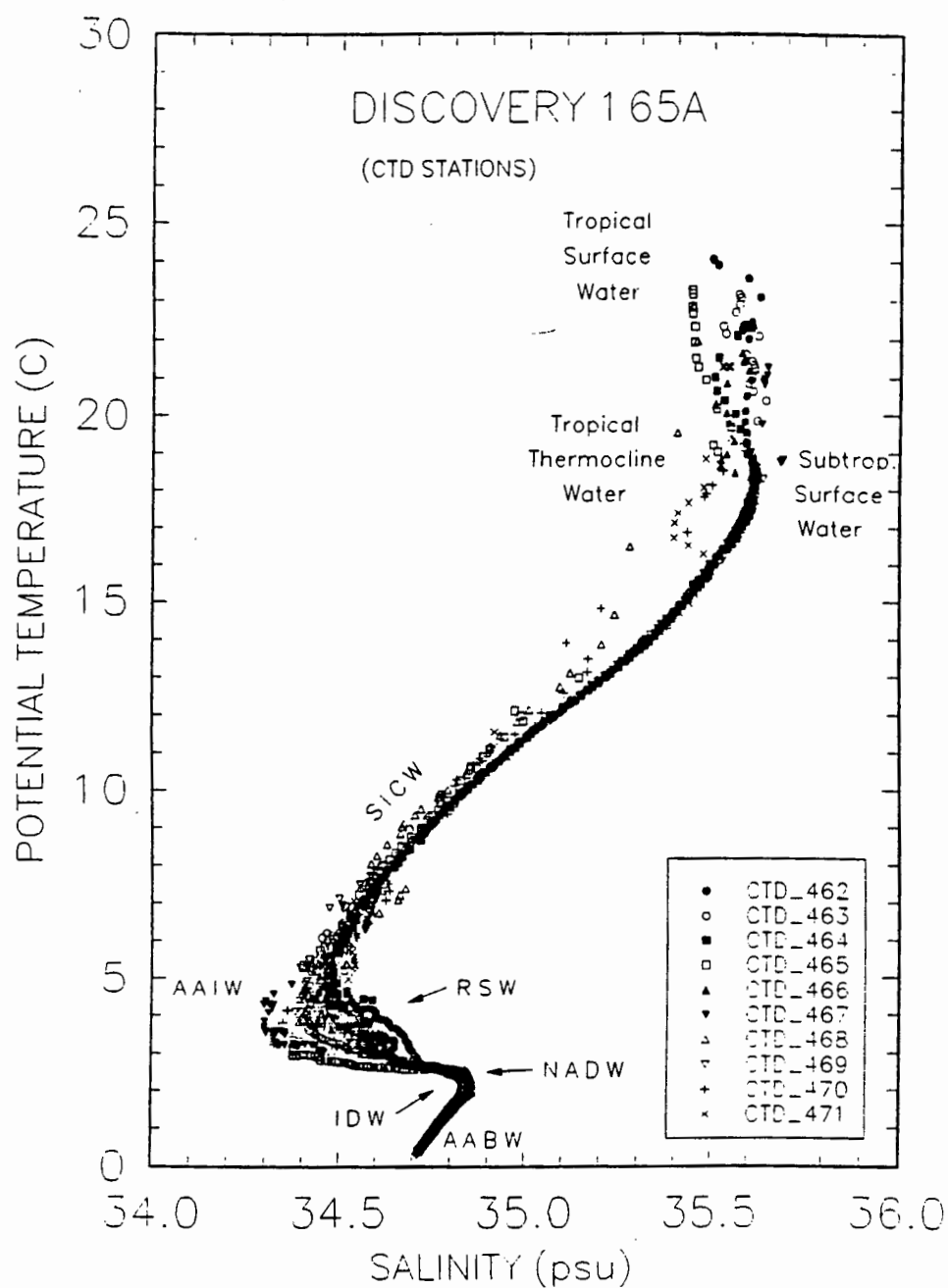


Figure 6.7: A multiple potential temperature - salinity (Θ/T) plot of the ten CTD casts of the *Discovery 165A* cruise (February - March 1987). South Indian Central Water (SICW), Antarctic Intermediate Water (AAIW), Red Sea Water remnants (RSW), North Atlantic Deep Water (NADW), Indian Deep Water (IDW) and Antarctic Bottom Water (AABW) are identified.

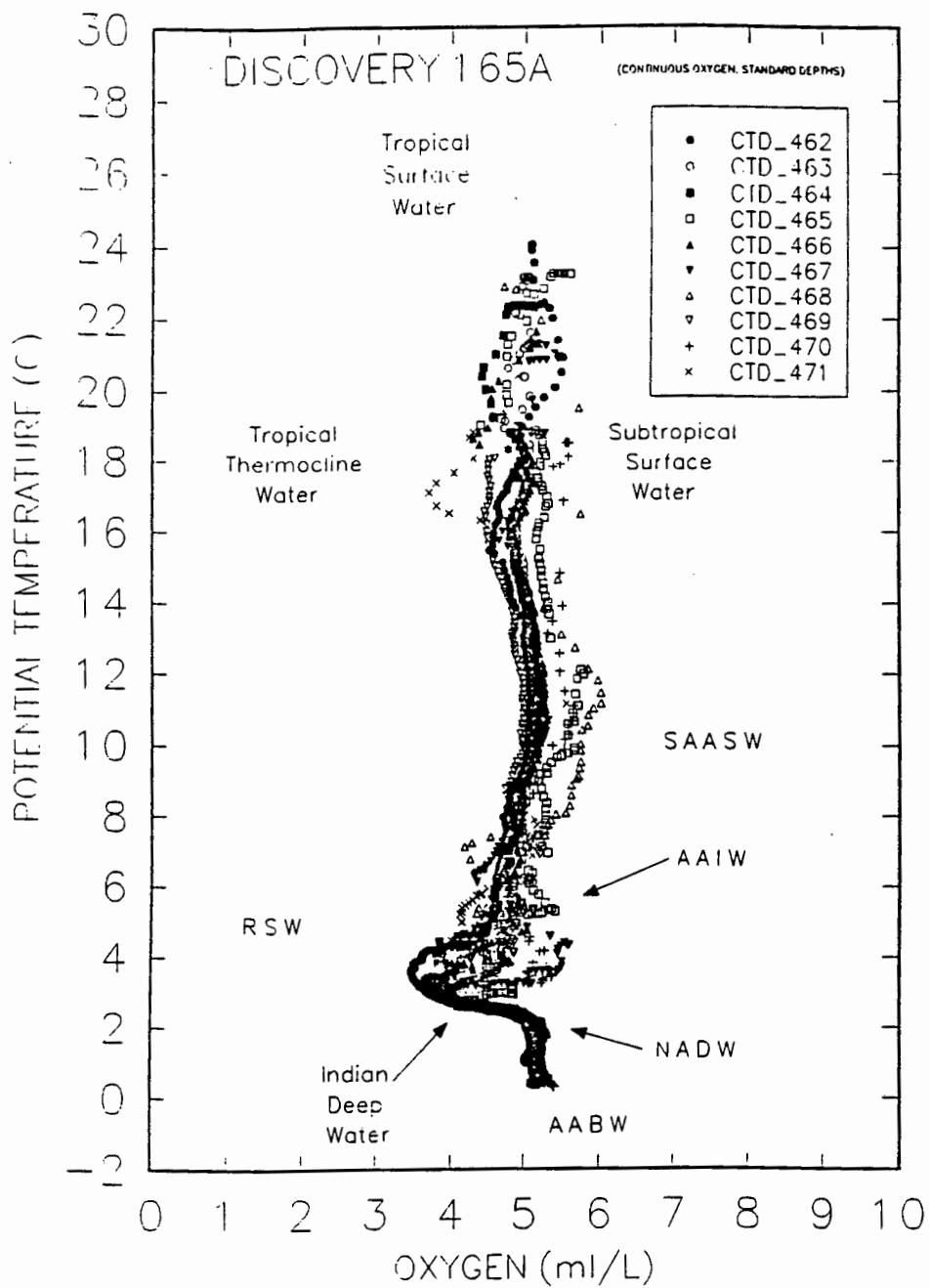


Figure 6.8: A multiple potential temperature - oxygen (Θ/O_2) plot of the ten CTD casts of the *Discovery 165A* cruise (February - March 1987). South Indian Central Water (SICW), Antarctic Intermediate Water (AAIW), Red Sea Water remnants (RSW), North Atlantic Deep Water (NADW), Indian Deep Water (IDW) and Antarctic Bottom Water (AABW) are identified.

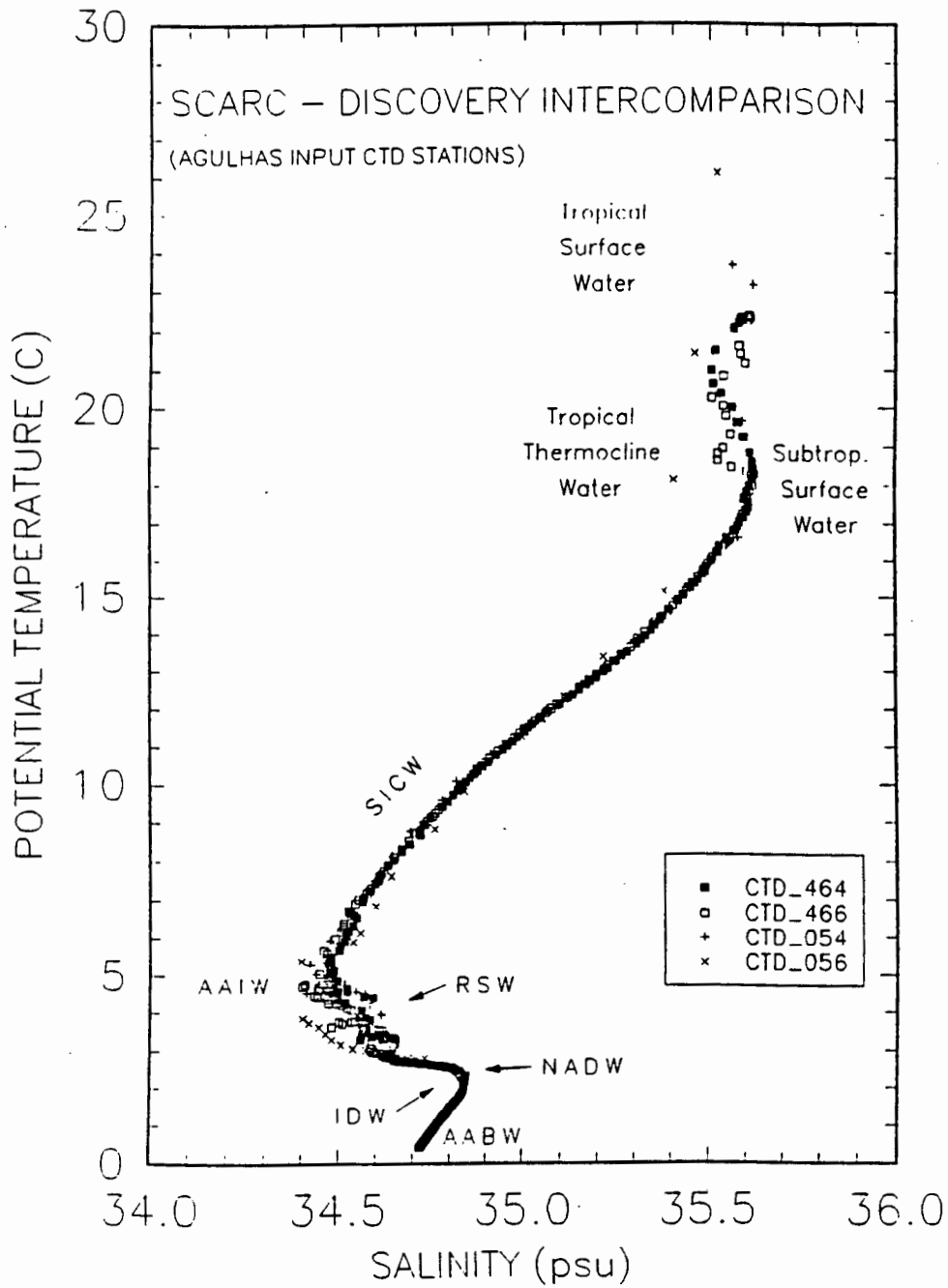


Figure 6.9: A multiple potential temperature - salinity (Θ/S) plot of the two Agulhas input stations from both the *SCARC* and *Discovery 165A* cruises. South Indian Central Water (SICW), Antarctic Intermediate Water (AAIW), Red Sea Water remnants (RSW), North Atlantic Deep Water (NADW), Indian Deep Water (IDW) and Antarctic Bottom Water (AABW) are identified.

6.3) Water Masses - *SCARC* (and *Discovery 165A*) data sets

Section 6.1 introduced the general water masses identified in the *SCARC* data whilst Section 6.2 compared the *SCARC* hydrographic data with other data in the Retroflection region. The section that follows describes in more detail the individual water masses evident in the *SCARC* data (and complimented by the *Discovery 165A* data where possible). The identification of the individual water masses of the Retroflection during the *SCARC* are loosely based on the property extremes identified by Bennett (1988) for the same region. However, the Retroflection is a domain where extensive modification of water masses occurs. Not surprisingly then, the *SCARC* data do not always comply to the boundaries defined in her work. For the purposes of this thesis then, different property extrema are identified, and the water masses classified accordingly. The property extrema by which the water masses of the Agulhas Retroflection region are defined are listed in Table 10.

Surface Waters (TSW, SSW, MSSW, STMW, TTW, SAASW)

Tropical Surface Water (TSW)

Tropical Surface Water (TSW) has its origin in the tropical zone of the Indian Ocean and is consequently warm and fresh. Evidence of a saline variety of TSW is identified in the *SCARC* data, restricted to a shallow layer (0 - 50 db) within the Agulhas input stations (CTD_054, CTD_056 & CTD_055). The freshest variety of TSW ($< 35, 50$) is located within the surface thermal core of the Current. Since TSW is not identified in any other *SCARC* CTD stations, it is tempting to surmise that this anomalously warm water ($\geq 23^{\circ}\text{C}$) is eroded along its' course through the Retroflection. *Discovery 165A* CTD stations (CTD_062, CTD_063 & CTD_064) also identify TSW in the upper 50 db of the water column. The fact that CTD_062 exhibits TSW is not surprising since this station is located within the near-shore core of the Agulhas input, some 400 km upstream of the *SCARC* stations (see Figure 5.28b). However, *Discovery 165A* stations CTD_065 and CTD_063 lie within the core of the Return Current, which suggests that remnants of TSW can complete the Retroflection circuit, although they may not remain in the form of an intact surface streamer. The *Discovery 165A SeaSoar* data provide further evidence of TSW within the Retroflection, which suggests that this water may take the form of a narrow stream (< 35 km) located along the surface core of the Current, becoming increasingly discontinuous along the length of its' path (see Figure

6.10). No TSW is identified within the cores of the six Agulhas eddies sampled during the *SCARC* (and *Discovery 165A*) cruises.

Subtropical Surface Water (SSW)

Subtropical Surface Water (SSW) is transported by the Agulhas Current into the Retroflection area and is expected to dominate the surface waters of the Agulhas Retroflection. Unfortunately, the hydrographic sampling of the *SCARC* is noticeably sparse over this region (37°S - 40°S; 19° - 25°E). Indeed, the only *SCARC* CTD stations that actually sample the Agulhas input and Return Current (besides CTD_056 & CTD_054) are CTD_055 and CTD_053. As was mentioned above, CTD_054 exhibits TSW in the upper 50 db of the water column, beneath which SSW extends to a depth of 280 db. This situation suggests that CTD_054 is located along the southern edge of the surface core of TSW input (see Figure 6.10). Station CTD_053, which is located along the southern edge of the Return Current, exhibits SSW and no TSW, possibly indicating a discontinuity in the "TSW stream".

Fortunately, the *Discovery 165A SeaSoar* data (and CTD_067) indicate that SSW dominates the "interior" of the Retroflection (between the TSW's of the Agulhas input and Return Current). Ring A2 and Eddies A3, A4, A5 and A6 also exhibit SSW in their cores, verifying the Agulhas Retroflection as their source.

Modified Subtropical Surface Water (MSSW)

As is noted above, all the rings and eddies sampled (barring A1) exhibit Subtropical Surface Water (SSW) characteristics in their cores. Interestingly, Ring A2 (CTD_007, CTD_008, CTD_010, CTD_011 & CTD_012), Eddy A3 (CTD_016 & CTD_017), Eddy A4 (CTD_031 & CTD_031) and Eddy A5 (CTD_037) all display a Modified type of Subtropical Surface Water (MSSW), where surface salinities are "boosted" ($S \geq 35.63$) by evaporation. Eddy A6 exhibits no MSSW in its' core, which suggests that it was recently re-shed from the Retroflection or was still interacting with the Return Current over the period of it being hydrographically sampled. Ring A1 exhibits anomalously fresh surface waters as illustrated by the salinity pattern along the ($\sigma_{\theta} = 25.8$) density surface (see Figure 5.16).

Subtropical Mode Water (STMW)

Subtropical Mode Water was first studied in detail by Worthington (1959) ("Worthington's 18°C water") in the North Pacific. Mode Water is a type of water mass characterized by strong vertical homogeneity, acquired by the process of deep vertical convection in winter. Since it is formed from winter mixing it is expected to be colder than the normal gyre Central Water (ie. frequently 16° - 18°C). A typical potential temperature profile displaying the thermal homogeneity characteristic of Mode Waters is given in Figure 6.11.

Three stations from the *SCARC* data (CTD_012, CTD_016 & CTD_047) are observed to exhibit STMW, with potential temperatures ranging from 16,5° - 17,8°C, and oxygen concentrations in excess of 5,2 ml.L⁻¹. These stads of STMW range in thickness from about 50 - 80 m, and are often identified beneath the deep mixed layer of the Agulhas rings and eddies (CTD_012 - centre of Ring A2; CTD_016 - centre of Eddy A3; CTD_047 - within Eddy A6). There also seems to be a weak signature of STMW at CTD_030 (centre of Eddy A4). The only vortices that do not display STMW in their cores are Ring A1 and Eddy A5. A1 is an anomalous feature (and seems not to exhibit any of the classic features of a true Agulhas ring). Eddy A5 exhibits the deepest mixed layer (158 db), which may have eroded any possible STMW signature. Since most of the *SCARC* rings and eddies exhibit STMW in their cores, one can assume that the vortices have been recently formed since continued deep convective overturning would have eroded it away.

Tropical Thermocline Water (TTW)

Water exhibiting Tropical Thermocline (TTW) characteristics is the most common surface water encountered in the Retroflection region. 67% of the *SCARC* CTD stations identify (TTW). However, the Θ/S characteristics of this water mass in the *SCARC* data are diverse. Trends of these waters often seem to indicate that although they occupy the desired Θ/S space characteristic of TTW, this water may in fact be a mixture of warm (and saline) SSW and cool (and fresh) Subantarctic Surface Water (SAASW). Whether this water does indeed originate from the tropics is questionable.

Tropical Thermocline Water (TTW) is evident at the edges of all six eddies identified in the *SCARC* stations. The surface waters in the centre of the eddies exhibit no TTW, but are dominated by SSW as is mentioned above (see Figure 6.10). Ring A1 is

anomalous in that its' surface waters are comprised entirely of TTW, including the centre. This suggests that perhaps there has been contamination of the expected SSW core of Ring A1 by SAASW from filament (C4), the resultant water becoming progressively cooler and fresher with increasing SAASW contamination. Such an event results in the Θ/S characteristics of the surface waters being "pulled" towards the fresher part of the property - property plot, resulting in TTW identification (see Figure 6.12).

Interestingly, the Agulhas shear-edge plume (41°S ; 18°E - Figure 5.1b and 5.1c) does not exhibit TSW nor SSW in its surface waters, but rather water with Tropical Thermocline Water (TTW) characteristics. The Θ/S characteristics of the plume (CTD_038, CTD_039, CTD_040 and CTD_071) yields some interesting results. CTD_038 is located within the Subantarctic filament (C1), and exhibits TTW from the surface to a depth of about 45 db. Beneath this thin "over-wash" of TTW lies a 200 m thick layer of SAASW, constituting C1. CTD_039 exhibits a thickening of the plume of TTW (0 - 80 db), with evidence of SAASW interleaving with the Central Waters at a depth of 120 - 260 db. Moving further east into the Agulhas Retroflexion, CTD_040 exhibits a Θ/S profile typical of Agulhas water. The Agulhas plume therefore is a surface feature of TTW, extending from the surface to 80 db, over-washing the Subantarctic filament (C1) (see Figure 6.10). *Discovery 165A* station CTD_071, which lies some 120 km south of CTD_039, exhibits a strong TTW signature - presumably the southern edge of the Agulhas plume.

As was mentioned earlier, a surface thermal core exists along the inshore edge of the Agulhas input. Associated with this core is a shallow oxygen minimum feature ranging in depth from 65 - 140 db, within the TTW. The *SCARC* and *Discovery 165A* data both seem to indicate that a shallow oxygen minimum ($\text{O}_2 \leq 4.5 \text{ ml.L}^{-1}$) is associated with the main Agulhas flow. This phenomenon has also been observed by Chapman *et al.* (1987) and Gordon *et al.* (1987) in the thermal core of the Agulhas Current for the *Knorr (ARC)* hydrographic data of 1983 and for the *Thomas Washington* data of 1985 (Bennett, 1988). This shallow oxygen minimum probably results from the density changes that occur across the thermocline in tropical and subtropical waters (Chapman, 1998). It is within these regions of rapid density change that organic matter tends to accumulate (Biggs and Wetzel, 1968; Harder, 1978). The density stratification will tend to prevent oxygen diffusion down through the water column, and the resident oxygen content then becomes depleted during the decay of the organic material.

Chapman (1988) suggests that this oxygen-depleted layer can be used as a possible tracer of Agulhas water into the Atlantic. However, none of the *SCARC* vortices exhibit a shallow oxygen minimum of the same magnitude as that of the Agulhas main flow. This result is not surprising since deep convective mixing within these vortices will tend to erode this shallow oxygen minimum. Interestingly, even Eddy A6 does not exhibit this oxygen minimum, although A6 is believed to be interacting with the Agulhas Current at the time. However, by relaxing the oxygen minimum concentration to $O_2 \leq 5,0 \text{ ml.L}^{-1}$, Ring A2 and Eddies A4 & A6 exhibit a shallow oxygen minimum layer. Figure 6.13 shows typical vertical oxygen profiles from the Agulhas input, Return Current, Eddy A4 and Subantarctic Waters. Notice the characteristic shallow oxygen minimum at the surface core of the Agulhas input (denote by the solid triangle). The Return Current station exhibits somewhat similar trends to that of the Agulhas input, although oxygen values are higher, with a less intense shallow minimum located at a similar depth. The Agulhas eddy station exhibits a relatively high oxygen concentration ($5,25 \text{ ml.L}^{-1}$), mixed from the surface down to a depth of 180 db, thus eroding any shallow oxygen minimum which may have been present. The Subantarctic station displays the expected oxygen maximum ($>6,00 \text{ ml.L}^{-1}$), far exceeding the surface values of waters of Agulhas origin. Notice the oxyclad of about $5,7 \text{ ml.L}^{-1}$ at a depth of 260 - 650 db (CTD_044), indicative of the relative oxygen maximum intrusion associated with anomalously fresh Antarctic Intermediate Water (AAIW). Also notice the steep oxycline at about 700 db, where the base of the relative oxygen maximum gives way to the deeper, oxygen poor waters (with smaller intrusions of oxygen rich AAIW).

A detailed analysis of the shallow oxygen minimum identified in the Agulhas waters of the *SCARC* is beyond the scope of this thesis and should be the topic of further work. From the preliminary findings above it does seem that this shallow oxygen minimum layer may be a useful tracer of core Agulhas Waters. However, this shallower signal is less useful in tracing Agulhas Water within isolated vortices since this oxygen minimum layer is likely to be eroded out by mixed layer deepening. For more details concerning the shallow oxygen minimum of the Agulhas waters I refer the reader to Chapman (1988).

Subantarctic Surface Water (SAASW)

As was mentioned earlier, Subantarctic Surface Waters (SAASW) that invade the Retroflexion region from the south exhibit anomalously cool, fresh and oxygen rich characteristics. This invasion often takes the form of surface filaments entrained along the eastern perimeter of the Agulhas rings and eddies, which can extend well into the Retroflexion region (eg. Subantarctic filament (C4) extends to within 450 km of Cape Town). Figure 6.10 shows the pattern of the SAASW at the surface. Interestingly, the SAASW associated with filament (C4), extends to within 150 km of Ring A1. Notice the limited northward surface extent of Subantarctic filament (C1), primarily due the shallow surface over-wash of Agulhas Water associated with the shear-edge plume mentioned earlier.

SAASW is frequently identified in the *SCARC* hydrographic stations (present in 32% of the stations) and provides an effective mechanism for contamination of the warm, saline surface waters of the Retroflexion. The northward invasion of SAASW can occur at shallow and thermocline depths, identified north of the STC as filaments of Subantarctic origin. As one moves from the Retroflexion south across the STC, the South Indian Central Waters (SICW) diminish, to be dominated by SAASW overlying the Intermediate Waters (since Central Water is formed through subduction at the STC).

Station CTD_026 exhibits a rather interesting phenomenon. CTD_026 is located within the northern extension of Subantarctic filament (C4). The surface SAASW signal at this station is a mere 20 m thick, below which two major intrusions of saline ($S \geq 35.20$) TTW occurs, centered at depths of 30 and 80 db (see Figure 6.14). This situation is unique in that the temperature (and salinity) inversions cause increased stability (1918×10^{-8} and $1884 \times 10^{-8} \text{ m}^{-1}$ respectively). As a result of this increase stability one would expect that no matter how much the cold surface water mixes with the slightly more saline water beneath it, it would remain lighter and would have to move further northward and mix with the water of greater salinity in order to eventually sink. I believe that this may possibly be the reason why the salt anomalies of Ring A1 are negative (ie. anomalously fresh), as a consequence of contamination of the expected SSW by SAASW (C4), to form a less saline mixture of TTW character.

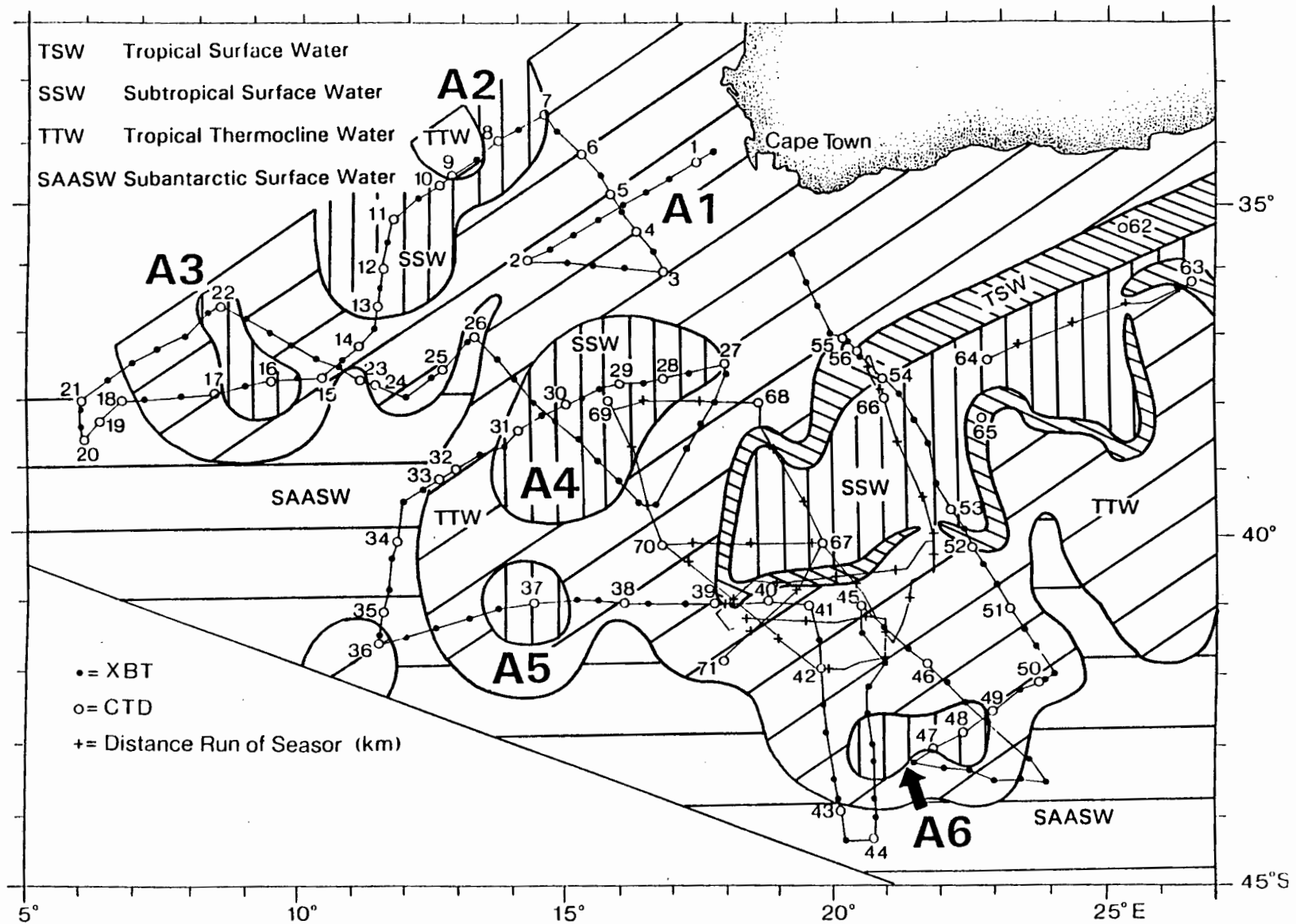


Figure 6.10: Distribution of the surface water masses of the Agulhas Retroflexion as revealed by the *SCARC* and *Discovery 165A* cruises. CTD stations are numbered (1-56 = *SCARC*; 62-71 = *Discovery 165A*). The warm-core Agulhas rings and eddies are labeled (A1 TO A6).

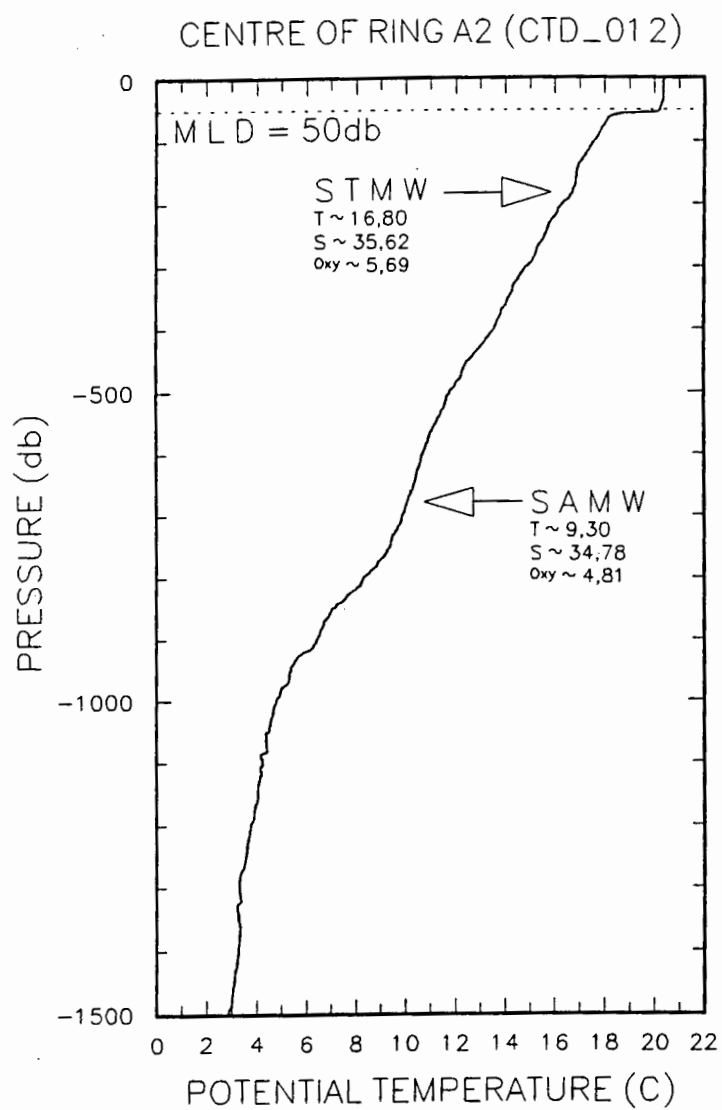


Figure 6.11: A potential temperature profile at the centre of Ring A2 (CTD_012) showing the classic thermal homogeneity of the surface mixed layer, Subtropical Mode Water (STMW) and deeper Subantarctic Mode Water (SAMW).

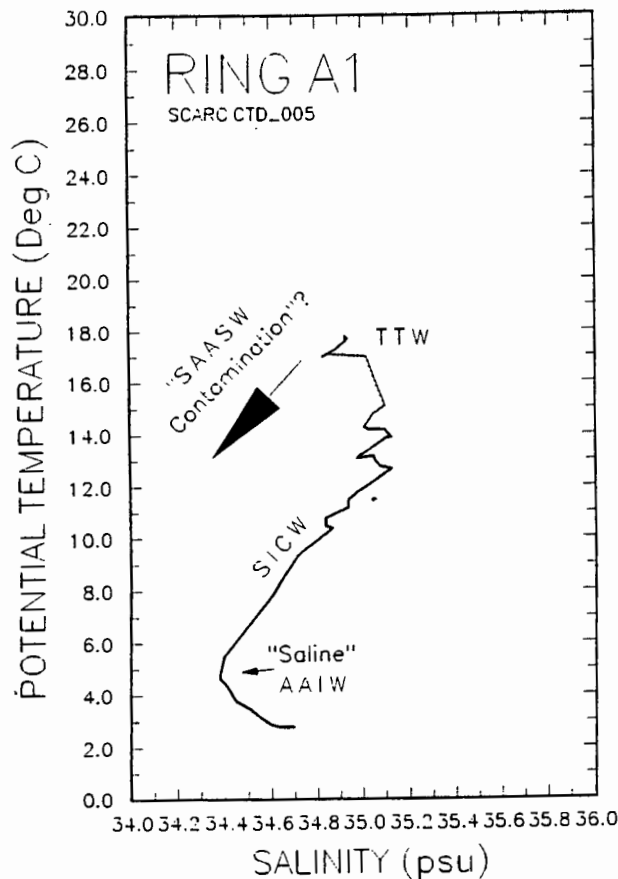


Figure 6.12: Potential Temperature - Salinity (θ/S) plot at the centre of Ring A1 (CTD 005). Notice the apparent lack of saline Subtropical Surface Water (SSW). Tropical Thermocline Water (TTW) dominates the surface waters of A1, possibly resulting from fresh water "contamination" of SSW in the form of Subantarctic Surface Water (SAASW).

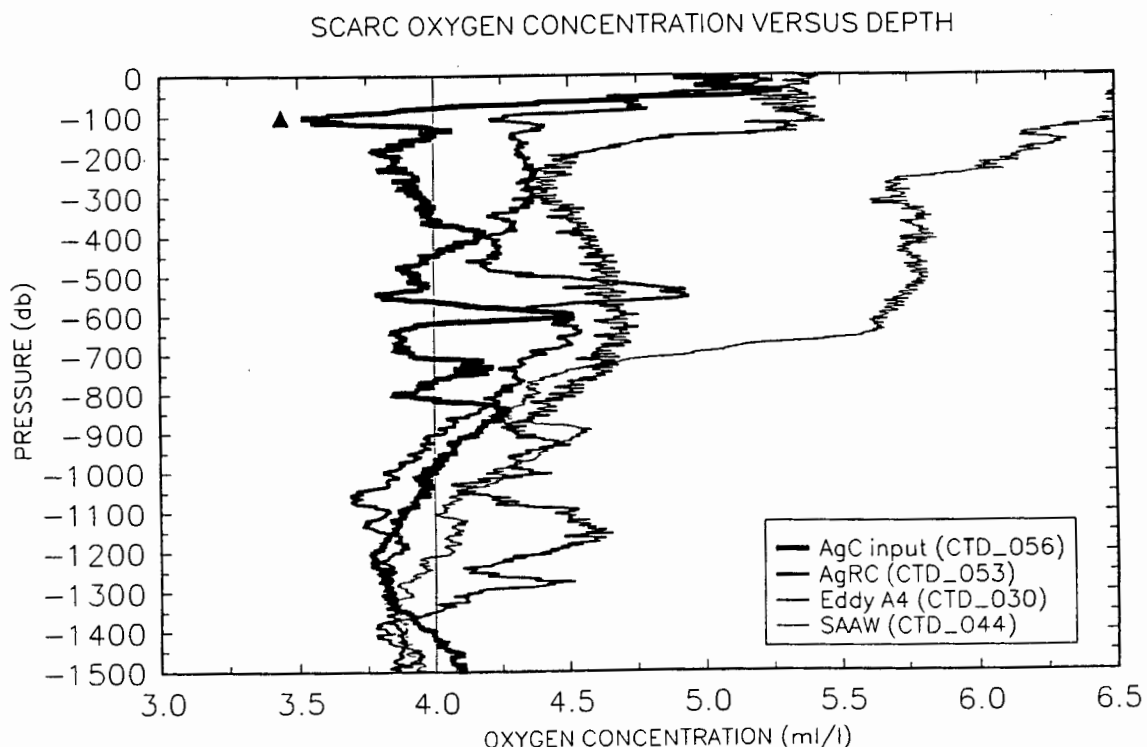


Figure 6.13: Multiple Oxygen plot versus Pressure for the near-shore Agulhas input (CTD_056), the Agulhas Return Current (CTD 053), Eddy A4 centre station (CTD_030) and a Subantarctic station (CTD_044). Notice the shallow oxygen minimum characteristic of the near-shore Agulhas Input (CTD_056) (denoted by the solid triangle) and weaker trend in the Agulhas Return Current (CTD 053). The Eddy A4 centre station (CTD_030) exhibits a classic erosion of this shallow oxygen minimum, together with ventilation of its' thermocline waters. Subantarctic station (CTD_044) exhibits two oxyclines, one at around 260 db and another at around 720 db. The shallow oxycline denotes the base of the high oxygen Subantarctic Surface Waters, whilst the deeper oxycline denotes the transition into the relative oxygen minimum of the Intermediate Waters.

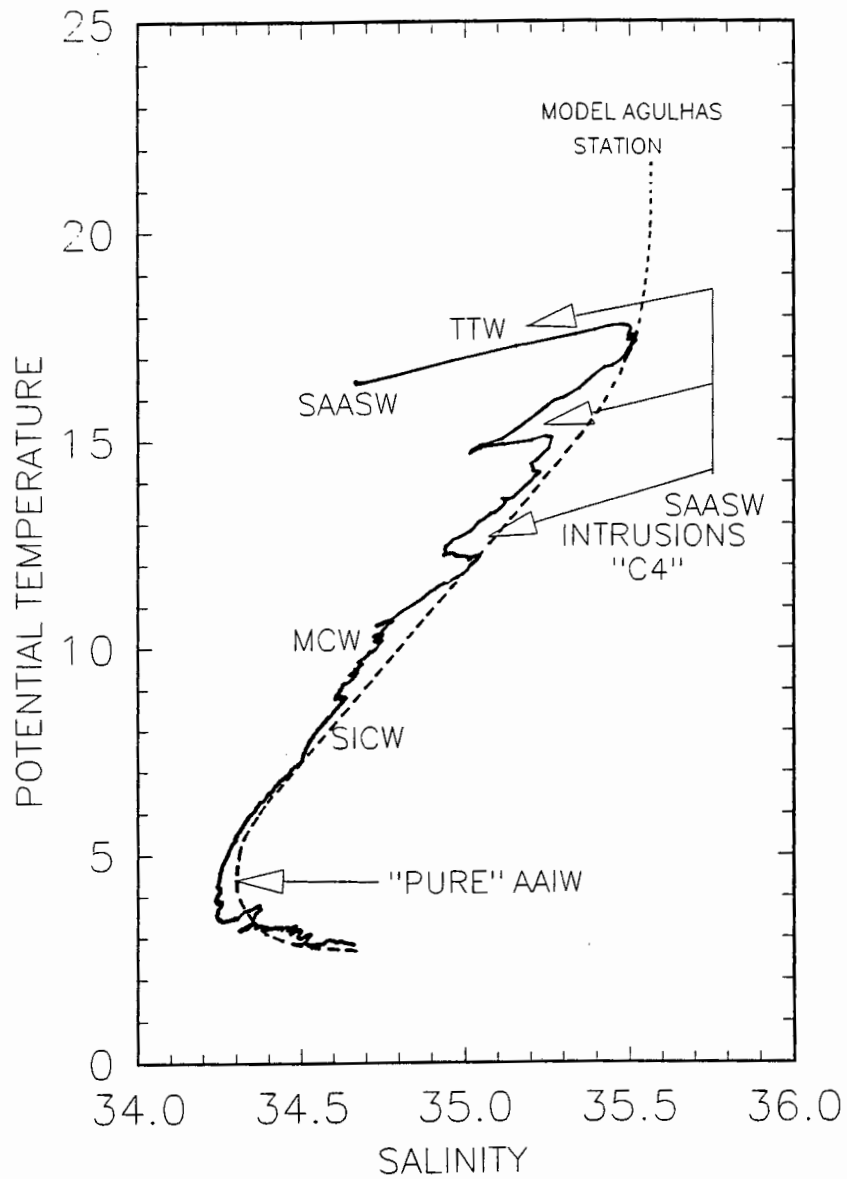


Figure 6.14: Potential Temperature - Salinity (Θ/S) plot of SCARC CTD_026 showing the surface and thermocline intrusions of subantarctic influence constituting Subantarctic filament (C4).

Central Waters (SICW, SAMW)

South Indian Central Water (SICW)

Differences between the Southwest Indian and Southeast Atlantic Central Waters in the Retroflexion region are difficult to determine because of their similar Θ/S characteristics. Indeed, Fine *et al.* (1988) suggest that the similar Θ/S characteristics of South Atlantic and South Indian thermoclines are a result of the active mixing in the Retroflexion region. For the purposes of this thesis then, no attempt has been made to resolve the identity of the Central Waters, and have been labeled South Indian Central Water (SICW), consistent with the results of Gordon *et al.* (1987) and Holford (1990). Both fresh (possibly Southeast Atlantic) and saline (possibly Southwest Indian) varieties of Central Water are identified, with the fresh variety of Central Water dominant (particularly in the upper reaches of the linear portion of the Central Waters). For the purposes of this thesis the fresh variety of SICW is labeled Modified Central Water (MCW).

The Central Water of the rings and eddies of the *SCARC* are similar (if not identical) to Central Waters of the Agulhas input stations. Modification of the Central Waters of the Agulhas vortices is usually restricted to within the Upper Thermocline. Otherwise, the Central Waters within the core of the Agulhas rings and eddies are remarkably linear, with increased step-like Θ/S profiles as one moves from the centre to the edge of the vortex, indicating enhanced interleaving of water masses at the vortex edge (see Figure 6.15).

Subantarctic Mode Water (SAMW)

SAMW is embedded in the Central Waters of the Retroflexion region, a renewal agent of high oxygen in the main thermocline waters (McCartney, 1977). SAMW is (almost) isothermal and isohaline water lying between the range of salinity (34,80 - 35,20), and close to the range of temperature (10° - 12°C). The SAMW high-oxygen influence has been identified by Bennett (1988) across the Agulhas upstream of the Retroflexion. The *SCARC* data reveal a single Agulhas station (CTD_056) which exhibits a deep stad of SAMW, some 80 m thick. The only other hydrographic stations which exhibit SAMW are those within Rings A1 & A2. Interestingly, the stads of SAMW within A1 & A2 range in thickness from about 100 - 180 db (somewhat thicker than the Agulhas station). An example of the thermal signature of a deep stad of SAMW is shown in

Figure 6.11. The stads of SAMW seem to be more pronounced within Rings A1 and A2, compared to the SCARC Agulhas station (CTD_056), and those identified within the Agulhas Current by Bennett (1988) and Gordon *et al.* (1987).

Sources for the deep stad of SAMW within Rings A1 and A2 are varied. Should the SAMW be supplied purely from the Agulhas Current, the increased thickness could be the result of "stretching" or concentration of the source thermocline water within the rings during the process of ring shedding (see Onken *et al.*, 1990). Duncombe Rae and Shillington (1994) suggest that a second possible source of the deep SAMW stad may be the Subantarctic, since water of Subantarctic origin is often observed to be drawn into the gap created by ring separation from the Retroflection during shedding (see Figure 2.3). Observation of the shedding of an Agulhas ring at sea (Lutjeharms and Gordon, 1987) confirms that both surface and subsurface waters entering the gap could be of Subantarctic origin. However, in the sections presented in that publication (and from profiles in Camp *et al.*, 1986), although a SAMW signature (thermostad between 10° - 12°C) is evident in the section outside the ring, this layer is only slightly enhanced within the newly shed ring. Again the dynamics of ring formation suggested by Duncombe Rae and Shillington (1994) may contribute to an enhanced deep stad of SAMW. A third possible source is the Agulhas Bank. A bottom mixed layer up to 50 m thick is frequently observed over the Bank (Swart and Largier, 1987; Chapman and Largier, 1989). This bottom mixed layer has temperature and salinity characteristics (approximately 8° - 11°C ; 34,70 - 34,90) close to those of the lower stad observed in Duncombe Rae and Shillington's (1994) "Winter Ring". Wind induced upwelling and topographically induced shelf-edge upwelling may continuously draw water from 600 - 800 db depth in the Agulhas Current onto the eastern Agulhas Bank. Here it may reside for a time, becoming mixed and modified, before leaving the Bank on the western edge. It may be that this water is entrained within the Retroflection during the formation of an Agulhas ring. It is possible that a combination of all the above sources have an influence on the composition of the deep SAMW stad within Agulhas rings. The dynamical explanation for the enhanced deep stad within vortices is the most attractive, and it is within these features that an enhanced SAMW layer is most often observed.

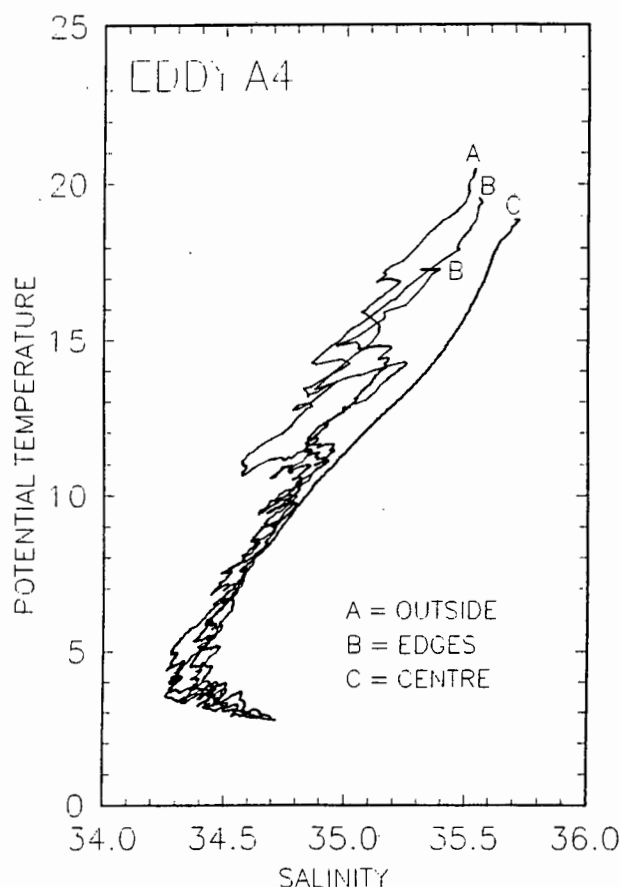


Figure 6.15: Multiple temperature - salinity plot at the centre (CTD_030), edge (CTD_028 & CTD_032) and outside (CTD_027) of Eddy A4. Notice the smooth linear profile of the Central Waters and "boosted" salinity of the Surface Waters within the center of the eddy. Those stations at the eddy-edge and outside display remarkably stepped Θ/S profiles indicative of enhanced interleaving.

Intermediate Waters (AAIW, RSW)

Antarctic Intermediate Water (AAIW)

The main oxygen minimum in the Agulhas Retroflection is found below 1000 db (3,7 - 4,4 ml.L^{-1}), centered on a depth of about 1380 db. AAIW forms a relative oxygen maximum (and salinity minimum) layer that intrudes into this main oxygen minimum, usually at a depth of about 1250 db. However, the Intermediate Waters of the Retroflection are surprising diverse, primarily a consequence of low salinity (relative oxygen maximum) AAIW mixing with the more saline (relative oxygen minimum) Red Sea Water (RSW) remnants. Because these two Intermediate Water masses display contrasting properties, identification of the extremes of these two water masses is relatively simple. The multiple Θ/S and Θ/O_2 plots (Figures 6.1 and 6.2) clearly show

the extremes of AAIW (CTD_044) and RSW (CTD_041 & CTD_054) evident in the *SCARC* data. Between these salinity (and oxygen) extremes exists a host of AAIW / RSW mixtures.

The salinity minimum of AAIW in the dynamical core of the Agulhas Current exceeds 34,40, becoming more fresh as one moves southwestward through the Retroflexion region and into the Subantarctic waters of the southeast Atlantic ($S < 34,30$). The oxygen concentration decreases from the overlying maximum of the Central Waters through the AAIW core down to a minimum ($< 4 \text{ ml.L}^{-1}$) in the lower AAIW at a temperature of about $3,0^{\circ} - 4,0^{\circ}\text{C}$. The oxygen-minimum layer is more pronounced in the Agulhas input stations where the salinity minimum is more saline (RSW influence). Consequently, the more saline (and less oxygenated) AAIW is found within the centre of the Agulhas eddies (see Table 11). Ring A2 and Eddy A4 exhibit this trend, whilst Ring A1 and Eddies A3, A5 and A6 seem to display a somewhat weaker trend. This suggests that Ring A2 and Eddy A4 may have the most deeply developed vortices - a result consistent with the Flierl (1981) volume trapping results for the same vortices (listed in Table 6). However, according to the results listed in Table 6, Eddies A5 and A6 are equally intense as Ring A2 and Eddy A4, yet A5 and A6 do not seem to exhibit AAIW of Agulhas origin. This suggests that either the shedding mechanism of A5 and A6 is different to that of A2 and A3, or A5 & A6 have mixed considerably with their surrounding (Subantarctic) waters, causing their saline AAIW to be contaminated with the exceedingly fresh variety of AAIW which has been identified in the immediate vicinity of the STC. This latter scenario is more likely, and one that is supported by the volume trapping of salt anomalies (SA's) $\geq 0,00$ within these vortices, presented in **Section 5.3.3**. No estimate of the relative ages of the *SCARC* rings and eddies is attempted using the relative "freshness" of the AAIW in their cores since this phenomenon seems to be largely a function of the characteristics of the background waters into which they are shed. In other words, vortices shed to the south are more likely to lose their saline AAIW signal compared to their anticyclonic counterparts shed to the west of the Retroflexion. There seems to be no evidence of a less saline (relative oxygen maximum) within the centre of the *SCARC* vortices, suggesting that a true annulus of Agulhas water does not exist within these features.

The above results seem to indicate that Agulhas rings and eddies can trap water within their vortices to depths well within the Intermediate Water range. This result is consistent with that observed by Visser (1969) in his treatment of Duncan's (1968,

1970) data set of an eddy in the vicinity of the STC as well as McCartney and Woodgate-Jones' (1991) Agulhas eddy in the South Atlantic.

Red Sea Water Remnants (RSW)

As was mentioned above, Red Sea Water (RSW) remnants are evident in the *SCARC* data and can be relatively easily identified by their characteristic salinity maximum and oxygen minimum within the Intermediate Waters. Table 12 below lists eight *SCARC* CTD stations which exhibit an extreme RSW signal (an additional three stations (CTD_045, CTD_046 & CTD_051) exhibit a RSW signal but are not listed in Table 12 since they are not extreme). RSW remnants are associated with the Agulhas input, Agulhas Return Current and the shear-edge plume extending from the Agulhas Retroflection, and in all cases exhibit strong interleaving with the cold and fresh AAIW. Such extreme interleaving of RSW within the Retroflection region is also noted by Bennett (1988). The inshore Agulhas Current station (CTD_055) exhibits no RSW signal, presumably because this station is located on the shelf and extends to a mere 1000 db ($\sigma_t = 27,36 \text{ kg.m}^{-3}$). Agulhas stations CTD_054 & CTD_041 exhibit the most saline and warmest variety of RSW respectively. Thick stads of RSW within the Agulhas input and Retroflection (300 m and 200 m respectively) are not unusual. Comparable strata of RSW (300 - 800 m thick) have been documented by Gründlingh (1985) further upstream in the Agulhas Current in 1981. Interestingly, RSW remnants are identified as far south as $41,9^\circ\text{S}$ (CTD_042) in the *SCARC* hydrographic data, associated with the "southward spill" of Agulhas water (some $1,9^\circ$ further south than that documented by Clowes and Deacon, 1935).

None of the *SCARC* rings and eddies seem to exhibit "pure" RSW remnants within their core stations. Ring A1 exhibits a mixture of AAIW / RSW, with the Intermediate Waters of Eddies A2, A3, A4 and A6 tending towards RSW, yet failing positive identification as RSW. The only eddy station that could possibly be considered to exhibit "pure" RSW is station CTD_049, along the northeastern edge of Eddy A6. Eddy A3, which is located furthest west of all the *SCARC* rings and eddies, exhibits no RSW remnants. In fact the Intermediate Waters within A3 tend to the fresher AAIW side of the Θ/S property-property plot - a function of its location rather than the depth to which the vortex can trap water.

Table 11: Salinity minima and relative oxygen maxima associated with the Intermediate Waters of the Agulhas Retroflection region during the SCARC.

Feature	Description	Station	Salinity (psu)	Oxygen (ml.L ⁻¹)
Ag. Current	Input	CTD_054	<u>34,41</u>	4,21
AgR. Current	Return	CTD_053	34,39	4,53
Ring A1	SE Edge	CTD_003	34,28	No data
	Middle	CTD_005	34,38	No data
	NW Edge	CTD_006	34,36	No data
Ring A2	NE Edge	CTD_008	34,39	4,71
	Middle	CTD_009	<u>34,40</u>	4,87
		CTD_010	<u>34,41</u>	4,53
		CTD_012	<u>34,34</u>	5,22
		CTD_013	34,36	4,77
	SW Edge			
Eddy A3	Eastern Edge	CTD_015	34,26	5,64
	Middle	CTD_016	34,35	5,37
	Western Edge	CTD_017	34,32	5,32
Eddy A4	NE Edge	CTD_028	34,38	4,48
	Middle	CTD_030	<u>34,40</u>	4,41
	SW Edge	CTD_032	34,28	5,04
Eddy A5	Western Edge	CTD_036	34,25	5,26
	Middle	CTD_037	34,28	5,07
	Eastern Edge	CTD_038	<u>34,45</u>	4,48
Eddy A6	SW Edge	CTD_043	34,25	5,41
	Middle	CTD_048	34,31	4,88
	NE Edge	CTD_049	34,25	5,24
Subantarctic	South of STC	CTD_044	34,20	5,80
Those figures <u>underlined</u> exhibit a relatively high salinity minimum (and low oxygen) as a result of "contamination" by remnant Red Sea Water (RSW)				

Table 12: A list of the salinity maxima, oxygen minima and corresponding density surfaces for "pure" Red Sea Water (RSW) remnants evident in the SCARC data.

Station	Location	Sal _(Max) (psu)	O ₂ _(Min) (ml.L ⁻¹)	σ_1 (kg.m ⁻³)	σ_t (kg.m ⁻³)
CTD_038	Agulhas Plume	34,554	3,67	31,927	27,340
CTD_039		34,563	3,63	32,036	27,429
CTD_040		34,548	3,63	32,033	27,425
CTD_041		34,585	3,53	31,818	27,254
CTD_042	"Southward Spill"	34,580	3,58	32,127	27,504
CTD_053	Agulhas Return	34,500	3,81	32,003	27,416
CTD_054	Agulhas Input	34,591	3,45	32,127	27,502
CTD_056		34,483	3,85	31,902	27,308
Mean*		34,550	3,64	31,996	27,397
Std. Dev.		0,039	0,130	0,108	0,089
n		8	8	8	8
* The above means and standard deviations are for the eight stations showing extreme RSW remnant signals and therefore differ from those listed for all RSW remnants of the SCARC data listed in Table 10					

Deep Waters (UCDW, NADW, LCDW)

Unfortunately the majority of the SCARC data set extend to a maximum depth of 1500 db, thus limiting the identification of the relative contribution of the different Deep Waters in the Retroflection region. However, ten CTD casts to the bottom were executed within the Retroflection region during the *Discovery 165A* cruise, the results of which are presented below.

Distinctions between the Deep Waters of the Retroflection are difficult to make because of the mixing of the North Atlantic Deep Water (NADW - salinity and oxygen maximum) with the Upper Circumpolar Deep Water (UCDW - oxygen minimum) above, and the Lower Circumpolar Deep Water (LCDW - oxygen minimum) beneath (Reid *et al.*, 1977). Figures 6.16a - 6.16d show the $\Theta/S/O_2/\text{Sigma-2}$ relationships of the Deep (and Bottom) Waters identified in the ten *Discovery 165A* stations. Variations

in salinity and oxygen over the NADW regime are a mere 0,07 and 0,35 ml.L⁻¹ respectively. Figure 6.16d clearly shows a classic S-shaped Sigma-2 - O₂ plot, which is particularly useful in identifying the UCDW, NADW, LCDW and AABW. For the purposes of this thesis the inflection points (37,00; 37,09 and 37,12 kg.m⁻³) of the Sigma-2 - O₂ curve indicate the "boundaries" of water masses comprising the Deep Waters of the Retroflection. The boundaries defined by these inflection points identify the range of T/S/O₂ for UCDW and LCDW within the Retroflection region for the first time. A possible exception is Gordon *et al.*'s (1987) rather qualitative identification of UCDW and LCDW in their analysis of a selection of *Geosecs* and *Conrad 17* data for the western Indian Ocean.

Since the Deep Waters of the Southeast Atlantic are expected to consist of Circumpolar Deep Water, with an invasion of NADW from the north, Figures 6.16a - 6.16b are interpreted accordingly. In fact, this active invasion of NADW in the Retroflection region dominates the Deep Waters, a finding that is consistent with the fine-scale volumetric results of Valentine *et al.* (1993). Those hydrographic stations which exhibit a "weak" invasion of NADW (ie. they exhibit relatively low salinity and oxygen) are restricted to the northeast sector of the Retroflection region (CTD_062 - CTD_065), with CTD_063 exhibiting the "weakest" NADW signal. In fact, CTD_063 seems to exhibit some evidence of Indian Deep Water (IDW) in the LCDW range, illustrated in Figure 6.16d by a significant oxygen minimum (<5,05 ml.L⁻¹) in the 37,09 - 37,12 kg.m⁻³ Sigma-2 range. Figure 6.17 also identifies the remnant Indian Deep Water in a "zoomed in" Θ/O_2 plot. Hydrographic stations further west show greater NADW influence, consistent with the expected passage of NADW in the global "Thermohaline Conveyor Belt" of Gordon (1985). There seems to be no evidence in support of Bennett's (1988) finding of extremely saline NADW on the inshore edge of the Agulhas Current input.

The only deep CTD cast which lies within an Agulhas eddy is that of CTD_069 (Eddy A4). There is no noticeable modification of the Deep Waters within this station. Since the results presented in Chapter 5 suggest that Eddy A4 is perhaps the most deeply developed of the six Agulhas vortices, it is suggested that trapping Deep Water is unlikely to occur within rings and eddies in the Retroflection region. This result is supported by Gordon *et al.*'s (1992) finding that the Indian to South Atlantic linkage is restricted to the Surface, Thermocline and Intermediate Waters.

Bottom Waters (AABW)

For the purposes of this thesis Antarctic Bottom Water (AABW) is defined by a potential temperature minimum and relative oxygen maximum at depths exceeding 3900 db ($\text{Sigma-4} \geq 45,96 \text{ kg.m}^{-3}$). AABW is identified in all but one of the ten *Discovery 165A* CTD stations. The exception is CTD_062, which only extends to a depth of 3800 db. The general characteristics of the AABW identified in the *Discovery 165A* data are listed in Table 10 and the $\Theta/\text{S}/\text{O}_2$ relationships characteristic of this water mass are shown in Figure 6.16.

6.4) Conclusions on the water masses of the Agulhas Retroflection region

The results presented above outline for the first time a detailed analysis of the water masses of the Retroflection region. The property extrema associated with each water mass are identified and discussed, thus fulfilling the second major objective of the thesis. Bennett (1988), in her analysis of the hydrographic data collected on board the *Thomas Washington* in 1985, constitutes possibly the only other attempt to define the property extrema characteristic of the water masses of the Agulhas Retroflection. Gordon *et al.* (1987) unfortunately neglected to provide a detailed analysis of the *Knorr* and *Meiring Naudè* hydrographic data of 1983 whilst Valentine *et al.* (1993) broadly define the characteristics of the Thermocline and Deeper waters yet fail to define the Surface water masses of the Agulhas Retroflection. In fact, most hydrographic studies of the Retroflection region have subscribed to a rather qualitative approach concerning the water masses. Gordon (1981, 1985 and 1986) restricted his studies to the thermocline waters of the Retroflection whilst Chapman *et al.* (1987) and Chapman (1988) restricted their analysis to the surface waters of the Retroflection region. It seems that detailed analyses of the water masses of the Agulhas Retroflection have been overshadowed by recent research interest in the dynamics of the Retroflection region alone.

A summary of the major findings of the water mass analysis is presented below.

Tropical Surface Water (TSW) is identified within the Agulhas Retroflection, assuming the form of a narrow stream ($< 35 \text{ km}$) located along the surface core of the Current, and becoming increasingly discontinuous along the length of its' path. No evidence of TSW is found within any of the Agulhas vortices sampled during the *SCARC*.

SSW dominates the interior of the Agulhas Retroflection and the core of all the Agulhas vortices (except A1). In fact, a Modified type of SSW ($>35,63$) is evident in the majority of the Agulhas vortices, resulting from evaporation processes over the Retroflection region. It is suggested that this MSSW may be a useful tracer for Agulhas vortices since this water type is not found in the Agulhas Current since it is only formed within discrete Agulhas vortices that are isolated from the Agulhas Current. Consequently, Eddy A6 does not exhibit MSSW in its surface core.

Subtropical Mode Water (STMW) ($16,5 - 17,8^{\circ}\text{C}$; $[\text{O}_2] > 5,2$) is identified within the Retroflection region and is identified beneath the deep mix layer of the majority of SCARC vortices. This STMW signature ranges in thickness (50 - 80 m) and is only identified in those vortices which do not exhibit surface mixed layers that are too deeply developed.

Tropical Thermocline Water (TTW) is the most common surface water mass within the Retroflection region. A shallow oxygen minimum layer is observed (65 - 140 db) within the TTW of the surface thermal core of the Agulhas Current. Despite the usefulness of this shallow minimum in tracing core Agulhas Water, none of the six vortices exhibit this feature due to mixed layer deepening which erodes (ventilates) the oxygen minimum layer.

Fresh and saline varieties of Central Water are identified. The Θ/S properties of the Central Waters within the core of the Agulhas vortices are distinctly linear, with an increased step-like Θ/S profile as one moves away from the centre of the vortex. This result is indicative of enhanced interleaving of water masses at the vortex edge.

Deep stads of Subantarctic Mode Water (SAMW) are identified within the core of Rings A1 and A2, ranging in thickness of between 100 - 180 m. These SAMW stads are more pronounced than the single SAMW signal evident in the near-shore edge of the Agulhas Current input (only 80 m thick). The increased thickness of SAMW within Agulhas vortices may be due to stretching or concentration of the source thermocline water during the process of ring shedding.

The contrasting Θ/S characteristics of Antarctic Intermediate Water (AAIW) and Red Sea Water (RSW) are identified. The range of thermochemical characteristics that may evolve through a blend of these two water masses of opposing character is recognized.

Thick stads (200 - 300 m) are identified within the core of the Agulhas Current with weaker remnants identified within the core of some of the Agulhas vortices.

The Deep Waters of the Retroflexion region are identified, dominated by an invasion of NADW into the Circumpolar Waters (splitting them into an Upper and Lower layer). I identify and define for the first time Upper Circumpolar Deep Water (UCDW) and Lower Circumpolar Deep Water (LCDW) within the Agulhas Retroflexion region. Both Gordon *et al.* (1987) and Bennett (1988) identify UCDW and LCDW within the Retroflexion region yet do not define them critically. A weak signal of Indian Deep Water is identified from a single *Discovery 165A* CTD station within the Agulhas input. The location of these Deep Waters are consistent with the expected passage of these water masses as described by Gordon's (1985) "Thermohaline Conveyor Belt", with Antarctic Bottom Water (AABW) residing in the deepest part of the Agulhas Basin (> 3900 db).

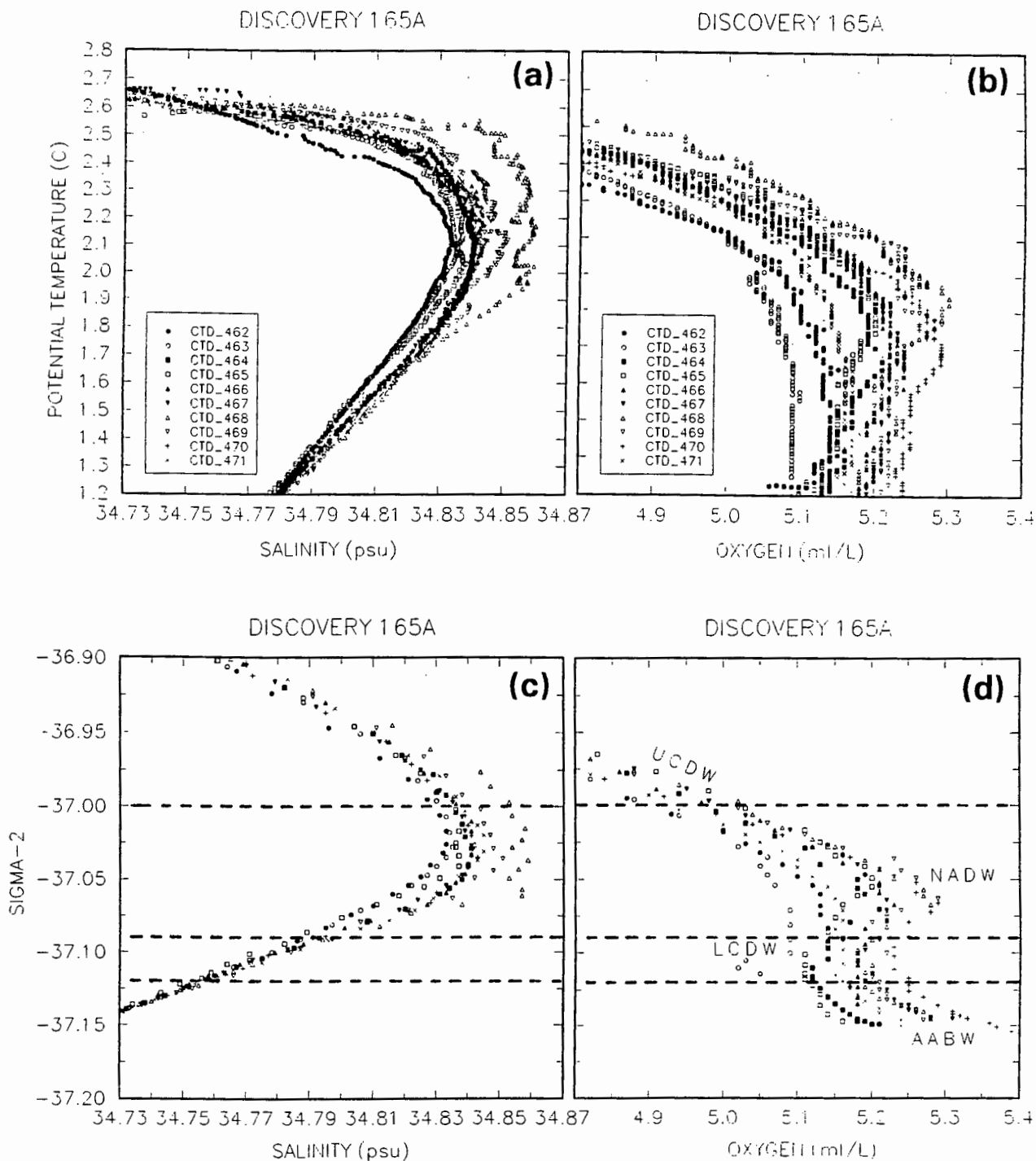


Figure 6.16: Multiple Potential Temperature - Salinity (a), Potential Temperature - Oxygen (b), Sigma-4 - Salinity (c) and Sigma-4 - Oxygen (d) plots of the Deep (and Bottom) Waters of the Agulhas Retroflection, derived from the *Discovery 165A* data. Water masses are labeled: Upper Circumpolar Deep Water (UCDW), North Atlantic Deep Water (NADW), Lower Circumpolar Deep Water (LCDW) and Indian Deep Water (IDW). The S-shaped oxygen inflection points of 37,00; 37,09 and 37,12 are shown on Figures 6.16c & 6.16d as dotted lines.

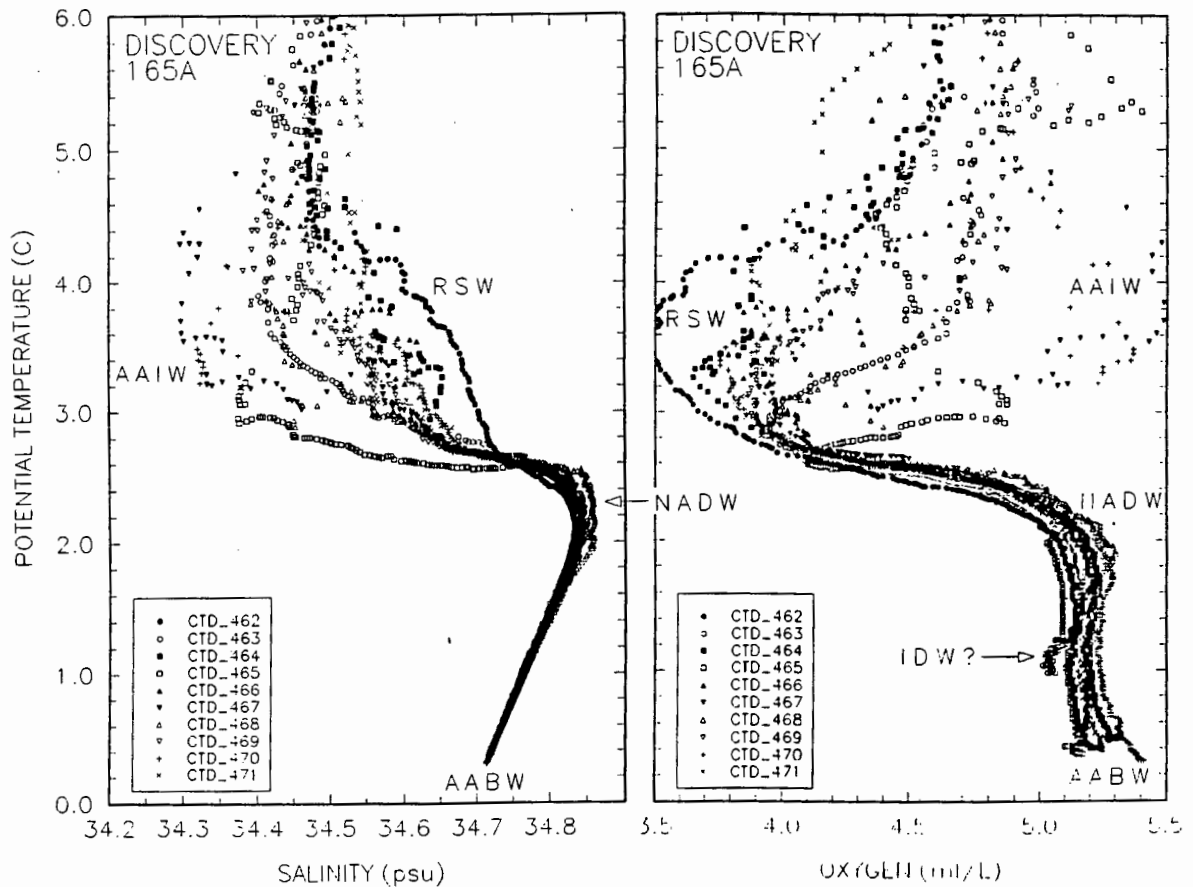


Figure 6.17: A "zoomed in" Multiple Potential Temperature - Salinity - Oxygen ($\Theta/S/O_2$) plot of the ten *Discovery 165A* CTD data. The relevant water masses are labeled as follows:

Red Sea Water (RSW), Antarctic Intermediate Water (AAIW), North Atlantic Deep Water (NADW), Indian Deep Water (IDW) and Antarctic Bottom Water (AABW). Notice the well-defined base of the Intermediate Waters ($T = 2.65^\circ\text{C}$) revealed by the multiple Θ/O_2 plot, beneath which the "tight" $\Theta/S/O_2$ space of the Deep and Bottom Waters are encountered.

CHAPTER 7

RESULTS AND DISCUSSION ON THE THERMOHALINE MODIFICATION WITHIN THE AGULHAS RETROFLECTION REGION

From the results presented in **Chapters 5 and 6** it is apparent that the waters within the Agulhas Retroflection are continually being modified by their surroundings. **Chapter 7** seeks to quantify the modification of these waters, and in so doing, fulfills the third and final objective of the thesis. To address this modification problem a heat and salt anomaly analysis of the *SCARC* data is presented. The waters of the Retroflection region are assumed to constitute a foreign environment. Pure Agulhas Water invades this environment from the northeast and is contaminated along its path by the water within the Retroflection region. Heat and salt anomalies are estimated throughout the Retroflection region, referenced to the Agulhas input of "pure" Agulhas Water. The results of the analysis presented below essentially quantify the contamination of Agulhas Water by the waters residing within the Retroflection region.

In order to estimate these heat and salt anomalies within the Agulhas Retroflection region, a suitable Agulhas input reference station is required. *SCARC* station CTD_054 is chosen to best represent the Agulhas Current input since it is located within the deep dynamical core of the Current, outside the near-shore surface thermal core of fresh Tropical Surface Water (TSW). For this reason, CTD_054 has a numerically larger near-surface salinity than either of the reference stations used by Gordon *et al.* (1987). As is mentioned earlier, stations CTD_056 and CTD_055 (located in the surface thermal core of the Agulhas input) exhibit fresh Tropical Surface Water. Since this thesis is interested in the thermohaline modification of Agulhas Water through the Retroflection region, the more saline station CTD_054 was chosen over the "fresher" near-shore Agulhas input stations. Integrated heat and salt anomalies are calculated between common potential density surfaces for all 55 *SCARC* CTD stations, referenced to the single Agulhas input station (CTD_054).

7.1) Salt Anomalies

Warm Indian Ocean Water advected into the Retroflexion region is exposed to a relative cold atmosphere and therefore experiences cooling (Bunker, 1980; Walker and Mey, 1988). Following the argument proposed by Gordon (1981), positive salt anomalies are likely to occur in the surface waters above the thermocline as a product of local cooling through evaporation. This is the case for many other current systems where warm-core rings are shed from western boundary regimes and drift into regions of strong surface cooling (eg. Gordon, 1981; Rochford, 1983; Olson *et al.*, 1985; Schmitt and Olson, 1985).

Figure 7.1a shows the salt anomalies (SA's) for all the *SCARC* CTD stations. Although there are weak positive SA's in the Surface (24,2 - 26,0 kg.m⁻³) and Intermediate Waters (26,9 - 27,3 kg.m⁻³), strong negative anomalies (SA < -1,0) are centered within the Surface and Thermocline Waters (25,4 - 26,6 kg.m⁻³). The Surface and Thermocline Waters within the potential density range (25,8 - 26,6 kg.m⁻³) seem to be dominated by these (strong) negative SA's (although the main Retroflexion and eddy core stations exhibit weakly negative SA's). In other words, water masses within the Retroflexion region become more like those of the South Atlantic water masses with increasing depth. The Retroflexion region can be perceived to consist of South Atlantic water masses which are been invaded from the northeast by Agulhas water and by Subantarctic waters masses from the south. From the SA results illustrated in Figure 7.1a it seems that the SA's are always near-zero or negative at potential densities equal to and exceeding 27,4 kg.m⁻³. Unfortunately, the *SCARC* data do not extend much deeper than the 27,5 kg.m⁻³ potential density surface. However, one would expect these anomalies to become negligible within the core Deep Waters (27,80 kg.m⁻³) of the Retroflexion region. The *SCARC* SA's therefore suggest that Indian Ocean Water enters the Retroflexion at potential densities not exceeding 27,4 kg.m⁻³ (1000 - 1400 db).

Figures 7.1b and 7.1c illustrate the relative contribution of the *SCARC* vortex centre stations and Subantarctic stations respectively, to the overall trend illustrated in Figure 7.1a. The SA's within the Agulhas vortices are generally positive and only become negative at about the 26,9 - 27,0 kg.m⁻³ potential density layer (700 - 950 db). A noticeable exception is Ring A1. Figure 7.2 shows a "zoomed-in" plot of Figure 7.1b, exaggerating the y-axis. Contrary to expected, positive SA's within the centre of Ring A2 and Eddies A3, A4 and A5 are not restricted to those waters above the thermocline.

Indeed, these four vortices exhibit (weakly) positive anomalies to well within the Lower Thermocline and Intermediate Waters. Although most of the six centre stations exhibit positive SA's within the Intermediate Waters (barring perhaps A4 - $27,2 \text{ kg.m}^{-3}$), they do seem to exhibit a mixture of Atlantic AAIW and RSW. This confirms the volume trapping and water mass results presented in **Chapters 5 and 6** which suggest that Agulhas vortices are capable of trapping water to Intermediate depths. Notice that Ring A1 and Eddy A6 are anomalously fresh throughout the their Surface and Thermocline Waters as a result of the entrainment of South Atlantic and Subantarctic waters into their cores.

Interestingly, the only station that exhibits anomalously saline surface water (and is not described by the centre stations of the six *SCARC* vortices) is CTD_007. This station is the northernmost station of the *SCARC* survey and displays the greatest positive surface SA ($\text{SA} = 0,142; 25,0 \text{ kg.m}^{-3}$), located some 880 km from the Retroflexion centre. This strong positive SA is not only restricted to the Surface and Thermocline Waters but also extends to depths well within the Intermediate Waters ($\text{SA} = 0,173; 27,2 \text{ kg.m}^{-3}$), where remnant RSW is identified. The anomalously saline Surface to Intermediate Waters of station CTD_007 suggest that this station may possibly have located yet another feature of Agulhas origin. Unfortunately no evidence of such a feature is observed in the satellite data.

Figure 7.1c shows the classic SA signal characteristic of waters of Subantarctic origin. Interestingly, station CTD_038, which is located within the Subantarctic filament (C1), displays a weakened negative SA contribution in the Surface Waters ($25,7 - 26,0 \text{ kg.m}^{-3}$), beneath which an intrusion of Subantarctic water extends to a depth of about 270 db ($26,9 \text{ kg.m}^{-3}$). The SA characteristics (supported by $\Theta/\text{S}/\text{O}_2$ properties) indicate that water of Agulhas origin plunges beneath the anomalously fresh intrusion, wherein positive identification of RSW is made. A possible source of this anomalously saline Intermediate Water could be the Agulhas plume to the east, extending from the southern terminus of the Agulhas Retroflexion.

It seems that Agulhas vortices are continually losing heat to their surroundings. In addition, they experience salinity boosting within their surface waters through evaporative processes. Are these heat and salt anomaly estimates useful in evaluating the relative age of these Agulhas vortices within the Retroflexion region? Consider a recently spawned Agulhas ring or eddy. Such a feature would have had insufficient time for substantial modification of its' surface waters by evaporation, and would

therefore display a SA (relative to its source) of about zero in its' core surface waters. In this regard, only Eddy A6 can be considered to have been recently shed from the Agulhas Current (or was possibly still interacting with the Agulhas Current during the period when it was hydrographically sampled). Ring A1 is atypical since its entire Surface and Thermocline Waters are contaminated by water of Subantarctic origin (identified as a strong negative SA - Figure 7.1b). Since the SA's for the Agulhas vortices generally seem to change sign at about $26,9 \text{ kg.m}^{-3}$, total salt (and heat) anomalies are calculated in two layers for all the stations relative to the Agulhas input station (CTD_054). The upper layer (surface to $26,9 \text{ kg.m}^{-3}$) anomalies can be expected to be influenced primarily by air-sea interaction (and to a lesser extent lateral mixing), whilst the lower layer ($26,9$ to $27,5 \text{ kg.m}^{-3}$) is isolated from the atmosphere and modified primarily by mixing with the surrounding waters. As one moves away from the Retroflection the heat : salt anomaly ratio for the stations at the centre of the rings and eddies in the upper layer is expected to decrease as the salinity increases (evaporation) and the heat decreases (due primarily to latent heat fluxes to the overlying atmosphere). Perhaps this heat : salt anomaly ratio could "age" the vortices? The results for the eddy centre stations in the upper and lower layer are shown in Table 13.

Table 13: (Heat / Salt) Anomaly Ratios for the upper and lower potential density strata within the six Agulhas rings and eddies sampled during the SCARC.

Feature	Station	(Heat / Salt) Upper	Rank	(Heat / Salt) Lower	Rank
Ring A1	CTD_005	1,34	4	2,65	3
Ring A2	CTD_012	0,84	5	2,66	2
Eddy A3	CTD_016	0,73	6	1,27	6
Eddy A4	CTD_030	1,71	3	2,46	5
Eddy A5	CTD_037	2,39	1	2,73	1
Eddy A6	CTD_048	1,74	2	2,47	4
Upper	Surface to $26,9 \text{ kg.m}^{-3}$				
Lower	$26,9 - 27,5 \text{ kg.m}^{-3}$				

Ranking the heat : salt anomaly (HA : SA) ratios reveals Eddy A5 as the "youngest" according to the above definition (a result confirmed by satellite altimetric data (see Figure 4.2). Eddy A6 (which may have been interacting with the Agulhas Current at the time) ranks second youngest. However, although some sense of ageing of the respective vortices is possible from the heat : salt anomaly ratio, caution must be taken since the assumption that lateral mixing is negligible compared to that of latent heat loss and evaporation, may be poorly adhered to.

The surface waters within the *SCARC* rings and eddies (barring A1 and A6) exhibit the most intense positive salt anomalies ($0,05 \leq SA \leq 0,21$) within the Retroflection region. The positive anomalies within the four Agulhas vortices mentioned above are associated with their atmospherically modified surface pycnostads, marking the salinity maximum of the Modified Subtropical Surface Water. It is important to note that any thickening of a density layer will markedly increase the integrated salt (and heat) anomaly estimated for that layer. Consequently, increased anomalies are estimated for the deeply developed surface pycnostads characteristic of Agulhas vortices. In addition to these thick surface pycnostads within Agulhas rings and eddies, the *Discovery 165A SeaSoar* potential density sections also reveal relatively deep surface pycnostads (± 50 db) within the Agulhas Retroflection (see Read *et al.*, 1987). Table 14 below provides a summary of the surface pycnostads within the centre of all six rings and eddies sampled during the *SCARC*. Notice yet again the anomalously low surface salinities of Ring A1 and Eddy A6. The low salinities of A1 are attributed to "contamination" by the northward intrusion of Subantarctic filament (C1). The surface salinities over Eddy A6 are of the order of the Agulhas input, indicating that there has been relatively little modification of the surface waters of A6.

Increased salt (and heat) anomalies associated with the surface pycnostads of the Agulhas vortices are noted above. Similarly, increased anomalies can be expected within subsurface pycnostads. This is particularly true for the Subtropical and Subantarctic Mode Waters. **Chapter 6** identifies the thermohaline characteristics of these stads observed in the *SCARC* data. Indeed, the vertical extent of these stads are illustrated in Figure 5.37, showing the positive SA's trapped within the Agulhas vortices.

Surface Salt Anomalies

The salt anomalies of the surface waters, calculated between potential density layers ($25,5 - 25,6 \text{ kg.m}^{-3}$) and ($25,9 - 26,0 \text{ kg.m}^{-3}$), are shown in Figures 7.3 and 7.4 respectively. These density layers identify the relatively strong salt anomalies ($SA \geq 0,000$) within the surface waters of four *SCARC* vortices (A2, A4 and A5). Notice that Ring A1 and Eddy A6 exhibit strong and weakly negative SA's respectively.

The potential density layer ($25,9 - 26,0 \text{ kg.m}^{-3}$; Figure 7.4) is situated deeper than the expected subsurface salinity maximum of the South Indian Ocean SSW. Consequently, the SA's are approximately zero (or weakly negative) within the Agulhas vortices. Ring A2 and Eddy A5 are the only mesoscale features that exhibit positive SA's along this density stratum, implying that either Modified Subtropical Surface Water (MSSW) is mixed down to this density surface within these two vortices, or there may be evidence of STMW within this density layer. Indeed, Ring A2 does exhibit STMW within its core (see **Chapter 6**), whilst Eddy A5 exhibits a deep surface mixed layer (158 db) of MSSW (described in **Chapters 5 and 6**). Although MSSW and STMW exhibit similar Θ/S characteristics, MSSW is not to be confused with STMW since MSSW is formed only in Agulhas vortices and can be formed all year round. By virtue of its formation process, MSSW is also always restricted to above the thermocline within Agulhas vortices in the Retroflection region.

The inshore edge of the Agulhas input (CTD_056 & CTD_055) shows evidence of negative salt anomalies ($-0,135$ and $-0,355$ respectively), representing the less saline Tropical Thermocline Water (and associated shallow oxygen minimum layer) described earlier. However, low salt anomalies are most intense in the southern and western areas of the *SCARC* grid, outside of the main Retroflection region. Negative SA's in excess of $-0,500$ are confined to the southwestern region of the *SCARC* hydrographic survey. These negative anomalies generally prograde further into the Retroflection region with increasing potential density, often in the form of filamentous intrusions entrained around the perimeter of the Agulhas vortices. These strongly negative SA intrusions are most likely a mixture of Subantarctic and South Atlantic Water. This South Atlantic Water is formed from a combination of Thermocline Water and Subantarctic Surface Water (perhaps within the Brazil-Falkland Confluence region (Gordon, 1981)).

Salt Anomalies within the Upper and Lower Thermocline

The potential density stratum ($26,4 - 26,5 \text{ kg.m}^{-3}$) is selected to represent the majority of the Upper Thermocline Waters of the Retroflection region (although this density layer is less representative of the Upper Thermocline Waters for the Subantarctic stations to the south). Figure 7.5 illustrates the SA's associated within this potential density stratum. Negative SA's dominate the Retroflection region within this layer, with weakly negative SA's ($0,000 \leq SA \leq -0,250$) restricted to the Agulhas Retroflection and Agulhas vortices (barring A1). The most notable feature in Figure 7.5 is the northward intrusion of Subantarctic filament (C1) along the eastern perimeters of Eddies A5 and A4 ($-0,500 \leq SA \leq -0,940$). Eddy A4 is the only vortex to display a positive salt anomaly ($SA = 0,012$), indicating that there is still MSSW at this level.

Table 14: A summary of the characteristics of the surface pycnostads of the Agulhas Current input and the six Agulhas vortices of the SCARC.

Feature	Station	Depth of Pycnostad (db)	Potential Temperature Range (°C)	Salinity Range (psu)	Potential Density Range (kg.m^{-3})
Ring A1	CTD_005	0 - 30	17,79 - 17,29	34,93 - 34,89	25,26 - 25,35
Ring A2	CTD_012	0 - 50	20,36 - 20,18	35,81 - 35,79	25,28 - 25,31
Eddy A3	CTD_016	0 - 100	19,00 - 18,92	35,74 - 35,73	25,57 - 25,60
Eddy A4	CTD_030	0 - 125	18,86 - 18,83	35,72 - 35,72	25,60 - 25,63
Eddy A5	CTD_037	0 - 150	17,57 - 17,41	35,66 - 35,62	25,85 - 25,92
Eddy A6	CTD_048	0 - 125	17,82 - 17,07	35,58 - 35,56	25,83 - 25,93
Ag C	CTD_054	0 - 30	23,69 - 23,67	35,56 - 35,56	24,20 - 24,29

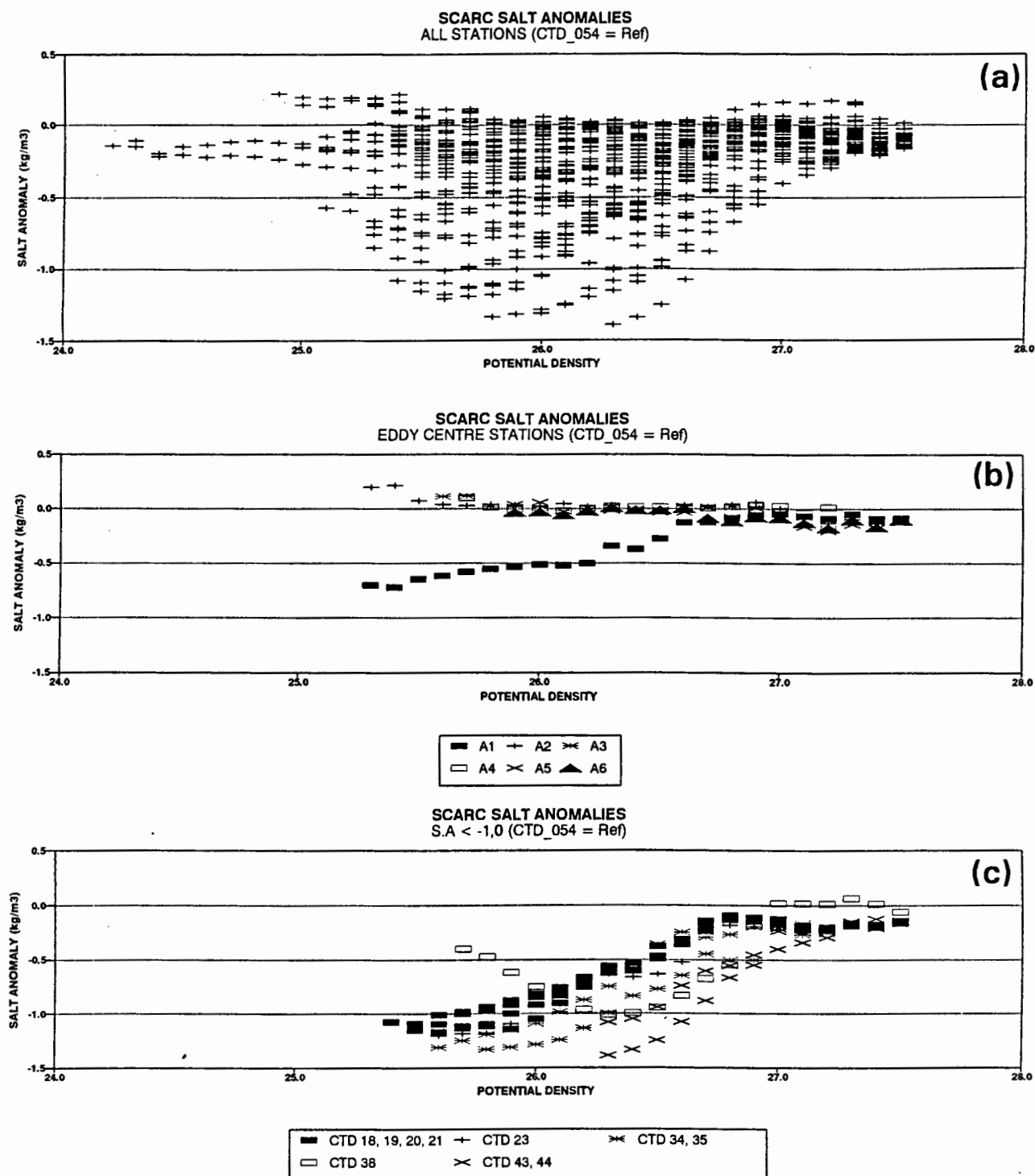


Figure 7.1: Integrated salt anomalies between common potential density surfaces for:

- a all the *SCARC* CTD stations
- b the center stations of all six *SCARC* rings and eddies
- c all *SCARC* Subantarctic stations

The salt anomalies are referenced to the Agulhas input (CTD_054).

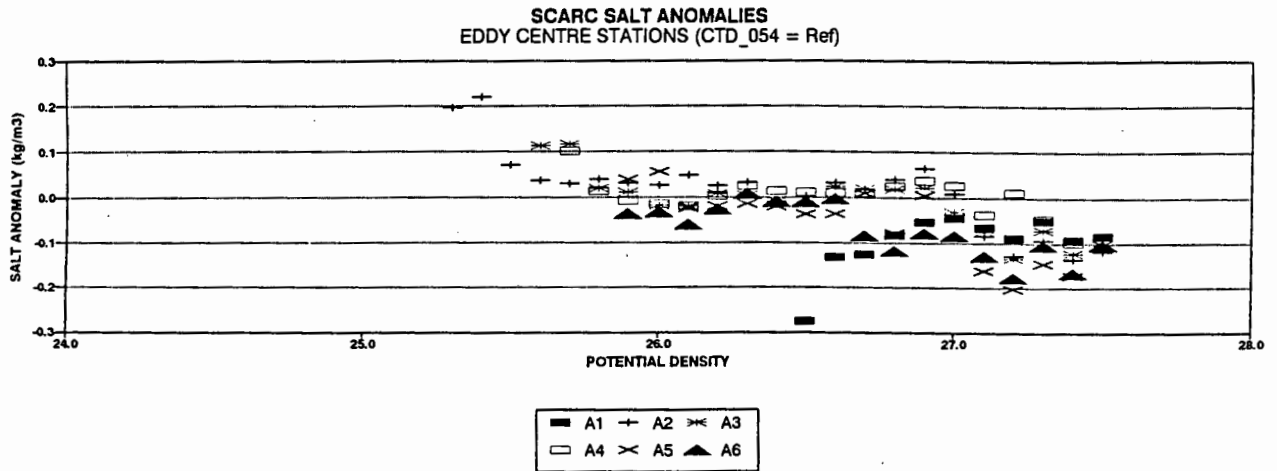


Figure 7.2: A "zoomed-in" plot of Figure 7.1b showing the integrated salt anomalies between common potential density surfaces for the centre stations of all six SCARC CTD stations. The salt anomalies are referenced to the Agulhas input (CTD_054).

The potential density stratum ($26,7 - 26,8 \text{ kg.m}^{-3}$) has been chosen to represent the majority of the Lower Thermocline Waters of the Retroflexion region. Figure 7.6 shows that most of the waters of the Retroflexion region exhibit weakly negative anomalies ($0,000 \leq SA \leq -0,250$) within this layer. Relatively strong positive SA's appear to exist within Ring A2 and Eddies A3 and A4 ($0,001 \leq SA \leq 0,040$). The reappearance of a positive salt anomaly within Ring A2 and Eddy A3 at the Lower Thermocline level may be attributed to the appearance of a relatively strong (and somewhat weaker) SAMW signal within this stratum. Interestingly, CTD_007 exhibits a remarkably strong positive SA ($SA = 0,107$). The reason for this strongly positive SA is also a result of SAMW identification, possibly indicative of an additional feature of Agulhas origin noted earlier.

Salt Anomalies within the Intermediate Waters

The potential density stratum ($27,2 - 27,3 \text{ kg.m}^{-3}$) has been chosen to represent the majority of the Intermediate Waters of the Retroflexion region. It is within this density stratum that remnant RSW may reside. Such a warm, saline signal can only be derived from the southeast Indian Ocean. Figure 7.7 shows that most of the SA's west of the Agulhas Retroflexion are all weakly negative ($-0,050 \leq SA \leq -0,150$). This is not surprising since the Agulhas input reference station (CTD_054) exhibits Red Sea Water (RSW) contamination within this stratum, and therefore produces somewhat less saline

anomalies (more negative) results than expected. Nevertheless, Figure 7.7 clearly shows that RSW is evident in Rings A1 & A2 and Eddy A4 ($-0,018 \leq SA \leq -0,049$), which suggests that these three Agulhas vortices can trap "South Indian" Intermediate Water within their vortices.

Strong positive anomalies ($0,038 \leq SA \leq 0,152$) are also associated with the introduction of "pure" RSW from the Agulhas Retroflection into the Agulhas shear-edge plume (CTD_040 - CTD_042). This is a remarkable result considering that the Agulhas reference station also has strong RSW contamination within its' Intermediate Waters (which would favour near-zero to negative SA's).

The most negative salt anomalies ($-0,195 \leq SA \leq -0,150$) are restricted to the southwestern region of the *SCARC* grid, and are considered to exhibit no contamination of Atlantic AAIW by RSW remnants. The weakly negative SA's down-stream of the Agulhas Retroflection suggest that the Return Current may transport Atlantic AAIW characteristics into the South Indian subtropical gyre.

7.2) Heat Anomalies

The heat anomalies (HA's) of the *SCARC* are estimated in much the same way as the salt anomalies. The results of this analysis are presented in Figures 7.8a, 7.8b and 7.8c. These results bear striking resemblance to the SA's presented in **Chapter 7**. The only noticeable difference between the results of the salt and heat anomaly analysis is that the HA's in the surface waters of the Agulhas vortices seem to drop rapidly to near-zero within their surface waters ($25,6 - 28,8 \text{ kg.m}^{-3}$). This result emphasizes the major contribution of heat loss to the atmosphere within the Agulhas Retroflection region. Since the HA's are referenced to the Agulhas input one would expect the surface heat anomalies to always be near-zero or negative (since solar heating of the surface waters of the Retroflection region is negligible). However, the HA's of the surface waters of Ring A2 and Eddies A3, A4 and A5 are all weakly positive. This result suggests that the HA's of the surface waters of the Agulhas input station (CTD_054) are too small. Indeed, CTD_054 lies outside of the surface thermal core of the Agulhas Current, causing weakly positive HA's in the surface waters of the vortices mentioned above. The surface pycnostads, characteristic of Ring A2 and Eddies A3, A4, A5 and A6 (see Table 14), further contribute to produce weakly positive HA's within the Agulhas rings and eddies.

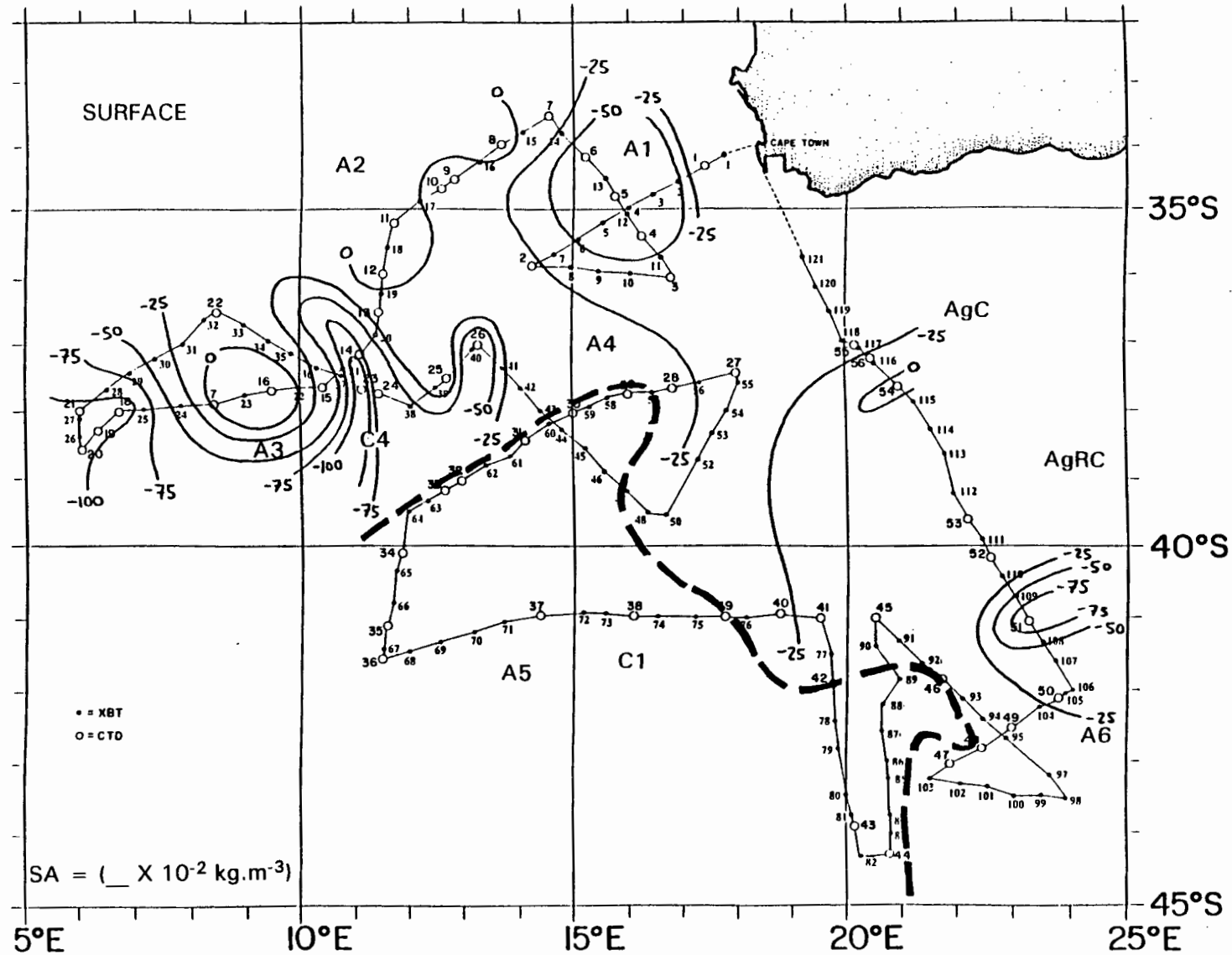


Figure 7.3: Surface salt anomalies ($\times 10^{-2} \text{ kg.m}^{-3}$) integrated within the potential density stratum ($25,5 - 25,6 \text{ kg.m}^{-3}$), superimposed on the SCARC cruise track. The salt anomalies are referenced to the Agulhas input station (CTD_054). The broken line indicates where this density stratum breaks the surface.

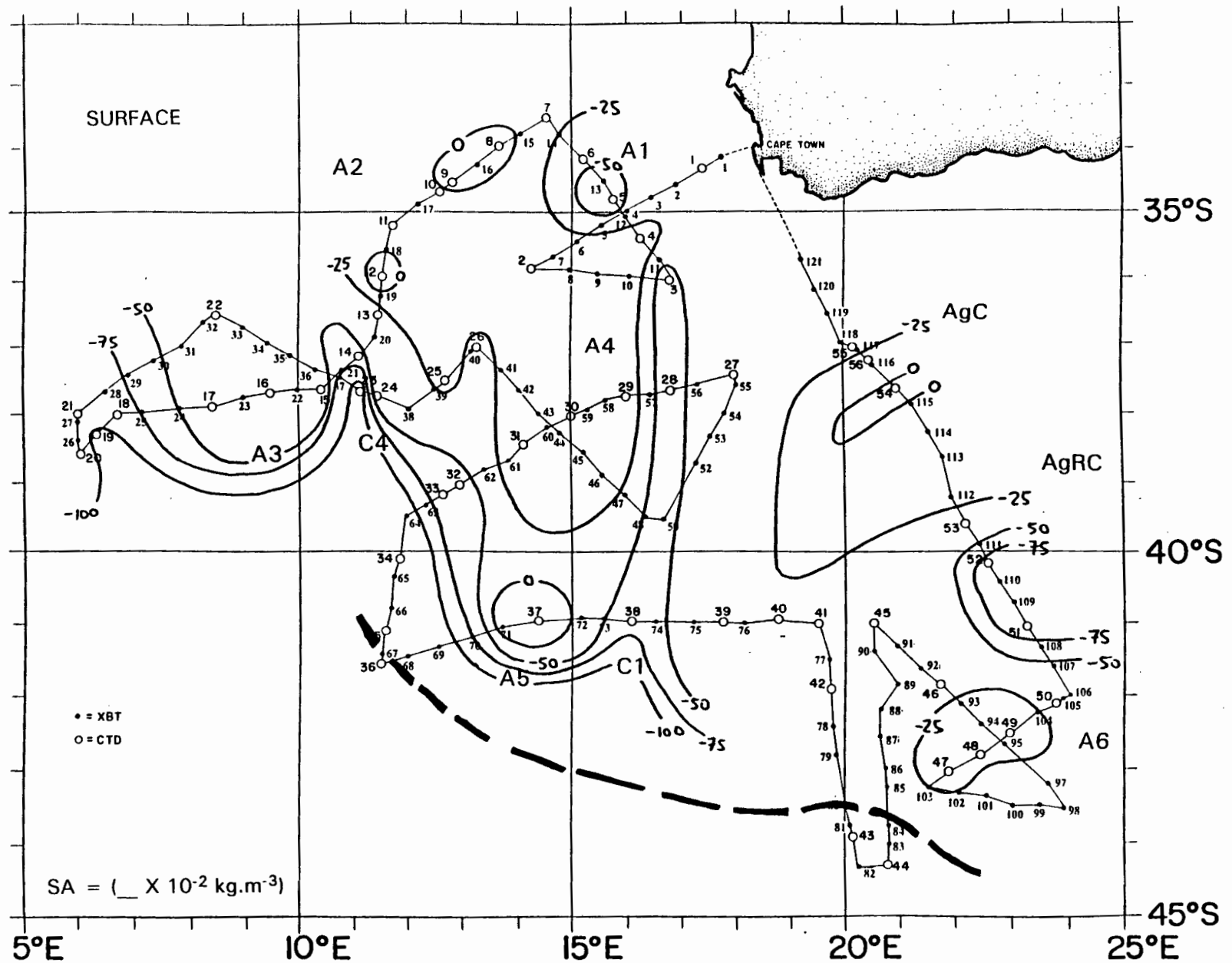


Figure 7.4: Surface salt anomalies ($\times 10^{-2} \text{ kg.m}^{-3}$) integrated within the potential density stratum ($25,9 - 26,0 \text{ kg.m}^{-3}$), superimposed on the SCARC cruise track. The salt anomalies are referenced to the Agulhas input station (CTD_054). The broken line indicates where this density stratum breaks the surface.

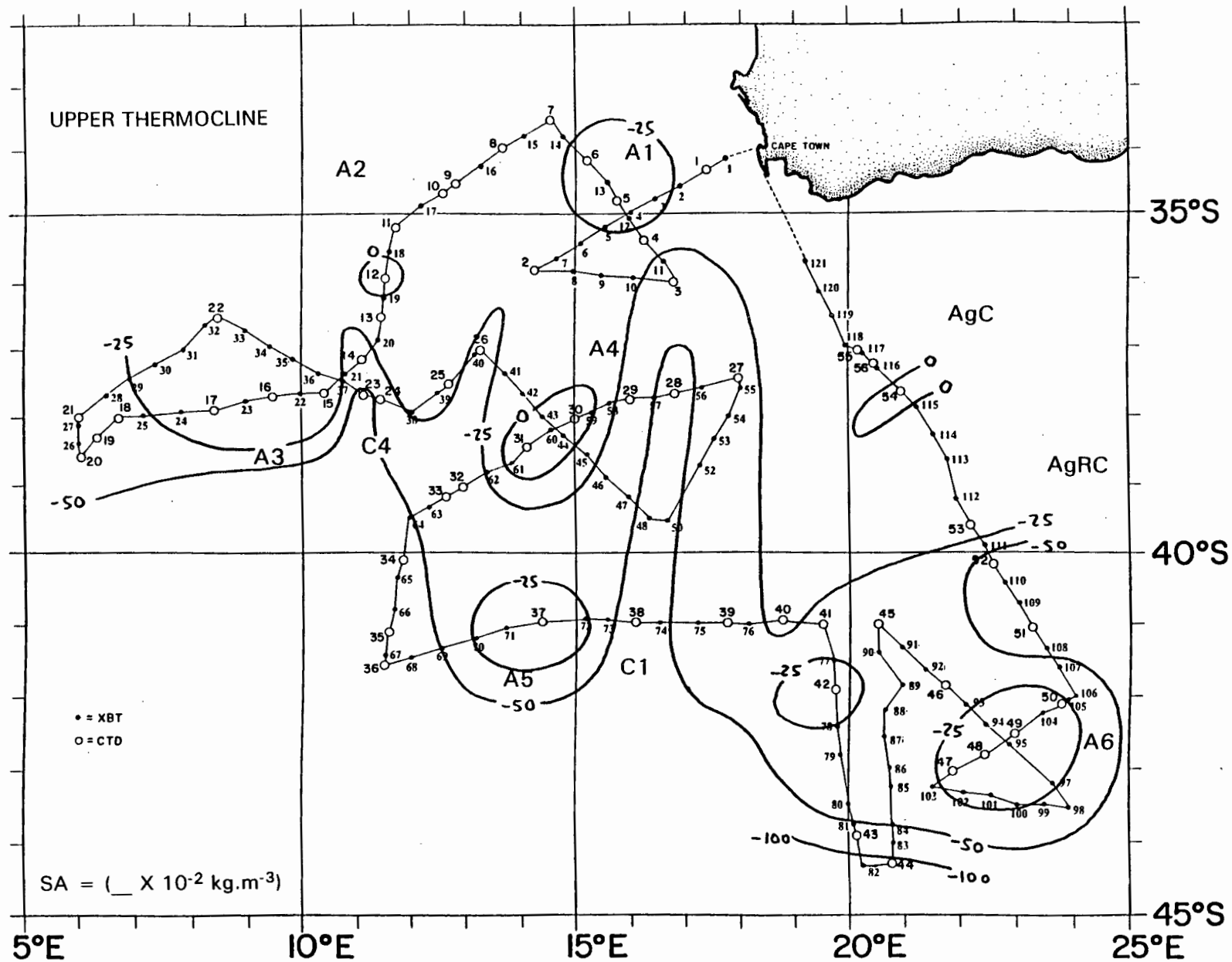


Figure 7.5: Upper thermocline salt anomalies ($\times 10^{-2} \text{ kg.m}^{-3}$) integrated within the potential density stratum ($26,4 - 26,5 \text{ kg.m}^{-3}$), superimposed on the SCARC cruise track. The salt anomalies are referenced to the Agulhas input station (CTD_054).

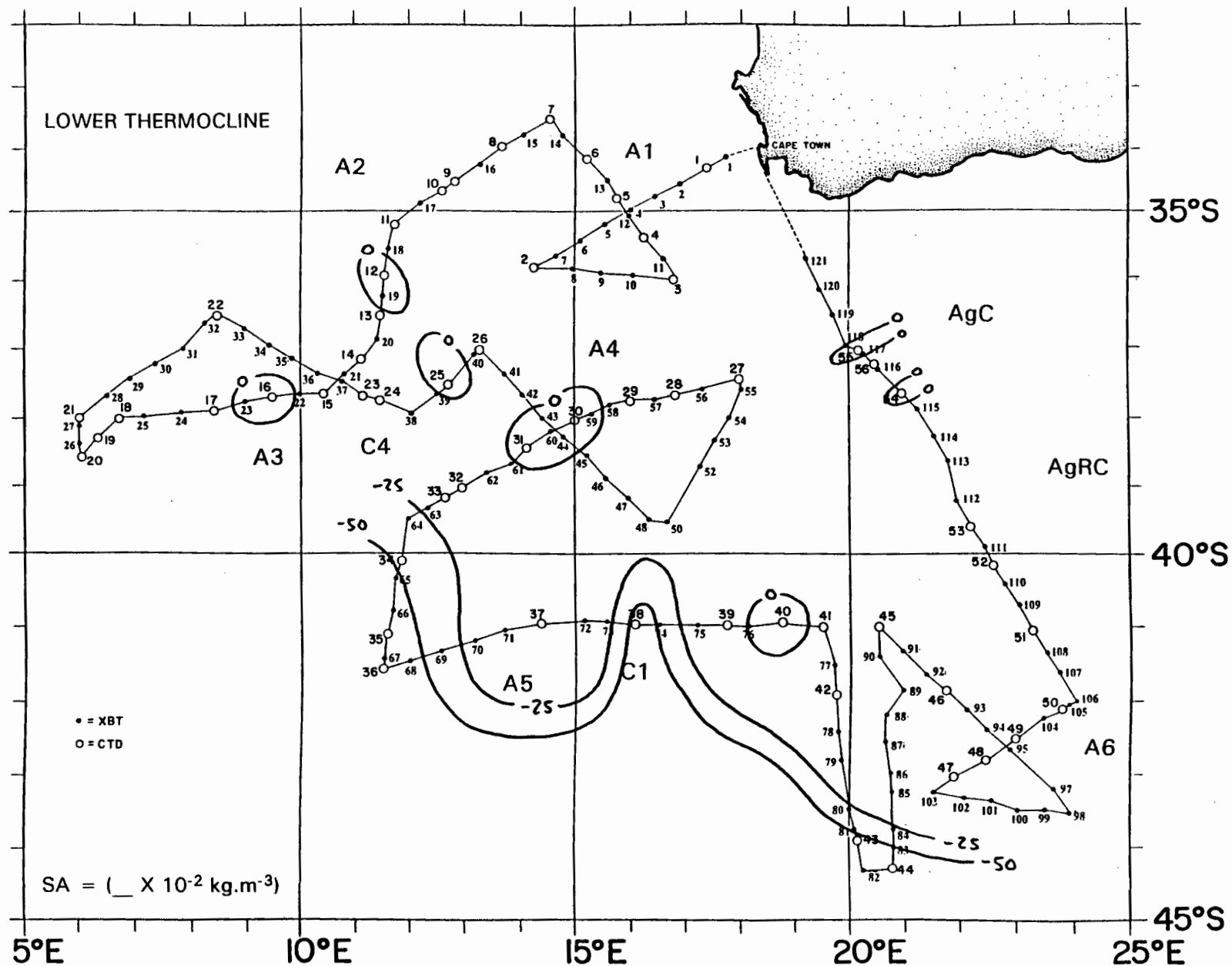


Figure 7.6: Lower thermocline salt anomalies ($\times 10^{-2} \text{ kg.m}^{-3}$) integrated within the potential density stratum (26,7 - 26,8 kg.m^{-3}), superimposed on the SCARC cruise track. The salt anomalies are referenced to the Agulhas input station (CTD_054).

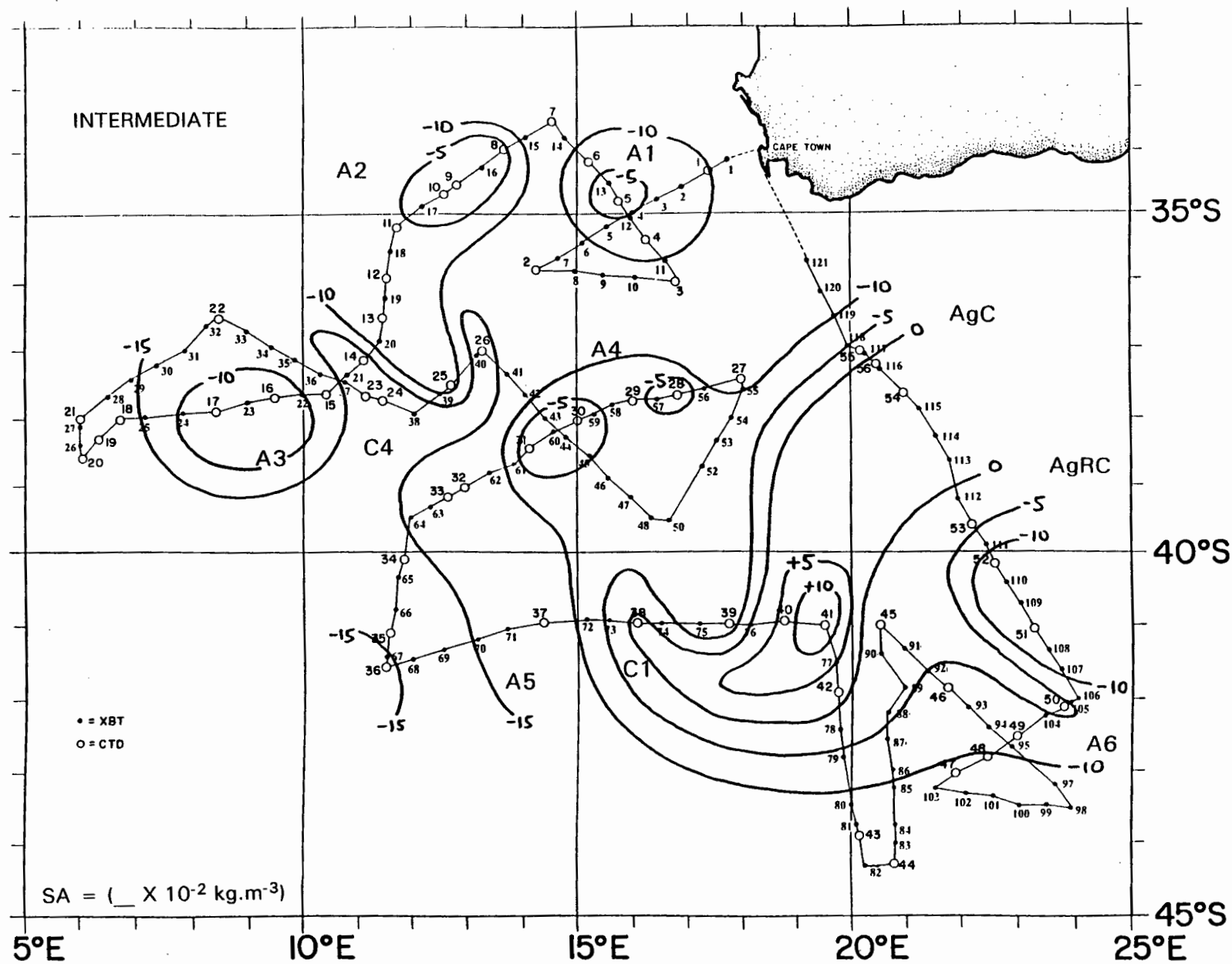


Figure 7.7: Intermediate salt anomalies ($\times 10^{-2} \text{ kg.m}^{-3}$) integrated within the potential density stratum ($27,2 - 27,3 \text{ kg.m}^{-3}$), superimposed on the SCARC cruise track. The salt anomalies are referenced to the Agulhas input station (CTD_054).

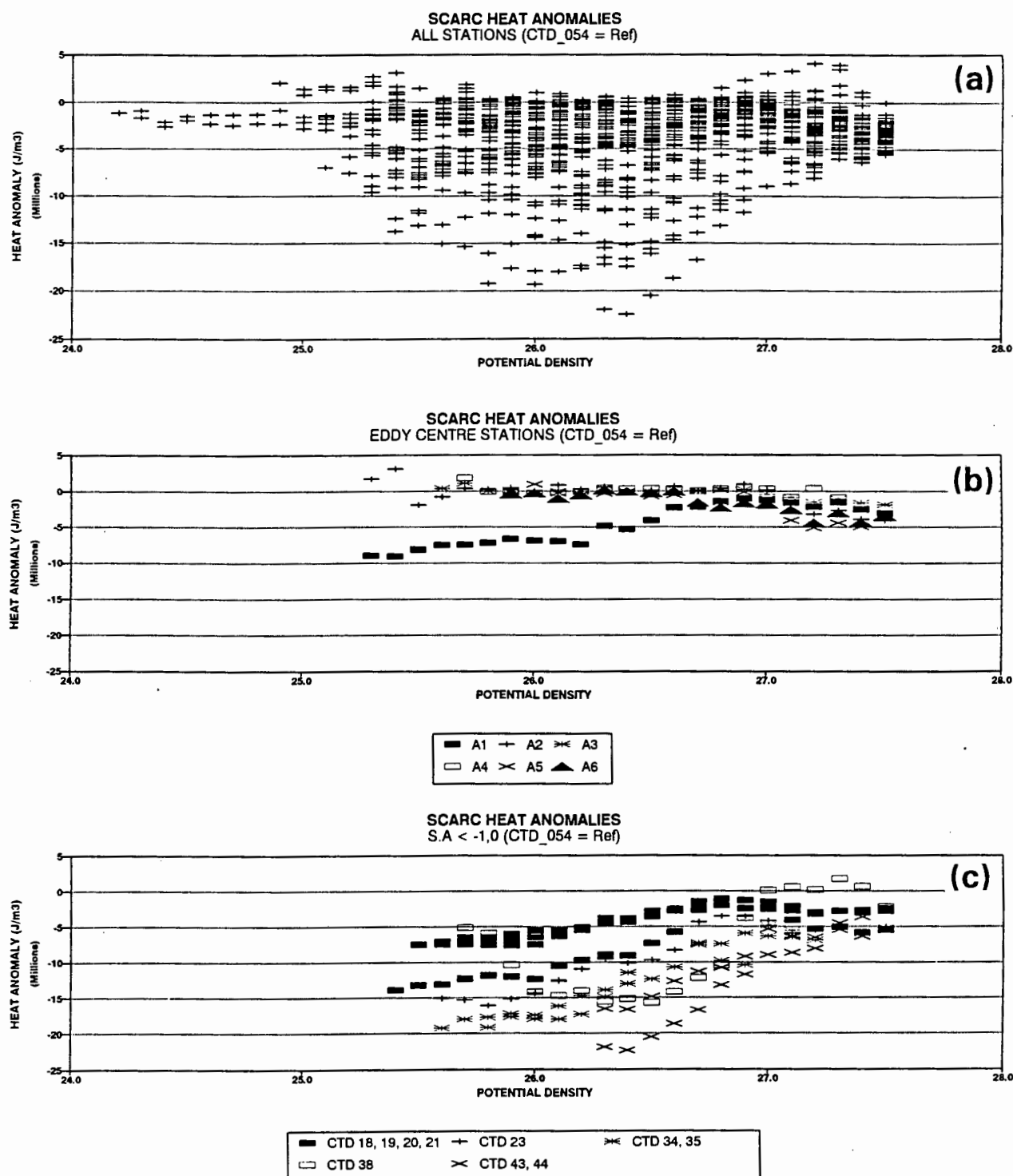


Figure 7.8: Integrated heat anomalies between common potential density surfaces for:

- a all the *SCARC* CTD stations
- b the center stations of all six *SCARC* rings and eddies
- c all *SCARC* Subantarctic stations

The heat anomalies are referenced to the Agulhas input (CTD_054).

7.3) Ocean - Atmosphere Exchange and Associated Thermohaline Modification: A Case Study

From the results presented above it is apparent that heat loss from the ocean to the atmosphere within the warm-core features of the Retroflexion region is an important process. Such heat loss from the surface cores of Agulhas rings and eddies drives convective overturning and subsequent deepening of the surface mixed layer. It is shown that the water masses comprising the surface mixed layer of the Agulhas vortices are substantially modified by these dynamic processes. Eddy A4 is chosen to illustrate this process of mixed layer deepening.

Assuming XBT_044 and CTD_030 both sampled the centre of Eddy A4, an estimate of the heat loss from the surface waters and subsequent deepening of the mixed layer is determined. The mixed layer deepened from 130 db (XBT_044) to 164 db (CTD_030) over a period of two days during the *SCARC*. Assuming the depth and temperature accuracy of the XBT to be adequate, estimates of the heat loss from the surface mixed layer of A4 are made.

A two layer model is adopted, separating the surface waters into an upper layer (0 - 130 db) and a lower layer (130 - 185 db). The lower layer is extended to 185 db so as to accommodate for mixing of the colder waters below the thermocline (see **Addendum 3**). Assuming negligible lateral mixing and allowing for the mixed layer to deepen from 130 to 164 db over two days (as observed in the hydrographic data), a net heat flux of $379,6 \text{ W.m}^{-2}$ and temperature drop due to heat loss to the atmosphere of $0,10^{\circ}\text{C}$ per day is estimated. An estimated temperature drop of $0,05^{\circ}\text{C}$ per day is caused by mixing of cold water from beneath the thermocline.

Although the above calculations are rather crude, the estimated heat flux of 379 W.m^{-2} compares well with a maximum of 400 W.m^{-2} measured by Mey *et al.* (1990) over Eddy A4 during the *SCARC*. A heat flux of 400 W.m^{-2} and deepening of the mixed layer by 34 db in two days is substantial. However, Eddy A4 was sampled during post-frontal conditions (an intense mid-latitude cyclone of 980 hP was directly over Eddy A4 during the deployment of XBT_044). It is proposed that such rapid mixed layer deepening is an episodic event, driven by extreme short-period, cold-air outbreak conditions such as those experienced by Eddy A4 on the 20 February, 1987. For direct measurements of heat fluxes encountered during the *SCARC* the reader is referred to Mey *et al.* (1990).

7.4) Conclusions on the thermohaline modification within the Agulhas Retroflection region

The Agulhas Retroflection region is perceived to consist of South Atlantic water masses which are invaded from the northeast by Agulhas Water and from the south by Subantarctic water. The Agulhas Waters are observed to enter the Retroflection region at depths not exceeding 1400 db (somewhat shallower than that estimated by Gordon *et al.* (1987)) and are continually being modified by the waters of the Retroflection. Salt (and heat) anomaly estimates (relative to the Agulhas Current input) indicate that extreme positive anomalies are present within the majority of the Agulhas vortices. These positive anomalies can extend from the Surface to depths well within the Lower Thermocline and possibly into the Intermediate Waters of Agulhas vortices. Positive anomalies within the surface layers are a result of well-developed stads of Subtropical Surface Water and Modified Subtropical Surface Water. A case study is presented illustrating the modification and deepening of a surface stad within an Agulhas eddy (A4). A surface mixed layer deepening rate of 34 m in two days is observed as a result of an estimated nett heat flux of 379 W.m^{-2} from the ocean to the atmosphere. A drop in temperature of $0,10^{\circ}\text{C}$ per day is estimated due to heat loss to the atmosphere, with a temperature drop of $0,05^{\circ}\text{C}$ per day caused by mixing of cold water from beneath the thermocline.

Positive anomalies within the Upper and Lower Thermocline layers of the Retroflection region are the result of thickened stads of Subtropical and Subantarctic Modes Waters respectively. These thickened stads seem to be restricted to the core waters of Agulhas vortices. Positive anomalies at Intermediate depths are attributed to the presence of significant Red Sea Water remnants, identified within a shear-edge plume extending from the terminus of the Agulhas Retroflection. Eddy A4 is the only vortex to exhibit significant positive anomalies within its core at Intermediate depths, identifying RSW. In addition, three other vortices (A2, A3 and A5) all exhibit a mixture of RSW, highlighting the fact that even at such depths, Indian Ocean Water is preserved within these Agulhas vortices.

Weakly negative anomalies are identified along the near-shore edge of the Agulhas input, associated with the Tropical Surface Water layer (with its shallow oxygen minimum). Negative salt (and heat) anomalies within the Surface and Thermocline layers are most intense in the southern and western areas of the SCARC grid, outside the main Retroflection region. These negative anomalies generally prograde further into

the Retroflection with increasing depth, identifying mixtures of Subantarctic and South Atlantic Water. Extremely negative salt anomalies are identified at Intermediate levels, and are restricted to the southwestern region of the *SCARC* survey. These extremely negative anomalies are associated with "Atlantic" Antarctic Intermediate Water (AAIW), uncontaminated by RSW. Evidence of weakly negative salt anomalies downstream of the Agulhas Retroflection suggests that the Agulhas Return Current may transport Atlantic AAIW characteristics into the South Indian subtropical gyre.

Gordon *et al.* (1987) present the only other salt anomaly analysis of the Retroflection region similar to the that introduced in this thesis. Gordon *et al.*'s (1987) analysis combine the *Knorr* and *Meiring Naudè* hydrographic data sets. Salt anomaly estimates in their study are also referenced to the Agulhas input (although their reference stations are slightly fresher as a result of being closer to the near-shore surface core of the Agulhas Current input). The estimated anomalies for their study are calculated on particular density surfaces (and not integrated between density surfaces as was done in this study). Such a methodology may have restricted their findings somewhat. By not integrating the anomalies between density surfaces they were not able to truly identify the anomalies associated with the thickened density layers which are associated with surface stads and Mode Waters of the Retroflection region. The results presented above suggest that the observed thickening of these layers are associated with the dynamics of the vortices. The results presented above do confirm the general trends observed by Gordon *et al.* (1987). However, in addition to Gordon *et al.*'s (1987) study, the results from the salt (and heat) anomaly analyses of the *SCARC* hydrographic data succeed in establishing the extent of modification of Agulhas Waters within the Retroflection during possibly extreme conditions. This is particularly true for the Surface and Thermocline Waters. Never before (nor since) has a hydrographic data set of the Agulhas Retroflection region been presented in which such a range of Agulhas vortices are identified. Many of these vortices exhibit extreme salinity boosting within their surface cores (in excess of 0,20 of that documented for Gordon *et al.*'s "Retroflection" and "Cape Town" Eddies). In addition, the *SCARC* data identify a most extreme invasion of Subantarctic water (filaments C1 and C4) into the Retroflection region. Such thermohaline extremes evident in the Surface and Thermocline Waters at one time make for an interesting study of the diverse range of modification these water masses experience within the Retroflection region.

CHAPTER 8

SUMMARY AND CONCLUSIONS

The Agulhas Retroflection region is an important location for the exchange of heat, salt and momentum from the southwest Indian Ocean into the southeast Atlantic Ocean. A mechanism for such interocean transfer is via the shedding of Agulhas rings and eddies westward into the South Atlantic. Estimates of the contribution these features may make in this interocean transfer rely heavily on a thorough understanding of the anomalous quantities trapped within their vortices and the modification of this water through the Retroflection region.

The results of this thesis identify a range of characteristics associated with six Agulhas vortices observed in the Retroflection region at one time. A detailed water masses analysis of the waters comprising the Retroflection region and its associated mesoscale features is presented. From the results of this analysis it is apparent that there is substantial modification of these water masses within the immediate vicinity of the Retroflection region. A heat and salt anomaly analysis is presented, quantifying the modification of Agulhas water referenced to the Agulhas Current input. A rather special combination of data is used to fulfill the primary aims of this thesis. Concurrent satellite (*Meteosat*, *NOAA*, *Geosat*) and hydrographic (*SCARC* and *Discovery 165A*) data of the Agulhas Retroflection region in February - March 1987 are analyzed. The principle results of this study are as follows:

General Hydrography and Dynamics

- (i) The Agulhas Retroflection region in February - March 1987 exhibits an atypical situation in which six Agulhas vortices are hydrographically sampled at one time. In addition to the anomalously large number of vortices identified, two substantial filaments of Subantarctic origin are entrained along the perimeters of the Agulhas vortices, invading the Retroflection region from the south.
- (ii) The morphology and thermohaline characteristics of each vortex is found to be different (see Table 9). Despite their varied hydrography, four of the six vortices display similar characteristics. Most notably, salinity boosting is identified within the surface core of the vortices, mixed to depths exceeding 100 db.
- (iii) Eddy - Current and Ring - Ring interaction are observed using satellite altimetric data. Hydrographic evidence of the interaction of Eddy A6 with the Agulhas

Retroflection is presented, where Agulhas Water is observed to spill southwards from the Agulhas Retroflection into the surface waters of the Eddy A6.

(iv) An indication of the depth to which Agulhas vortices trap water is shown to be important if we are to estimate those anomalous quantities of water which are likely to be transported into the South Atlantic via such features. Taking into account the unique dynamics of each vortex, estimates of volume trapping are determined using Flierl's (1981) parameter. From these results it seems that Agulhas vortices are capable of trapping water from the surface to depths well into the Intermediate Water range (910 - 1210 db). A volume transport contribution of between 11 - 18 Sv is estimated, should 5 to 8 vortices enter the South Atlantic per annum.

Water Mass Analysis

(i) From the identification of the property extrema associated with each water mass within the Agulhas Retroflection region (see Table 10), it is apparent that the Agulhas Current introduces a variety of Indian Ocean Water masses into the Retroflection region. Tropical Surface Water (TSW) is observed to enter the Retroflection region, confined to a narrow stream (< 35 km wide) located along the surface core of the Agulhas Current. This TSW stream becomes increasingly discontinuous along its path through the anti-cyclonic loop of the Retroflection.

(ii) A shallow oxygen minimum layer (65 - 140 db) is observed within the surface core of the Agulhas Current. Despite the usefulness of this signature in tracing the surface core of the Agulhas Current, none of the Agulhas vortices exhibit this shallow feature since it is eroded (and ventilated) by their surface mixed layer.

(iii) The interior of the Agulhas Retroflection (and the core of the Agulhas vortices) is dominated by Subtropical Surface Water (SSW). A Modified type of SSW is identified within the core of four of the six Agulhas vortices. Salinities in excess of 35.63 characterize Modified Subtropical Surface Water (MSSW) - a product of local evaporative processes. It is suggested that MSSW may be a useful tracer for Agulhas vortices since this water type is only found within these isolated features.

(iv) Subtropical Mode Water (STMW) is identified within the Agulhas Current and beneath the deep mixed layer some of the Agulhas vortices (provided the mixed layer is not too deeply developed). This STMW signature ranges in thickness from 50 - 80 m.

(v) Deep stads of Subantarctic Mode Water (SAMW) are identified within the core of Rings A1 and A2, ranging in thickness of between 100 - 180 m. This SAMW signal is more pronounced than the single SAMW signal evident in the near-shore edge of the Agulhas Current (only 80 m thick). The increased thickness of SAMW within the

Agulhas vortices may be due to stretching or concentration of the source thermocline water during the process of ring shedding.

(vi) The contrasting Θ/S characteristics of Antarctic Intermediate Water (AAIW) and Red Sea Water (RSW) are identified, and are recognized as a useful indicator of the extent to which Agulhas Water is contaminated within the Retroflexion region. Thick layers of RSW (200 - 300 m thick) are identified within the core of the Agulhas Current with weaker remnants identified within the core of some of the Agulhas vortices.

(vii) The Deep and Bottom Waters of the Retroflexion region are dominated by an invasion of North Atlantic Deep Water (NADW) into the Circumpolar Waters (splitting them into an Upper and Lower layer). It is suggested that the Upper Circumpolar (UCDW), NADW and Lower Circumpolar (LCDW) can be distinguished using their opposing oxygen characteristics, delineated by three critical density surfaces.

Heat and Salt Anomaly Analysis

(i) The Agulhas Waters are observed to enter the Retroflexion region at depths not exceeding 1400 db. Extreme positive anomalies are present within the majority of the Agulhas vortices, extending from the surface to depths well within the Lower Thermocline and Intermediate Waters. Positive salt anomalies within the surface layers are the result of well developed stads of Subtropical and Modified Subtropical Surface Water. Positive anomalies within the Upper and Lower Thermocline are the result of thickened stads of Subtropical and Subantarctic Mode Waters respectively. Positive anomalies at intermediate depths are attributed to the presence of Red Sea Water.

(ii) Weakly negative salt anomalies are identified along the near-shore edge of the Agulhas Current input, associated with the fresh Tropical Surface Water layer (with its shallow oxygen minimum). Negative anomalies in the Surface and Thermocline layers are located within the southern and western areas, outside the main Retroflexion region. These negative anomalies prograde further into the Retroflexion region with increasing depth, identifying the Subantarctic and South Atlantic Waters. Extremely negative anomalies are identified at intermediate levels and are restricted to the southwestern sector of the SCARC survey. These extreme negative anomalies are associated with "Atlantic" Antarctic Intermediate Water, uncontaminated by Red Sea Water. Evidence of weakly negative salt anomalies downstream of the Agulhas Retroflexion suggests that the Agulhas Return Current may transport Atlantic AAIW characteristics into the South Indian subtropical gyre.

REFERENCES

- Andrews, J.C., Lawrence, M.W. and Nilsson, C.S. (1979):** Observations of the Tasman Front. *Unpublished Manuscript*.
- Bang, N.D. (1970):** Dynamic interpretation of a detailed surface temperature chart of the Agulhas Current retroflexion and fragmentation area. *South African Geographic Journal*, **52**, 67-76.
- Bennett, S.L. (1988):** Where the three oceans meet: the Agulhas retroflection region. *PhD Thesis*, Woods Hole; Massachusetts Institute of Technology / Woods Hole Oceanographic Institution: xxvii + 367 pp.
- Biggs, R.B. and Wetzel, C.D. (1968):** Concentration of particulate carbohydrate at the halocline in Chesapeake Bay. *Limnology and Oceanography*, **13**(1), 169-171.
- Boudra, D.B. and Chassignet, E.P. (1988):** Dynamics of the Agulhas retroflection and ring formation in a numerical model. 1. The vorticity balance. *Journal of Physical Oceanography*, **18**(2), 280-303.
- Boudra, D.B. and de Ruijter, W.P.M. (1986):** The wind-driven circulation in the South Atlantic - Indian Ocean - II. Experiments using a multi-layer numerical model. *Deep-Sea Research*, **33**, 447-482.
- Boudra, D.B., Maillet, K.A. and Chassignet, E.P. (1989):** Numerical modelling of Agulhas retroflection and ring formation with isopycnal outcropping. In: *Mesoscale / Synoptic Coherent Structures in geophysical Turbulence*. Nihoul, J.C.J. and Jamart, B.M. (Eds). Amsterdam; Elsevier: 315-335.
- Brown, O.B., Olson, D.B., Brown, J.W. and Evans, R.H. (1983):** Satellite infrared observation of the kinematics of a warm-core ring. *Australian Journal of Marine and Freshwater Research*, **34**, 535-545.
- Brundrit, G. and Shannon, L.V. (1989):** Cape storms and the Agulhas Current: A glimpse of the future. *South African Journal of Science*, **85**, 619-620.

- Bryden, H.L. (1973):** New polynomials for thermal expansion, adiabatic temperature gradient and potential temperature of sea water. *Deep-Sea Research*, **20**, 401-408.
- Bunker, A.F. 1980:** Trends of variables and energy fluxes over the Atlantic Ocean from 1948 to 1972. *Monthly Weather Review*, **108**, 720-728.
- Byrne, D.A., Gordon, A.L. and Haxby, W.F. (1994):** Agulhas Eddies: A synoptic view using *Geosat ERM* data. Submitted to *Journal of Physical Oceanography*, 23 December 1993.
- Camp, D.B., Haines, W.E., Huber, B.A., Rennie, S.E. and Gordon, A.L. (1986):** Agulhas Retroflexion Cruise. *Hydrographic (CTD) data Final Technical Report*, **LDGO-86-1**,, Lamont-Doherty Geological Observatory of Columbia University Palisades, New York, February 1986.
- Chapman, P. (1988):** On the occurrence of oxygen-depleted water south of Africa and its implications for Agulhas-Atlantic mixing. *South African Journal of Marine Science*, **7**, 767-294.
- Chapman, P., Duncombe Rae, C.M. and Allanson, B.R. (1987):** Nutrients, chlorophyll and oxygen relationships in the surface layers at the Agulhas Retroflexion. *Deep-Sea Research*, **34(8A)**, 1399-1416.
- Chapman, P. and Largier, J.L. (1989):** On the origin of Agulhas Bank bottom water. *South African Journal of Science*, **85**, 515-519.
- Cheney, R.E. (1977):** Synoptic Observations of the Oceanic Frontal System East of Japan. *Journal of Geophysical Research*, **82(34)**, 5459-5468.
- Cheney, R.E., Marsh, J.G. and Beckley, B.D. (1983):** Global mesoscale variability from collinear tracks of SEASAT altimeter data. *Journal of Geophysical Research*, **88(C7)**, 4343-4354.

- Clowes, A.J. (1950): An introduction to the hydrology of South African waters. *Investigational Report of the Fisheries and Marine Biological Survey Division of South Africa*, 12, 42 pp. & 20 pp. of charts.
- Clowes, A.J. and Deacon, G.E.R. (1935): The deep-water circulation of the Indian Ocean. *Nature*, 136, 936-938.
- Crawford, A.B. (1972): Sea surface temperature measurements by direct sampling. Maritime Weather Office, Youngsfield, Cape Town.
- Cresswell, G.R. (1982): The coalescence of two East Australian warm-core eddies. *Science*, 215, 161-164.
- Deacon, G.E.R. (1933): A general account of the hydrology of the South Atlantic Ocean. *Discovery Reports*, 7, 171-238.
- Deacon, G.E.R. (1937): The hydrography of the Southern Ocean. *Discovery Reports*, 15, 1-24.
- de Ruijter, W.P.M. and Boudra, D.B. (1985): The wind-driven circulation in the South Atlantic - Indian Ocean - I. Numerical experiments in a one-layer model. *Deep-Sea Research*, 32, 557-574.
- Douglas, B.C. and Cheney, R.E. (1990): GEOSAT: Beginning a new era in satellite oceanography. *Journal of Geophysical Research*, 95, 2833-2836.
- Duncan, C.P. (1968): An eddy in the subtropical convergence southwest of South Africa. *Journal of Geophysical Research*, 73, 531-534.
- Duncan, C.P. (1970): The Agulhas Current. Ph.D. thesis, University of Hawaii, 76 pp.
- Duncombe Rae, C.M. (1991): Agulhas Retroflection rings in the South Atlantic Ocean: An overview. *South African Journal of Marine Science*, 11, 327-344.

- Duncombe Rae, C.M., Boyd, A.J. and Crawford, R.J.M. (1994): "Predation" of anchovy by an Agulhas ring: a possible contributory cause of the very poor year-class of 1989. In: *Benguela Trophic Functioning*. Payne, A.I.L., Brink, K.H., Mann, K.H. and Hilborn, R. (Eds). Submitted to *South African Journal of marine Science*.
- Duncombe Rae, C.M., Shannon, L.V. and Shillington, F.A. (1989): An Agulhas ring in the South Atlantic ocean. *South African Journal of Science*, **85**, 747-748.
- Duncombe Rae, C.M. and Shillington, F.A. (1994): A winter ring from the Agulhas. (*In preparation*).
- Duncombe Rae, C.M., Shillington, F.A., Agenbag, J.J. and Taunton-Clark, J. (1992): An Agulhas Ring in the South Atlantic Ocean and its interaction with the Benguela Upwelling Frontal System. *Deep-Sea Research*, **39**(11/12), 2009-2027.
- Emery, W.J. and Meincke, J. (1986): Global water masses: Summary and review. *Oceanologia Acta*, **9**, 383-391.
- Evans, R.H., Baker, K.S., Brown, O.B. and Smith, R.C. (1985): Chronology of Warm-Core Ring 82B. *Journal of Geophysical Research*, **90**(C5), 8803-8811.
- Feron, R.C.V., de Ruijter, W.P.M. and Oskam, D. (1992): Ring shedding in the Agulhas Current System. *Journal of Geophysical Research*, **97**(C6), 9467-9477.
- Fine, R.A., Warner, M.J. and Weiss, R.F. (1988): Water mass modification at the Agulhas retroflection: chlorofluoromethane studies. *Deep-Sea Research*, **35**(3A), 311-332.
- Flierl, G.R. (1981): Particle motions in large-amplitude wave fields. *Geophysics, astrophysics and Fluid Dynamics*, **18**, 39-74.

- Flierl, G.R. (1984): Model of the structure and motion of a warm-core ring. *Australian Journal of Marine and Freshwater Research*, **35**, 9-23.
- Fofonoff, N.P. (1977): Computation of potential temperature of seawater for an arbitrary reference pressure. *Deep-Sea Research*, **24**, 489-491.
- FRAM Group (1991): An eddy-resolving model of the Southern Ocean. *EOS, Transactions of the American Geophysical Union*, **72**(15), 169, 174-175.
- Franks, P.J.S., Wroblewski, J.S. and Flierl, G.R. (1986): Prediction of phytoplankton growth in response to the frictional decay of a warm-core ring. *Journal of Geophysical Research*, **91**(C6), 7603-7610.
- Fu, L-L. (1981): The general circulation and meridional heat transport of the subtropical South Atlantic determined by inverse methods. *Journal of Physical Oceanography*, **11**, 1171-1193.
- Fu, L-L. (1986): Mass, heat and freshwater fluxes in the South Indian Ocean. *Journal of Physical Oceanography*, **16**(10), 1683-1693.
- Fuglister, F.C. (1977): A cyclonic ring formed by the Gulf Stream, 1967. In: *A Voyage of Discovery*. Angel, M. (Ed). Oxford; Pergamon: 177-198.
- Georgi, D.T. (1979): Modal properties of Antarctic Intermediate Water in the southeast Pacific and the south Atlantic. *Journal of Physical Oceanography*, **16**(10), 1683-1693.
- Gordon, A.L. (1981): South Atlantic thermocline ventilation. *Deep-Sea Research*, **28**, 1239-1264.
- Gordon, A.L. (1985): Indian-Atlantic transfer of thermocline water at the Agulhas Retroflection. *Science*, **227**, 1030-1033.
- Gordon, A.L. (1986): Inter-ocean exchange of thermocline water. *Journal of Geophysical Research*, **91**, 5037-5046.

- Gordon, A.L. and Haxby, W.F. (1990):** Agulhas eddies invade the South Atlantic Ocean - evidence from GEOSAT altimeter and shipboard CTD. *Journal of Geophysical Research*, **95**, 3117-3126.
- Gordon, A.L., Lutjeharms, J.R.E. and Gründlingh, M.L. (1987):** Stratification and circulation at the Agulhas retroflection. *Deep-Sea Research*, **34**, 565-599.
- Gordon, A.L. and Piola, A.R. (1983):** Atlantic Ocean upper layer salinity budget. *Journal of Physical Oceanography*, **13**, 1293-1300.
- Gordon, A.L., Weiss, R.F., Smethie, W.M. and Warner, M.J. (1992):** Thermocline and intermediate water communication between the South Atlantic and Indian Ocean. *Journal of Geophysical Research*, **97**, 7223-7240.
- Gründlingh, M.L. (1980):** On the volume transport of the Agulhas Current. *Deep-Sea Research*, **27**, 557-563.
- Gründlingh, M.L. (1983):** On the course of the Agulhas Current. *South African Geographical Journal*, **65**, 49-57.
- Gründlingh, M.L. (1985):** Occurrence of Red Sea Water in the southwestern Indian Ocean, 1981. *Journal of Physical Oceanography*, **15**(2), 207-212.
- Harder, W. (1968):** Reactions of plankton organisms to water stratification. *Limnology and Oceanography*, **13**(1), 156-168.
- Harris, T.F.W. (1972):** Sources of the Agulhas Current in the spring of 1964. *Deep-Sea Research*, **19**(9), 633-650.
- Harris, T.F.W. and Bang, N.D. (1974):** Topographic Rossby waves in the Agulhas Current. *South African Journal of Science*, **70**(7), 212-214.
- Harris, T.F.W., Legeckis, R. and van Foreest, D. (1978):** Satellite infrared images in the Agulhas Current system. *Deep-Sea Research*, **25**, 543-548.

- Harris, T.F.W. and van Foreest, D. (1978): The Agulhas Current in March 1969. *Deep-Sea Research*, **25**, 549-561.
- Hastenrath, S. (1982): On the meridional heat transports in the world ocean. *Journal of Physical Oceanography*, **12**, 922-927.
- Höflich, O. (1984): Climate of the South Atlantic Ocean. In: *Climates of the Oceans. World Survey of Climatology*, **15**. Van Loon, H. (Ed). Amsterdam; Elsevier, 1-191.
- Holford, J.M. (1990): A description of the Agulhas Retroflexion Zone. Institute of Oceanographic Sciences, Deacon Laboratory, *Internal Report No. 294*, 13pp.
- Jacobs, S.S. and Georgi, D.T. (1977): Observations on the southwest Indian / Antarctic Ocean. *Deep-Sea Research*, **40**(suppl.), 43-84.
- Jeffrey, S.W. and Hallegraeff, G.M. (1987): Phytoplankton pigments, species and light climate in a complex warm-core eddy of the East Australian Current. *Deep-Sea Research*, **34**(5/6), 649-673.
- Joyce, T.M., Patterson, S.L. and Millard, R.C. (1981): Anatomy of a cyclonic ring in the Drake Passage. *Deep-Sea Research*, **28A**(11), 1265-1287.
- Kamenkovitch, V.M., Koshlyakov, M.N. and Monin, A.S. (1986): *Synoptic Eddies in the Ocean*. Dordrecht; D. Reidel: ix + 433 pp.
- Kawase, M. (1987): Establishment of deep ocean circulation driven by deep-water production. *Journal of Physical Oceanography*, **17**, 2294-2317.
- Killworth, P.D. (1983): Deep convection in the world ocean. *Review of Geophysical Space Physics*, **21**(1), 1-26.
- Lutjeharms, J.R.E. (1976): The Agulhas Current system during the Northeast Monsoon season. *Journal of Physical Oceanography*, **6**, 665-670.

- Lutjeharms, J.R.E. (1981a):** Features of the southern Agulhas Current circulation from satellite remote sensing. *South African Journal of Science*, **77**(5), 231-236.
- Lutjeharms, J.R.E. (1981b):** Spatial scales and intensities of circulation in the ocean areas adjacent to South Africa. *Deep-Sea Research*, **28**(11A), 1289-1302.
- Lutjeharms, J.R.E. (1987):** Die Subtropiese Konvergensie en Agulhasretrofleksievaart (SCARC). *South African Journal of Science*, **83**, 454-456.
- Lutjeharms, J.R.E. (1988a):** On the role of the East Madagascar Current as a source of the Agulhas Current. *South African Journal of Science*, **84**(4), 236-238.
- Lutjeharms, J.R.E. (1988b):** Meridional heat transport across the Subtropical Convergence by an eddy. *Nature*, **331**, 251-254.
- Lutjeharms, J.R.E., Bang, N.D. and Duncan, C.P. (1981):** Characteristics of the currents east and south of Madagascar. *Deep-Sea Research*, **28**(9A), 879-899.
- Lutjeharms, J.R.E. and Cooper, J. (1995):** Interbasin leakage through Agulhas Current filaments. *Deep-Sea Research*, accepted (August 1995).
- Lutjeharms, J.R.E. and Foldvik, A. (1986):** The thermal structure of the upper ocean layers between Africa and Antarctica during the period December 1978 to March 1979. *South African Journal of Science*, **16**(1), 13-20.
- Lutjeharms, J.R.E. and Gordon, A.L. (1987):** Shedding of an Agulhas ring observed at sea. *Nature*, **325**, 138-140.

- Lutjeharms, J.R.E., Lucas, M.I., Perissinotto, R., van Ballegooyen, R.C. and Rouault, M. (1993): Oceanic processes at the Subtropical Convergence; report of research cruise SAAMES-III. (*In press, South African Journal of Science*).
- Lutjeharms, J.R.E. and Valentine, H.R. (1984): Southern Ocean thermal fronts south of Africa. *Deep-Sea Research*, **31**(12), 1461-1475.
- Lutjeharms, J.R.E. and Valentine, H.R. (1988a): Evidence for persistent Agulhas rings south-west of Cape Town. *South African Journal of Science*, **84**, 781-774.
- Lutjeharms, J.R.E. and Valentine, H.R. (1988b): Eddies at the subtropical convergence south of Africa. *Journal of Physical Oceanography*, **18**(5), 761-774.
- Lutjeharms, J.R.E. and van Ballegooyen, R.C. (1984): Topographic control of the Agulhas Current System. *Deep-Sea Research*, **31**, 1321-1337.
- Lutjeharms, J.R.E. and van Ballegooyen, R.C. (1988): The Retroflection of the Agulhas Current. *Journal of Physical Oceanography*, **18**, 1570-1583.
- Lutjeharms, J.R.E. and Webb, D. (1992): Modelling the Agulhas Current with FRAM (Fine Resolution Antarctic Model). *Deep-Sea Research* (In press).
- Lutjeharms, J.R.E.; Weeks, S.J.; van Ballegooyen, R.D. (sic) and Shillington, F.A. (1992): Shedding of an eddy from the seaward front of the Agulhas Current. *South African Journal of Science*, **88**, 430-433.
- Luyten, J., Spencer, A., Tarbell, S., Luetkemeyer, K., Flament, P., Toole, J., Francis, M. and Bennett, S. (1990): Moored current meter, AVHRR, CTD and drifter data from the Agulhas Current and Retroflexion Region (1985-1987) Volume XLII. *WHOI - 02543 Technical Report*, July 1990.

- McCartney, M.S. (1977): Subantarctic mode water. In: *A Voyage of Discovery*. Angel, M. (Ed). New York; Pergamon, 103-119 (Supplement to *Deep-Sea Research*).
- McCartney, M.S. and Woodgate-Jones, M.E. (1991): A deep-reaching anticyclonic eddy in the subtropical gyre of the eastern South Atlantic. *Deep-Sea Research*, **38** (Supplement 1), S411-S443.
- Mey, R.D., Walker, N.D. and Jury, M.R. (1990): Surface heat fluxes and marine boundary layer modification in the Agulhas Retroflexion region. *Journal of Geophysical Research*, **95**(C9), 15997-16015.
- Mulhearn, P.J. (1983): On the climatology of warm-core rings from the East Australian Current. *Australian Journal of Marine and Freshwater Research*, **34**(4), 687-692.
- Nilsson, C.S. and Cresswell, G.R. (1981): The formation and evolution of East Australian Current warm-core eddies. *Progress in Oceanography*, **9**, 133-183.
- Nof, D. (1981): On the β -induced movement of isolated baroclinic eddies. *Journal of Physical Oceanography*, **11**, 1662-1672.
- Olbers, D., Gouretski, V., Seif, G. and Schröter, J. (1992): *Hydrographic atlas of the Southern Ocean*. Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany and the Arctic and Antarctic Research Institute, St. Petersburg, Russia, 82pp.
- Olson, D.B. (1980): The Physical oceanography of two rings observed in the Cyclonic Ring Experiment, Part 2, Dynamics. *Journal of Physical Oceanography*, **10**(4), 514-528.
- Olson, D.B. and Evans, R.H. (1986): Rings of the Agulhas Current. *Deep-Sea Research*, **37**, 27-42.

- Olson, D.B., Schmitt, R.W., Kennelly, M. and Joyce, T.M. (1985): A two-layer diagnostic model of the long-term physical evolution of Warm-Core Ring 82B. *Journal of Geophysical Research*, **90**(C5), 8813-8822.
- Onken, R., Fischer, J. and Woods, J.D. (1990): Thermocline finestructure and its relation to frontogenesis dynamics. *Journal of Physical Oceanography*, **20** (9), 1379-1394.
- Orren, M.J. (1963): Hydrological observations in the southwest Indian Ocean. *Investigational Report of the Division for Sea Fisheries of South Africa*, **45**, 1-61.
- Orren, M.J. (1966): Hydrology of the South West Indian Ocean. *Investigational Report of the Division for Sea Fisheries of South Africa*, **55**, 1-35.
- Piola, A.R. and Georgi, D.T. (1982): Circumpolar properties of Antarctic Intermediate Water and Subantarctic Mode Water. *Deep-Sea Research*, **29**(6A), 687-711.
- Piola, A.R. and Gordon, A.L. (1986): On oceanic heat and freshwater fluxes at 30°S. *Journal of Physical Oceanography*, **16**(12), 2184-2190.
- Piola, A.R. and Gordon, A.L. (1989): Intermediate waters in the southwest South Atlantic. *Deep-Sea Research*, **36**(1A), 1-16.
- Priddle, J., Heywood, R.B. and Theriot, E. (1986): Some environmental factors influencing phytoplankton in the Southern Ocean around South Georgia. *Polar Biology*, **5**, 65-79.
- Read, J.F., Pollard, R.T. and Smithers, J. (1987): CTD and *SeaSoar* data from the Agulhas Retroflection zone. *I.O.S. Report No.245*.
- Reid, J.L., Nowlin, D. and Patzert, W.C. (1977): On the characteristics and circulation of the Southwestern Atlantic Ocean. *Journal of Physical Oceanography*, **7**, 62-91.

- Rigg, G.M. (1991):** Correspondence between the surface and subsurface expression of some mesoscale oceanic features in South African waters. *Honours project*, Oceanography Department, University of Cape Town, 94 pp.
- Rigg, G.M., Attwood, C. and Lucas, M.L. (1994):** Biological enhancement at the eddy-edge of an Agulhas eddy in the vicinity of the Subtropical Convergence. (*In preparation*).
- Rigg, G.M., van Ballegooyen, R.C., Attwood, C., Newton, S., Lucas, M.L. and Lutjeharms, J.R.E. (1992):** Data report on the first cruise of the South African Antarctic Marine Ecosystems Study (SAAMES-I), April - May 1991. *University of Cape Town Oceanography Report 92 - 1*, September 1992.
- Rintoul, S.R. (1991):** South Atlantic Interbasin Exchange. *Journal of Geophysical Research*, **96**(C2), 2675-2692.
- Rochford, D.J. (1983):** Origin of water within warm-core eddies of the Western Tasman Sea. *Australian Journal of Marine and Freshwater Research*, **34**, 525-534.
- Sarukhanyan, E'.I. (1985):** Structure and variability of the Antarctic Circumpolar Current. Amerind Publishing Co., New Delhi, 108 pp., A.A. Balkema, Rotterdam., N.P. Smirnov (Ed.).
- Saunders, P.M. and Fofonoff, N.P. (1976):** Conversion of pressure to depth in the ocean. *Deep-Sea Research*, **23**, 109-111.
- Schmitt, R.W. (1981):** Form of the temperature-salinity relationship in the Central Water: evidence for double-diffusive mixing. *Journal of Physical Oceanography*, **11**, 1015-1026.
- Schmitt, R.W. and Olson, D.B. (1985):** Wintertime convection in warm-core rings: Thermocline ventilation and the formation of mesoscale lenses. *Journal of Geophysical Research*, **90**, 8823-8838.

- Schumann, E.H. and Van Heerden, I.L. (1988): Observations of the Agulhas Current frontal features south of Africa, October 1983. *Deep-Sea Research*, **35**(8A), 1355-1362.
- Seitz, R.C. (1967): Thermostad, the antonym of thermocline. *Journal of Marine Research*, **25**, 203.
- Semtner, A.J. and Chervin, R.M (1988): A simulation of the global ocean circulation with resolved eddies. *Journal of Geophysical Research*, **93**(C12), 15502-15522.
- Semtner, A.J. and Chervin, R.M (1991): A thermohaline conveyor belt in the World Ocean. *WOCE Notes*, **3**(2), 12-15.
- Shannon, L.V. (1966): Hydrology of the south and west coasts of South Africa. *Investigational Report of the Division for Sea Fisheries of South Africa*, **58**, 22pp. & 30 pp. of figures.
- Shannon, L.V. (1985): The Benguela ecosystem I. Evolution of the Benguela, physical features and processes. In: *Oceanography and Marine Biology. An Annual Review*, **23**, Barnes, M. (Ed). Aberdeen; University Press, 105-182.
- Shannon, L.V., Agenbag, J.J., Walker, N.D. and Lutjeharms, J.R.E. (1990): A major perturbation in the Agulhas retroflection area in 1986. *Deep-Sea Research*, **37**(3A), 493-512.
- Shannon, L.V., Lutjeharms, J.R.E. and Agenbag, J.J. (1989): Episodic input of Subantarctic water into the Benguela region. *South African Journal of Science*, **85**, 317-322.
- Smith, R.C. and Baker, K.S. (1985): Spatial and temporal patterns in pigment biomass in Gulf Stream warm-core ring 82B and its environs. *Journal of Geophysical Research*, **90**, 8859-8870.

- Spence, T.W. and Legeckis, R. (1981): Satellite and hydrographic observations of low-frequency wave motion associated with a cold core Gulf Stream ring. *Journal of Geophysical Research*, **86**(C3), 1945-1953.
- Stanton, B.R. (1976): An oceanic frontal jet near the Norfolk Ridge northwest of New Zealand. *Deep-Sea Research*, **23**(9), 821-829.
- Stevens, D.P. and Thompson, S.R. (1994): The South Atlantic in the Fine-Resolution Antarctic Model. *Annales Geophysicae*, **12**, 826-839.
- Stramma, L. (1991): Geostrophic transport of the South Equatorial Current in the Atlantic. *Journal of Marine Research*, **49**(2), 381-294.
- Sverdrup, H.U., Johnson, M.W. and Fleming, R.H. (1942): *The Oceans: Their Physics, Chemistry, and General Biology*. Prentice-Hall, Englewood Cliffs, New Jersey, 1087 pp.
- Swart, V.P. and Largier, J.L. (1987): Thermal structure of Agulhas Bank water. *South African Journal of Marine Science*, **5**, 243-253.
- Thompson, S.R., Stevens, D.P. and Doös, K. (1995): The importance of interocean exchange south of Africa in a numerical model. (*in preparation*)
- Tranter, D.J., Leech, G.S. and Airey, D. (1983): Edge enrichment in an ocean eddy. *Australian Journal of Marine and Freshwater Research*, **34**, 665-680.
- Tranter, D.J., Leech, G.S. and Vaudrey, D.J. (1981): Biological significance of surface flooding in warm-core ocean eddies. *Nature*, **293**, 751-755.
- Tranter, D.J., Parker, R.R. and Cresswell, G.R. (1980): Are warm-core eddies unproductive? *Nature*, **284**, 540-542.
- UNESCO (1983): Algorithms for computation of fundamental properties of seawater. *UNESCO Technical Papers in Marine Science*, **44**, 53 pp.

- Valentine, H.R. (1990):** A fine-scale volumetric census of water masses of the Agulhas Retroflexion Area. *CSIR Report, EMA-R 691*, 105 pp.
- Valentine, H.R., Duncombe Rae, C.M., van Ballegooyen, R.C. and Lutjeharms, J.R.E. (1988):** The Subtropical Convergence and Agulhas Retroflexion Cruise (SCARC) data report. *CSIR Report T/SEA 8804*, 258 pp.
- Valentine, H.R., Lutjeharms, J.R.E. and Brundrit, G.B. (1993):** The water masses and volumetry of the southern Agulhas Current region. *Deep-Sea Research*, **40**(6), 1285-1305.
- van Ballegooyen, R.C., Gründlingh, M.L. and Lutjeharms, J.R.E. (1994):** Fluxes of heat and salt from the southwest Indian Ocean into the southeast Atlantic Ocean: A case study. *Journal of Geophysical Research*, **99**(C7), 14053-14070.
- Vastano, A.C., Schmitz, J.E. and Hagan, D.E. (1980):** The physical oceanography of two rings observed by the Cyclonic Ring Experiment. 2. Physical structures. *Journal of Physical Oceanography*, **10**(4), 493-513.
- Visser, G.A. (1969):** Hydrological observations in the southeast Atlantic Ocean. 1. The Schmidt-Ott Seamount area. *Investigational Report 77*, Division of Sea Fisheries, Department of Industries, Republic of South Africa, 23 pp.
- Wakker, K.F., Naeije, M.C., Scharroo, R. and Ambrosius, B.A.C. (1990):** Extraction of mesoscale ocean currents information from *Geosat* altimeter data. *Proceedings of the Space and Sea Colloquium, Paris*, 24-26 September, ESA SP-312, 221-226.
- Walker, N.D. (1990):** Links between South African summer rainfall and temperature variability of the Agulhas and Benguela Current Systems. *Journal of Geophysical Research*, **95**, 3297-3320.

- Walker, N.D. and Mey, R.D. (1988): Ocean-atmosphere heat fluxes within the Agulhas retroflexion region. *Journal of Geophysical Research*, **93**, 15473-15483.
- Warren, B.A. (1981): Deep circulation of the world ocean. In: *Evolution of Physical Oceanography, Scientific Surveys in Honor of Henry Stommel*. Warren, B.A. and Wunsch, C. (Eds). Cambridge, Massachusetts; Massachusetts Institute of Technology Press: 6 - 41 & Reference List.
- Whitworth, T. and Nowlin, W.D. (1987): Water Masses and Currents of the Southern Ocean at the Greenwich Meridian. *Journal of Geophysical Research*, **92**(C6), 6462-6476.
- Williams, R.G. (1988): Modification of ocean eddies by air-sea interaction. *Journal of Geophysical Research*, **93** (12), 15,523-15,533.
- Woods, J.D. (1977): Parameterization of unresolved motions. In: *Modelling and prediction of the upper layers of the ocean*. Kraus, E.B. (Ed.), Pergamon Press, New York. pp. 118-140.
- Worthington, L.V. (1959): The 18° water in the Sargasso Sea. *Deep-Sea Research*, **5**, 297-305.
- Wyrtki, K. (1971): *Oceanographic Atlas of the International Indian Ocean Experiment*. Washington, D.C.; National Science Foundation: 531 pp.
- Yentsch, C.S. and Phinney, D.A. (1985): Rotary motions and convection as a means of regulating primary production in warm core rings. *Journal of Geophysical Research*, **90**(C2), 3237-3248.

Addendum 1

Contours of the depth (in meters) of the following density surfaces:

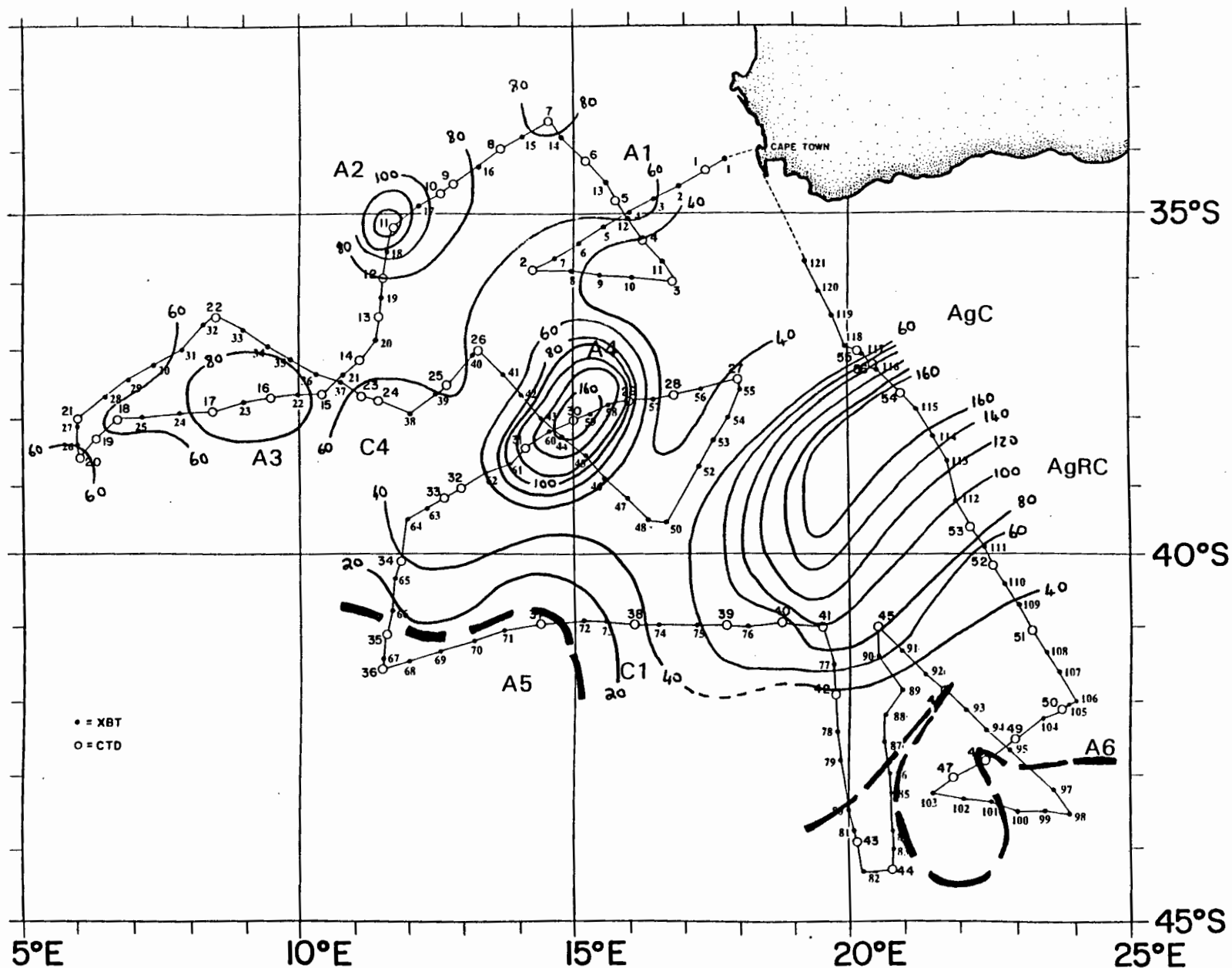
$$\text{Sigma-}\Theta = 25,80$$

$$\text{Sigma-}\Theta = 26,80$$

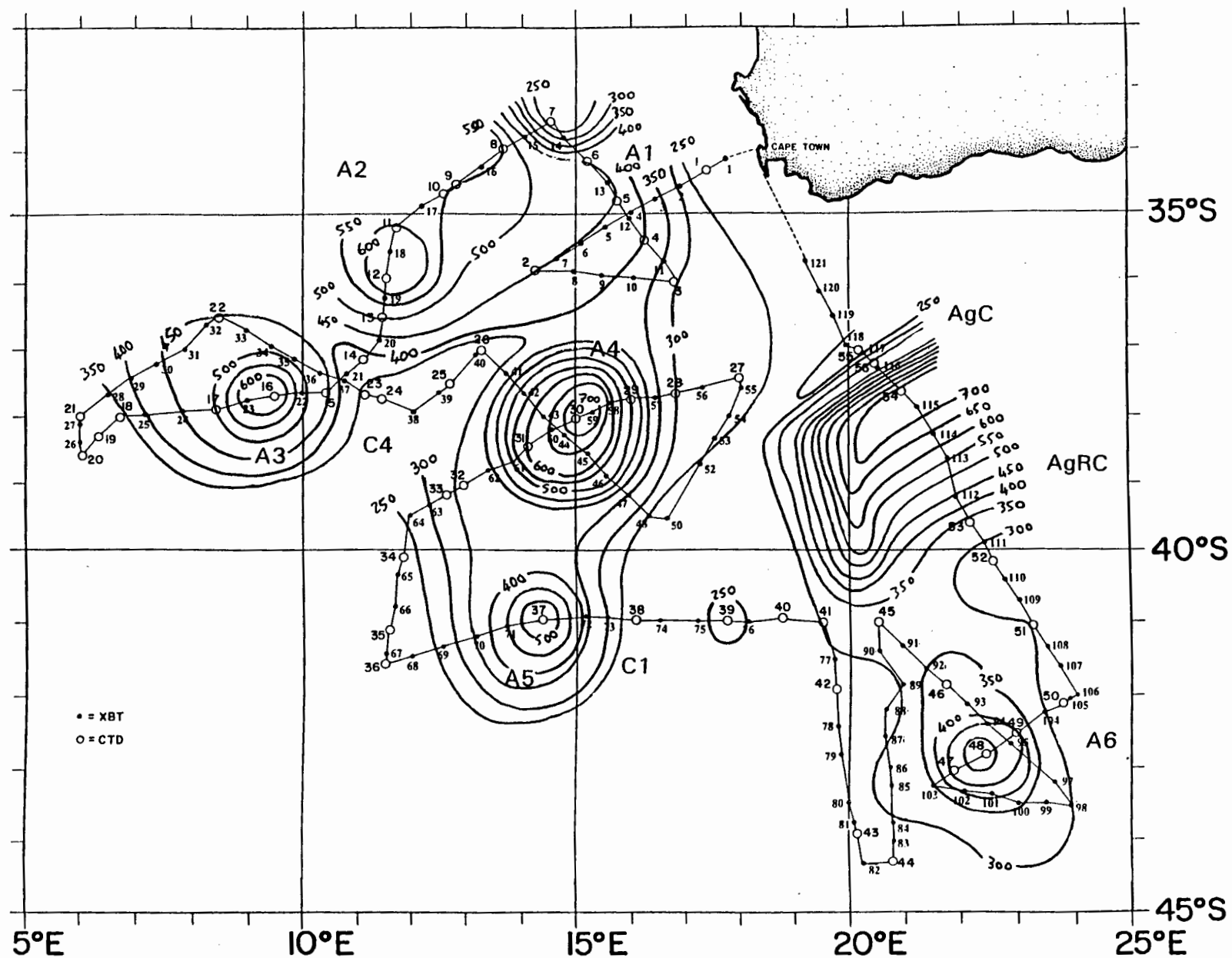
$$\text{Sigma-}I = 31,80$$

$$\text{Sigma-}I = 32,15$$

$$\text{Sigma-}t = 27,35$$

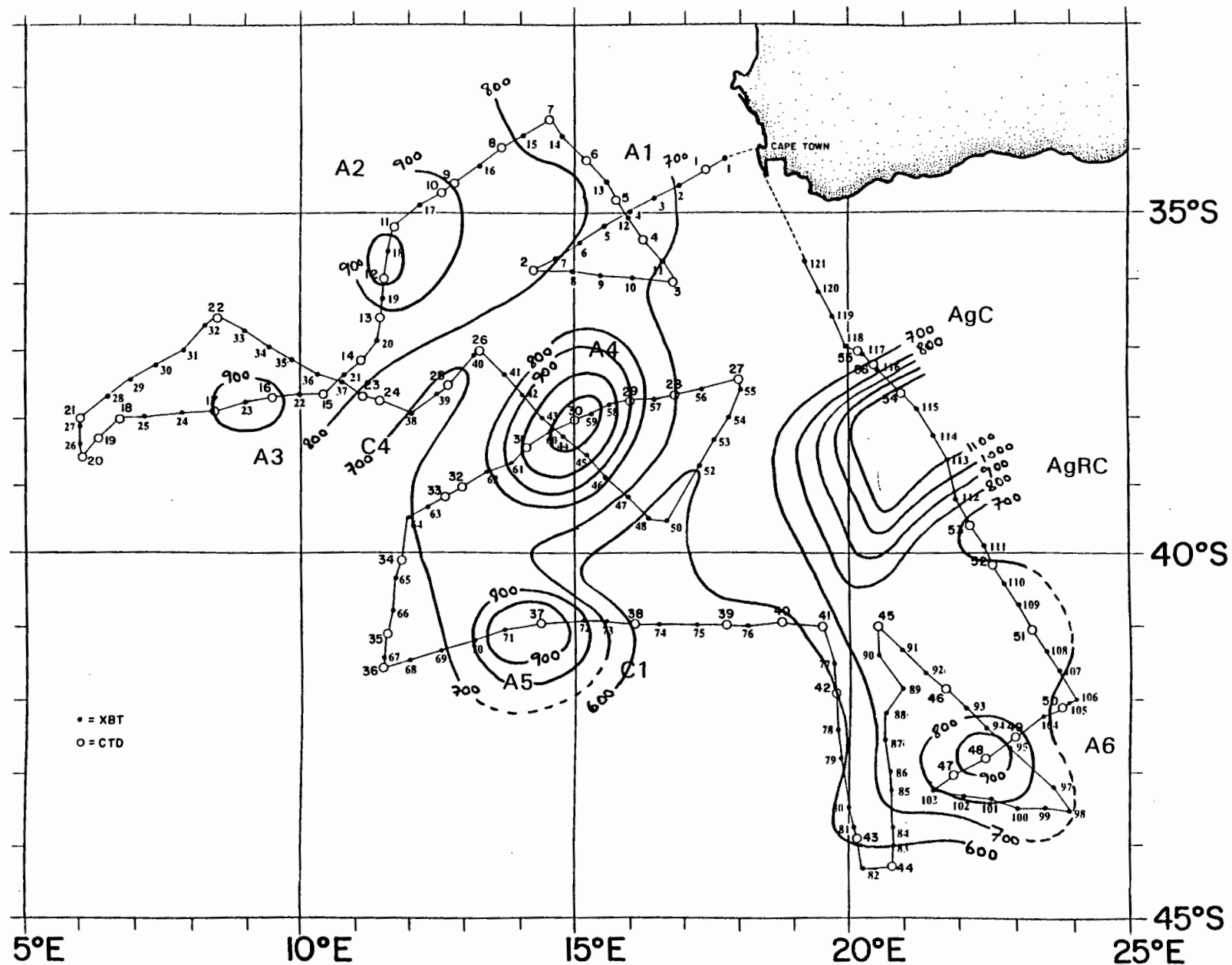


Contour plot of the depth (in meters) of the $\Sigma\theta = 25,80 \text{ kg.m}^{-3}$ density surface
SURFACE WATER



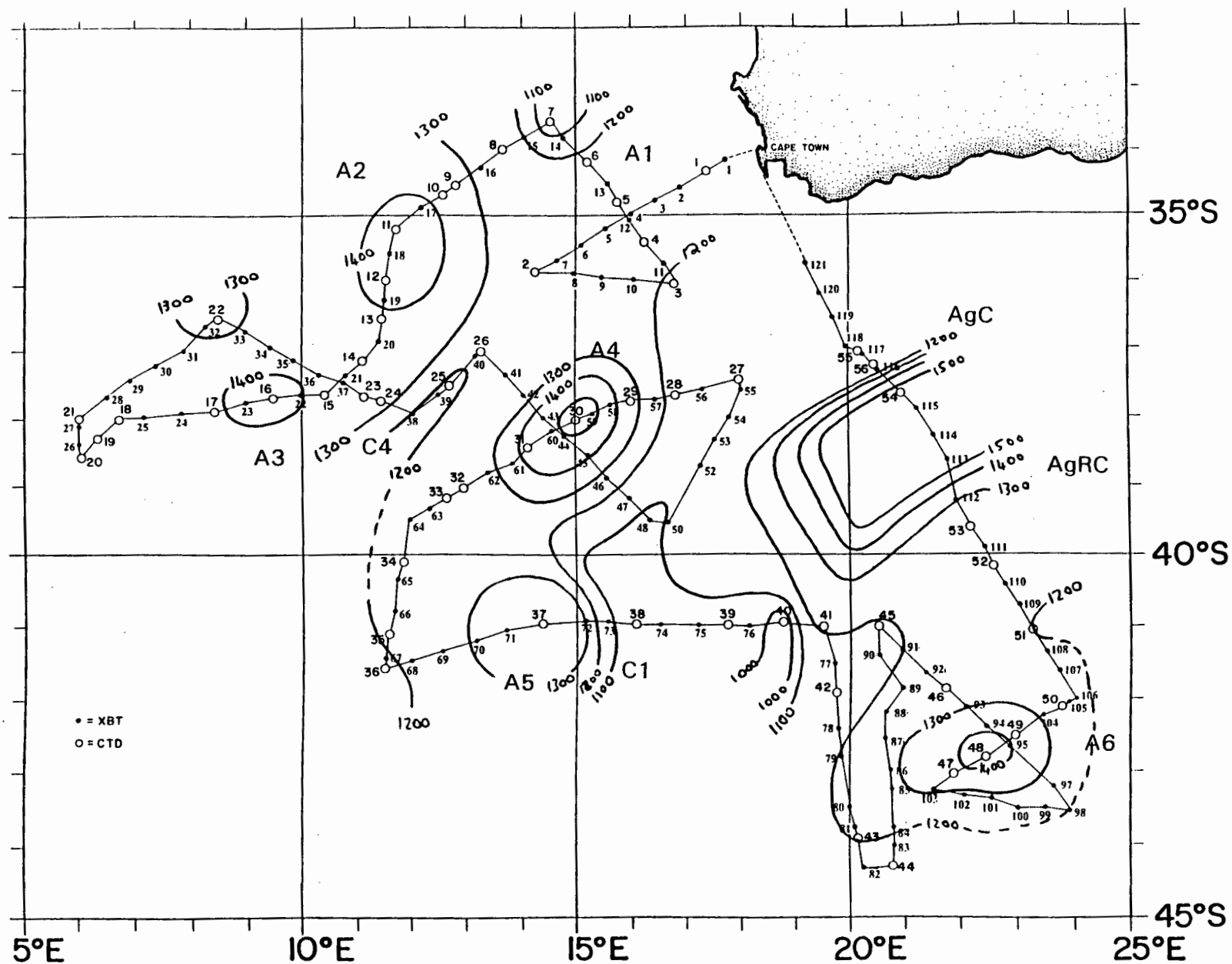
Contour plot of the depth (in meters) of the $\text{Sigma-}\Theta = 26,80 \text{ kg.m}^{-3}$ density surface

CENTRAL WATER



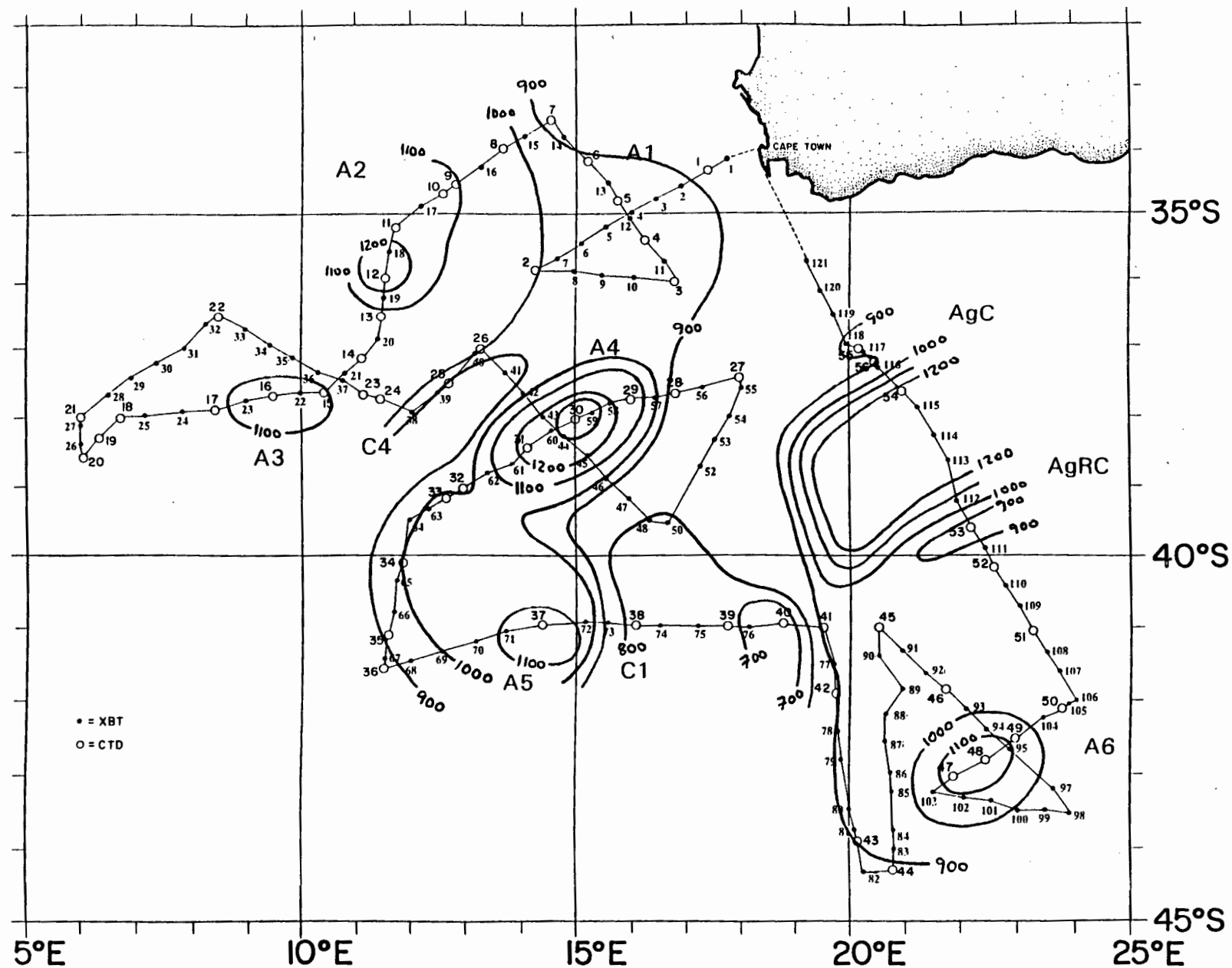
Contour plot of the depth (in meters) of the Sigma-1 = 31,80 kg.m⁻³ density surface

INTERMEDIATE WATER



Contour plot of the depth (in meters) of the Sigma-1 = 32,15 kg.m⁻³ density surface

RED SEA WATER REMNANTS



Contour plot of the depth (in meters) of the $\Sigma\text{-}t = 26,80 \text{ kg.m}^{-3}$ density surface

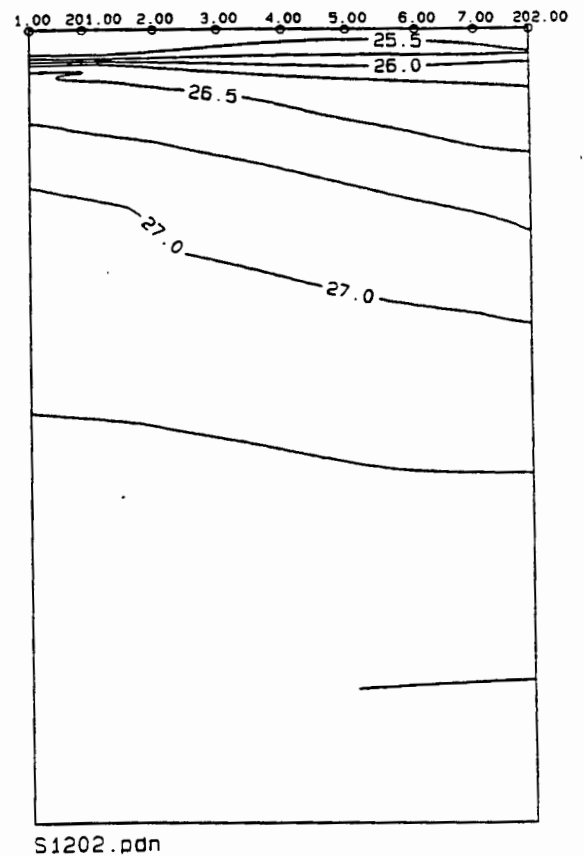
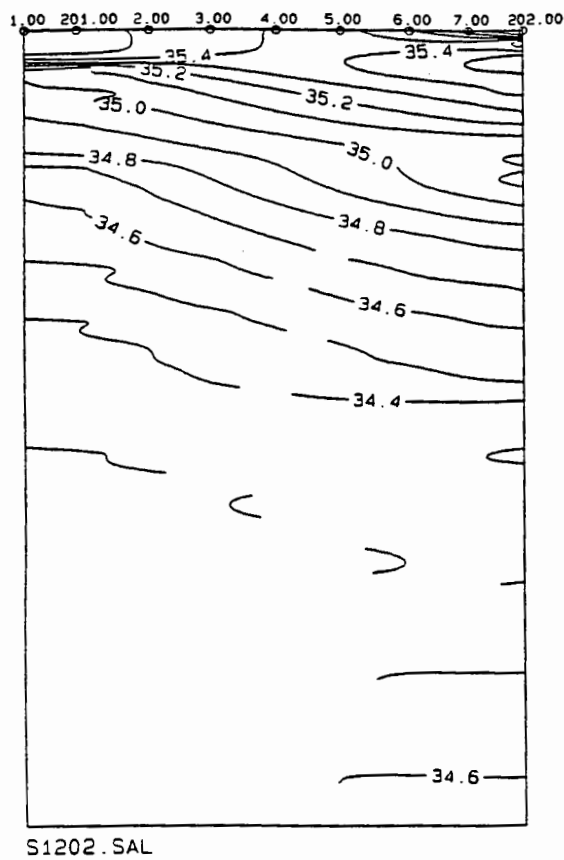
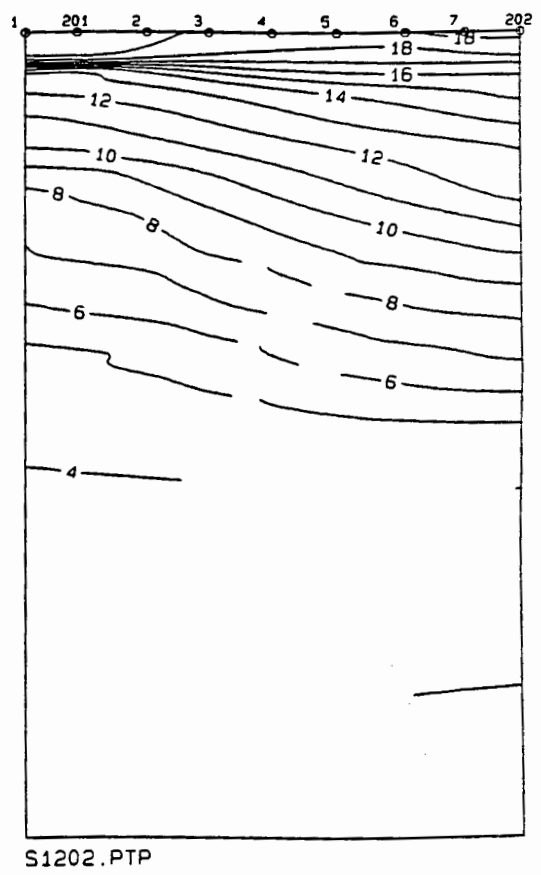
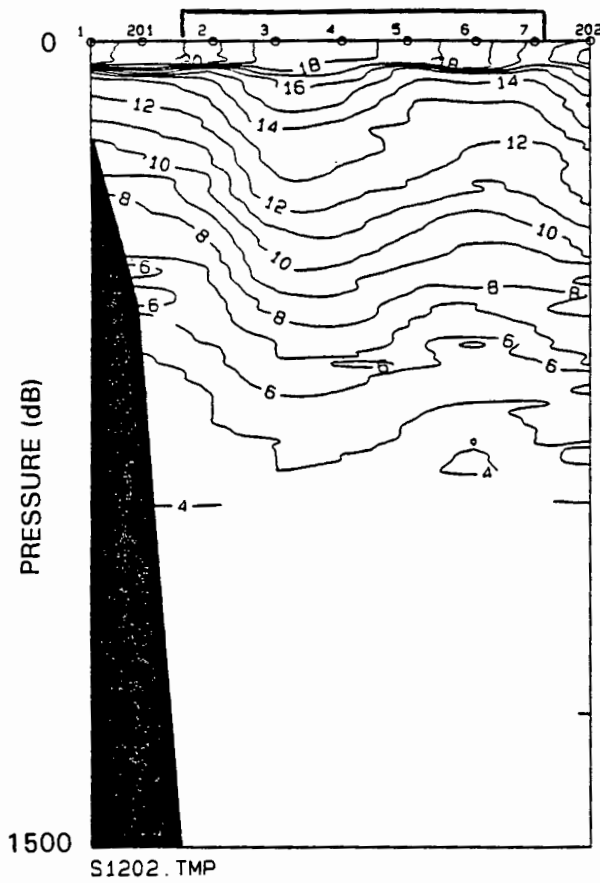
RED SEA WATER REMNANTS

Addendum 2

Temperature, Potential Temperature, Salinity and Potential Density, Geostrophic Velocity and Volume and Heat Flux Sections of the *SCARC*.

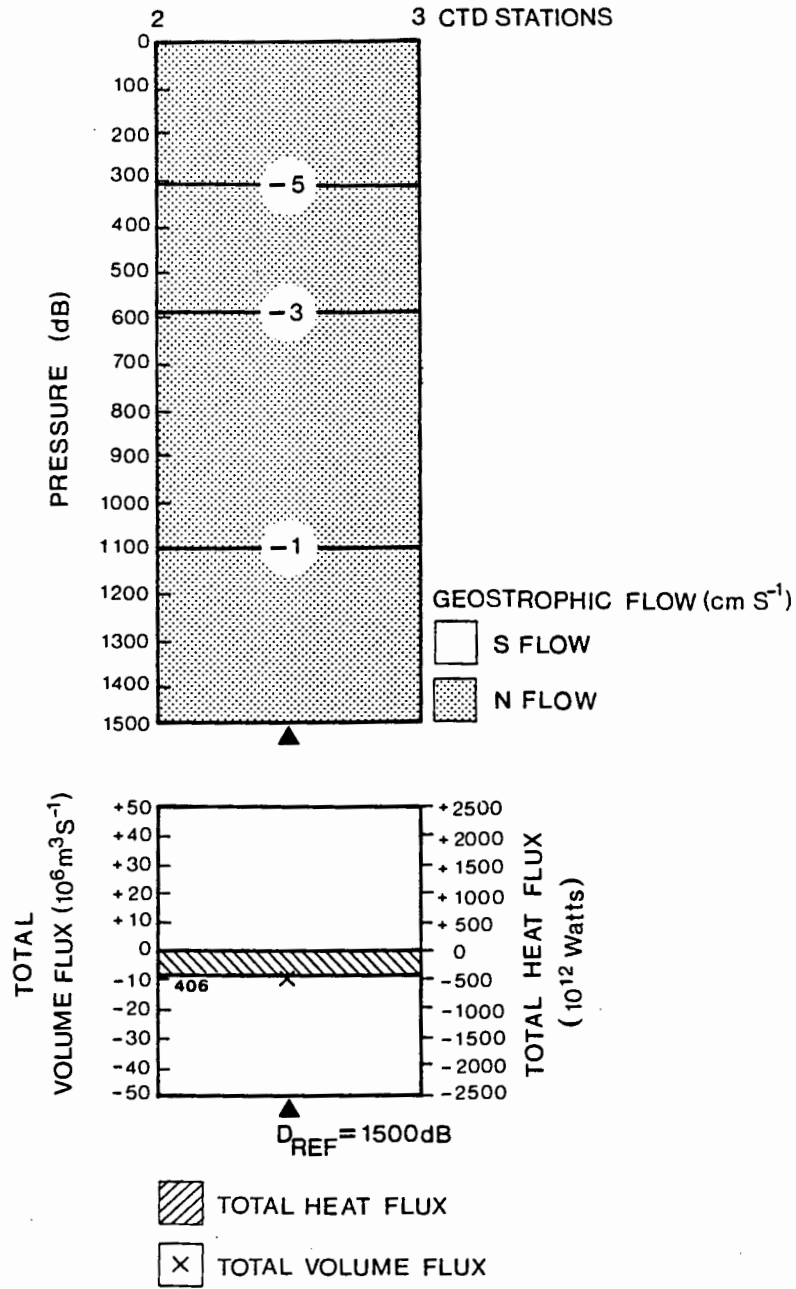
SECTION 1

RING A1



350 km

SECTION 1: Full-depth sections of temperature ($^{\circ}\text{C}$), potential temperature ($^{\circ}\text{C}$), salinity (psu) and potential density (kg.m^{-3}) versus pressure (db).

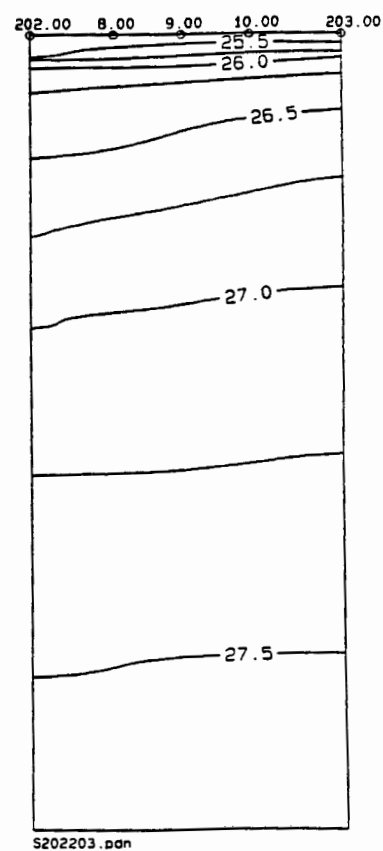
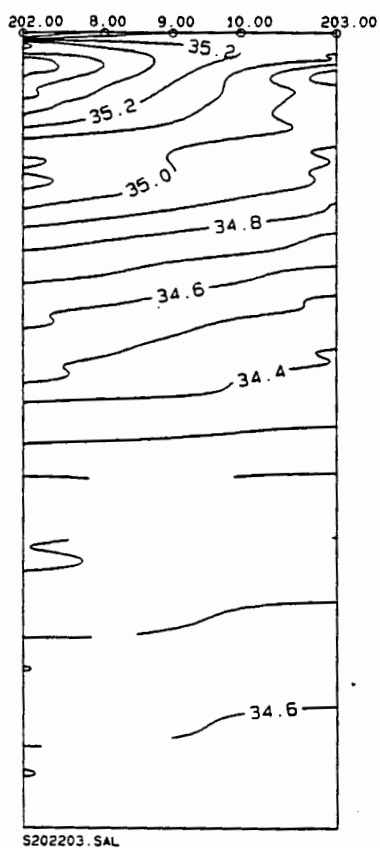
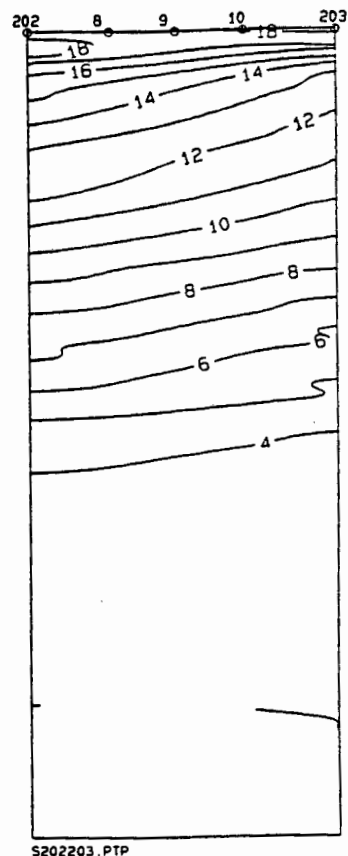
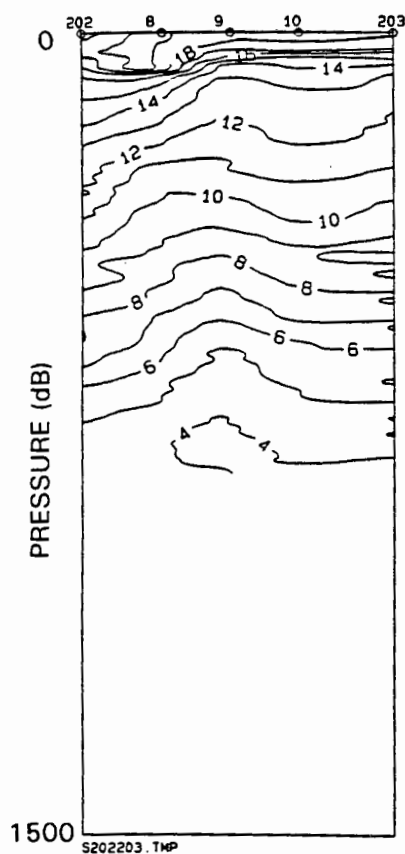


SECTION 1: Full-depth sections of geostrophic velocity (cm.s^{-1}) versus pressure (db), total geostrophic volume transport ($10^6 \text{m}^3.\text{s}^{-1}$) and total geostrophic heat flux (10^{12} Watts), referenced to 1000 db.

Addendum 2

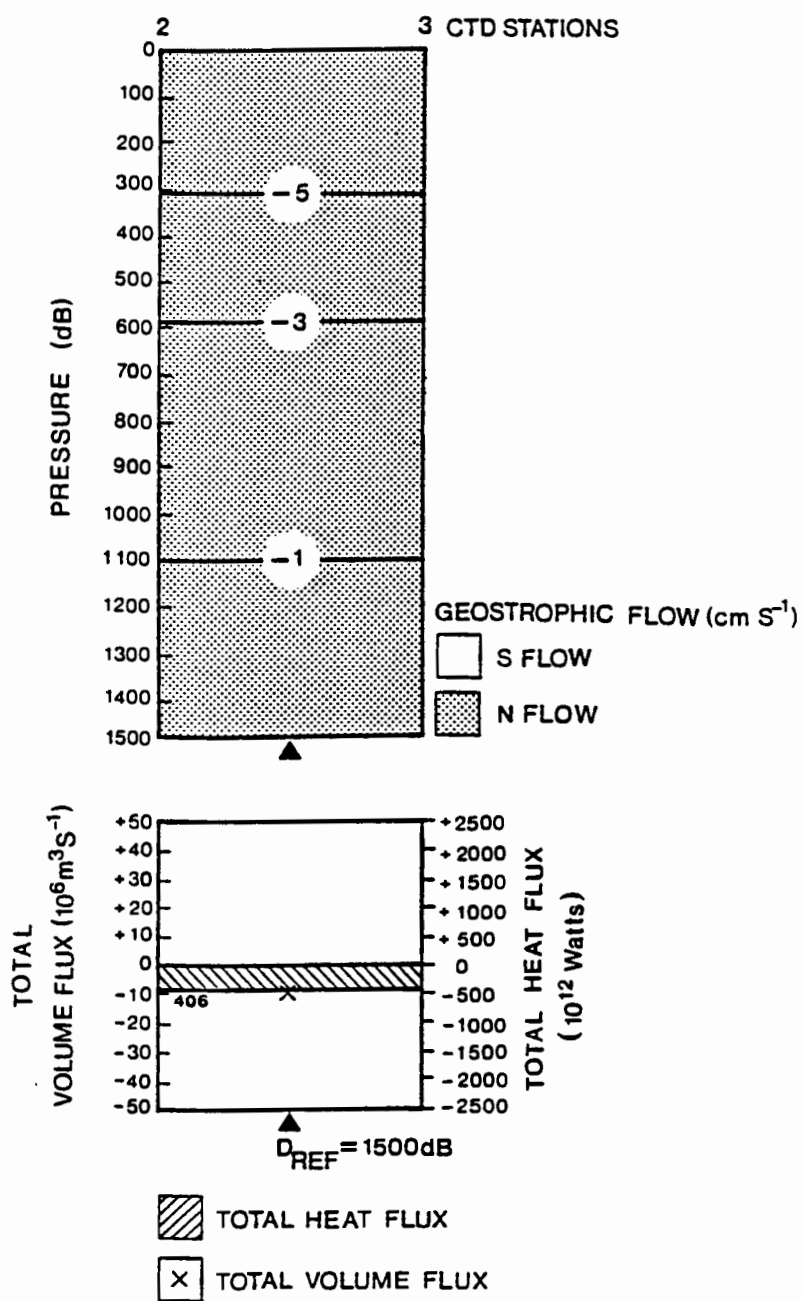
Temperature, Potential Temperature, Salinity and Potential Density, Geostrophic Velocity and Volume and Heat Flux Sections of the *SCARC*.

SECTION 2



230 km

SECTION 2: Full-depth sections of temperature ($^{\circ}\text{C}$), potential temperature ($^{\circ}\text{C}$), salinity (psu) and potential density (kg.m^{-3}) versus pressure (db).

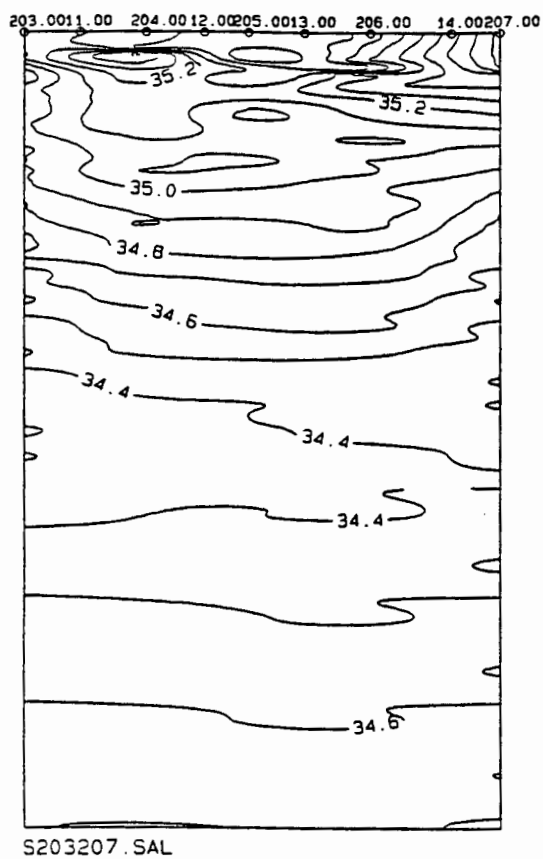
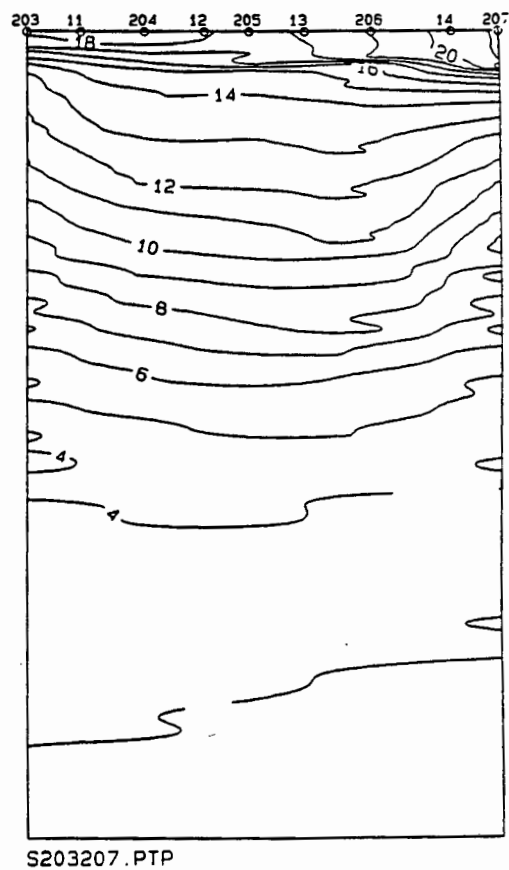
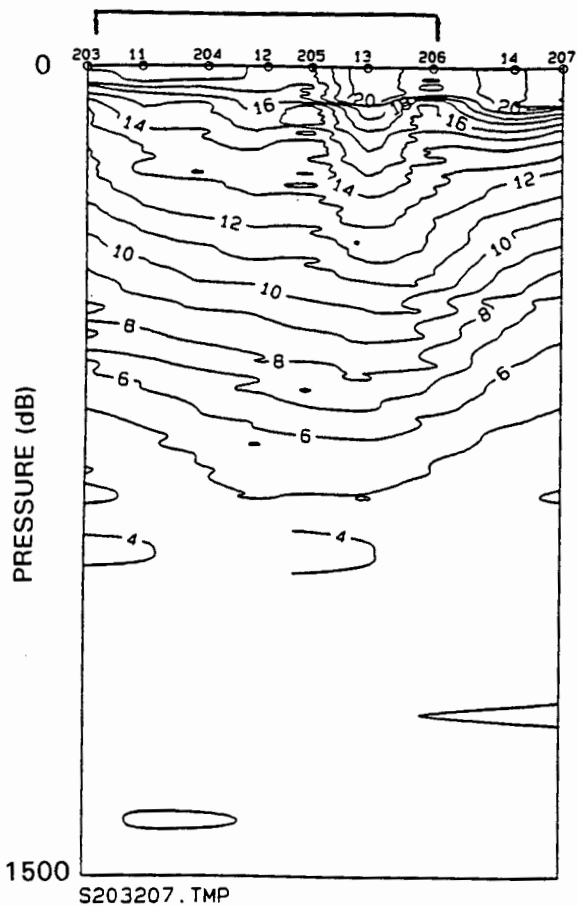


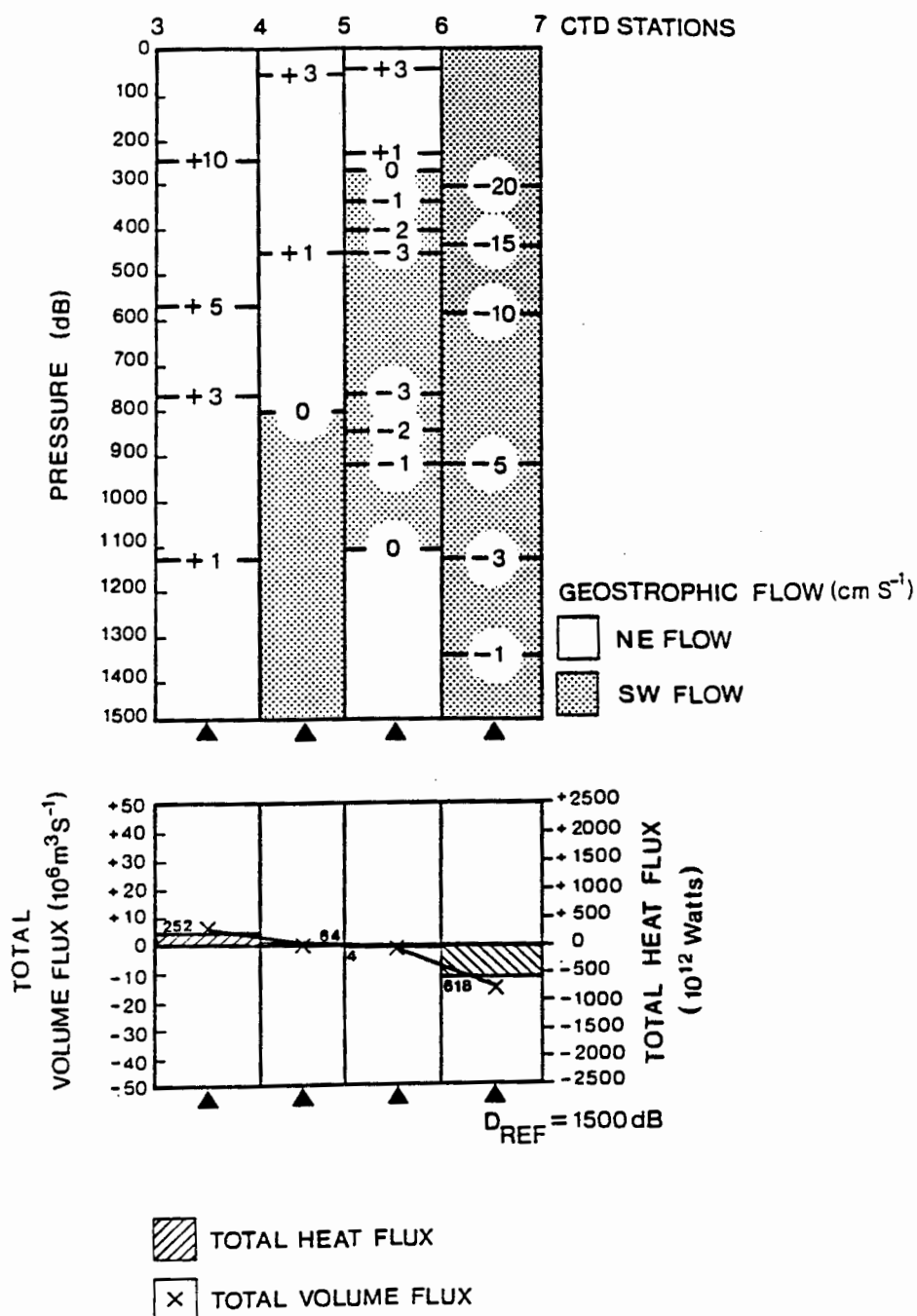
SECTION 2: Full-depth sections of geostrophic velocity (cm.s^{-1}) versus pressure (db), total geostrophic volume transport ($10^6 \text{ m}^3 \text{ s}^{-1}$) and total geostrophic heat flux (10^{12} Watts), referenced to 1500 db.

Addendum 2

Temperature, Potential Temperature, Salinity and Potential Density, Geostrophic Velocity and Volume and Heat Flux Sections of the *SCARC*.

SECTION 3



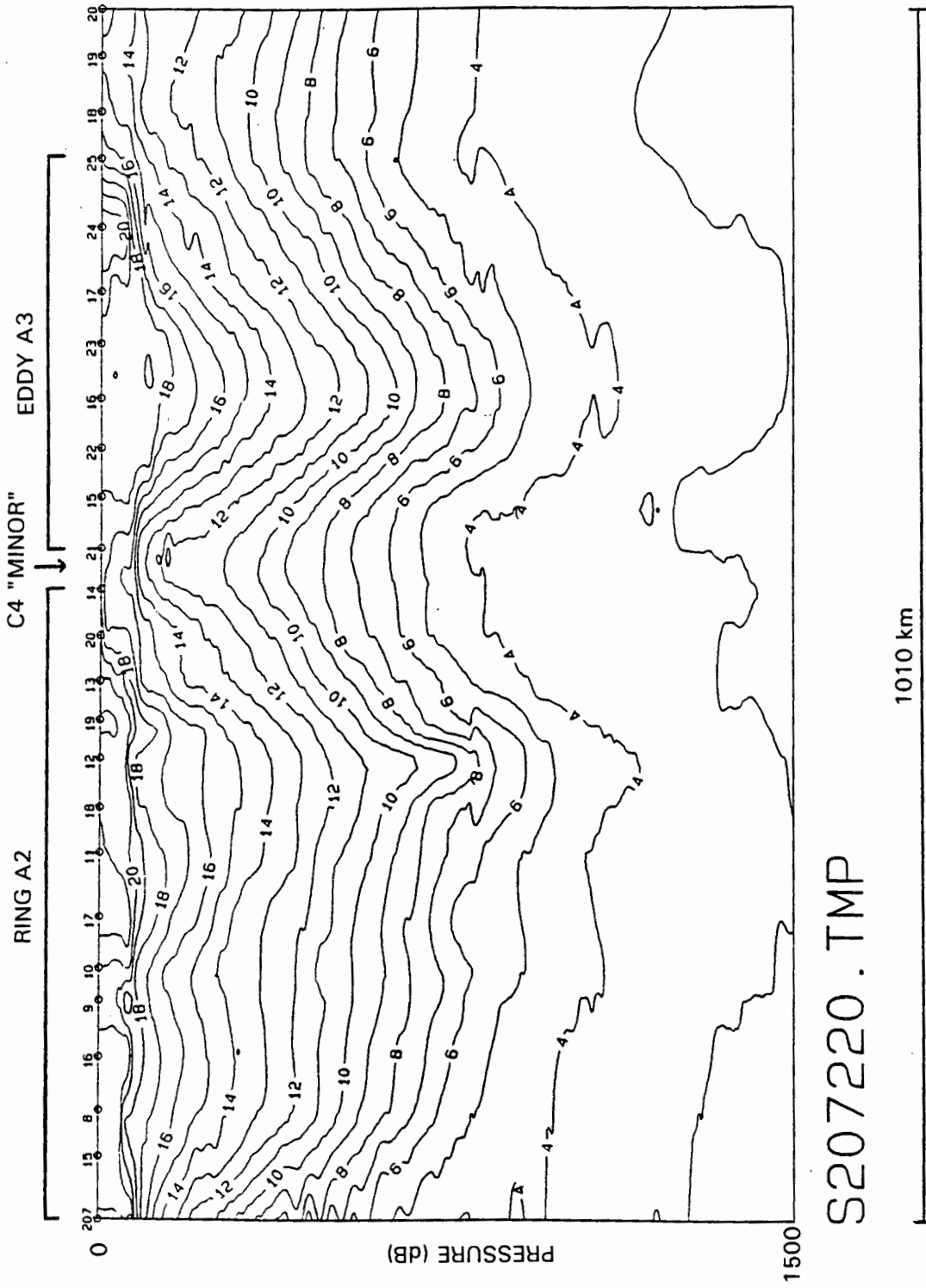


SECTION 3: Full-depth sections of geostrophic velocity (cm.s⁻¹) versus pressure (db), total geostrophic volume transport (10⁶m³.s⁻¹) and total geostrophic heat flux (10¹² Watts), referenced to 1500 db.

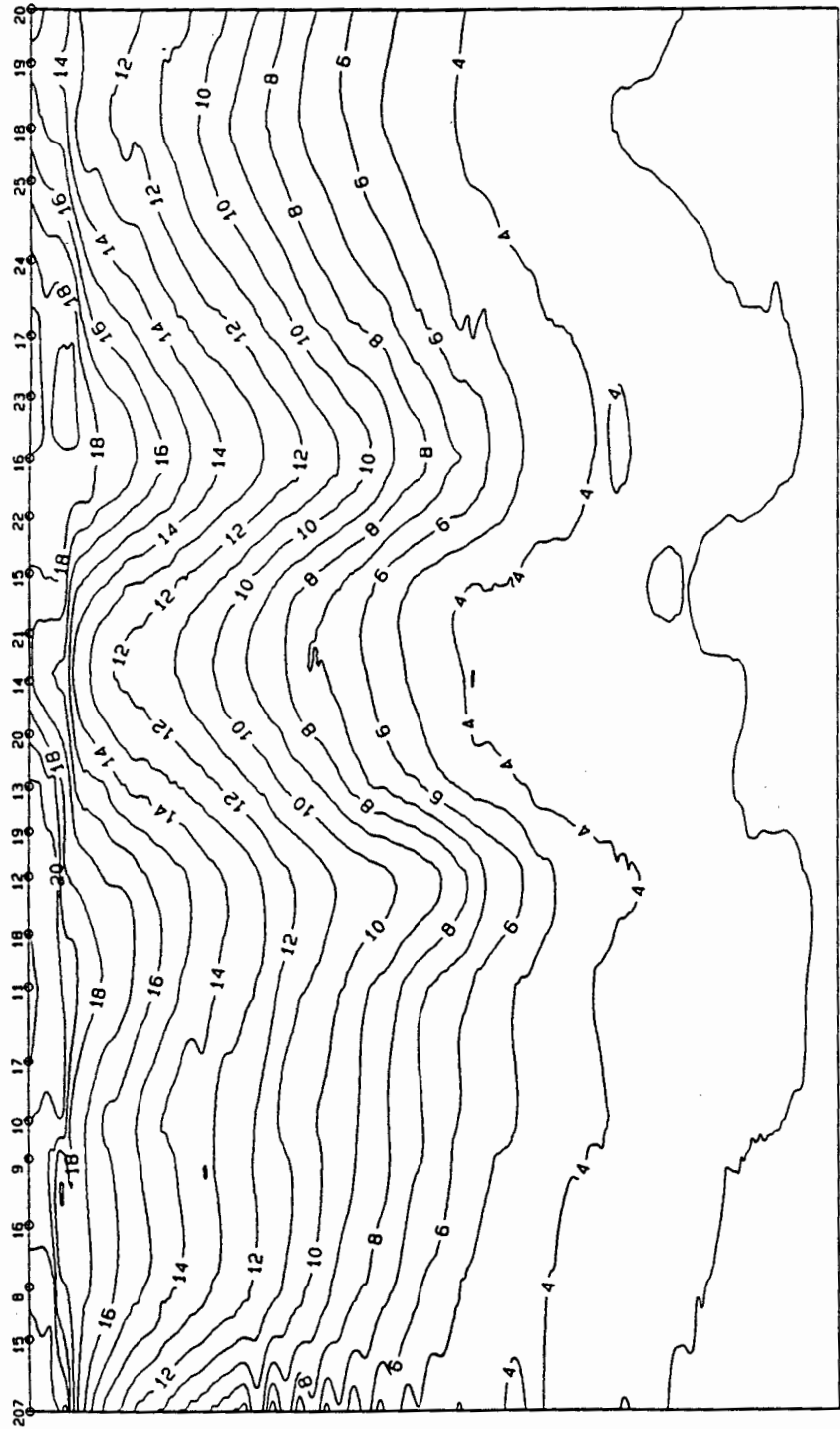
Addendum 2

Temperature, Potential Temperature, Salinity and Potential Density, Geostrophic Velocity and Volume and Heat Flux Sections of the *SCARC*.

SECTION 4



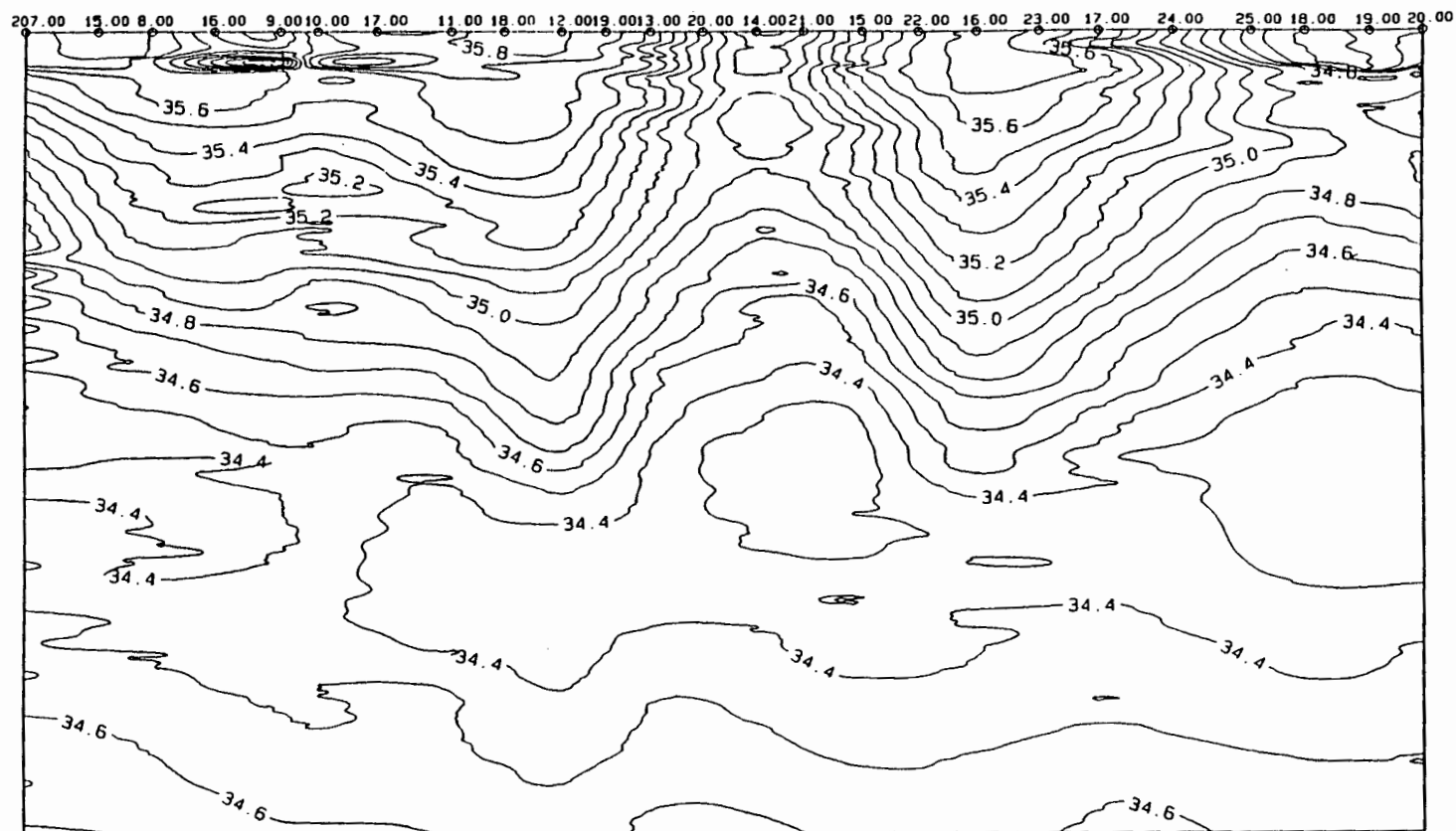
SECTION 4: Full-depth section of temperature (°C) versus pressure (db).



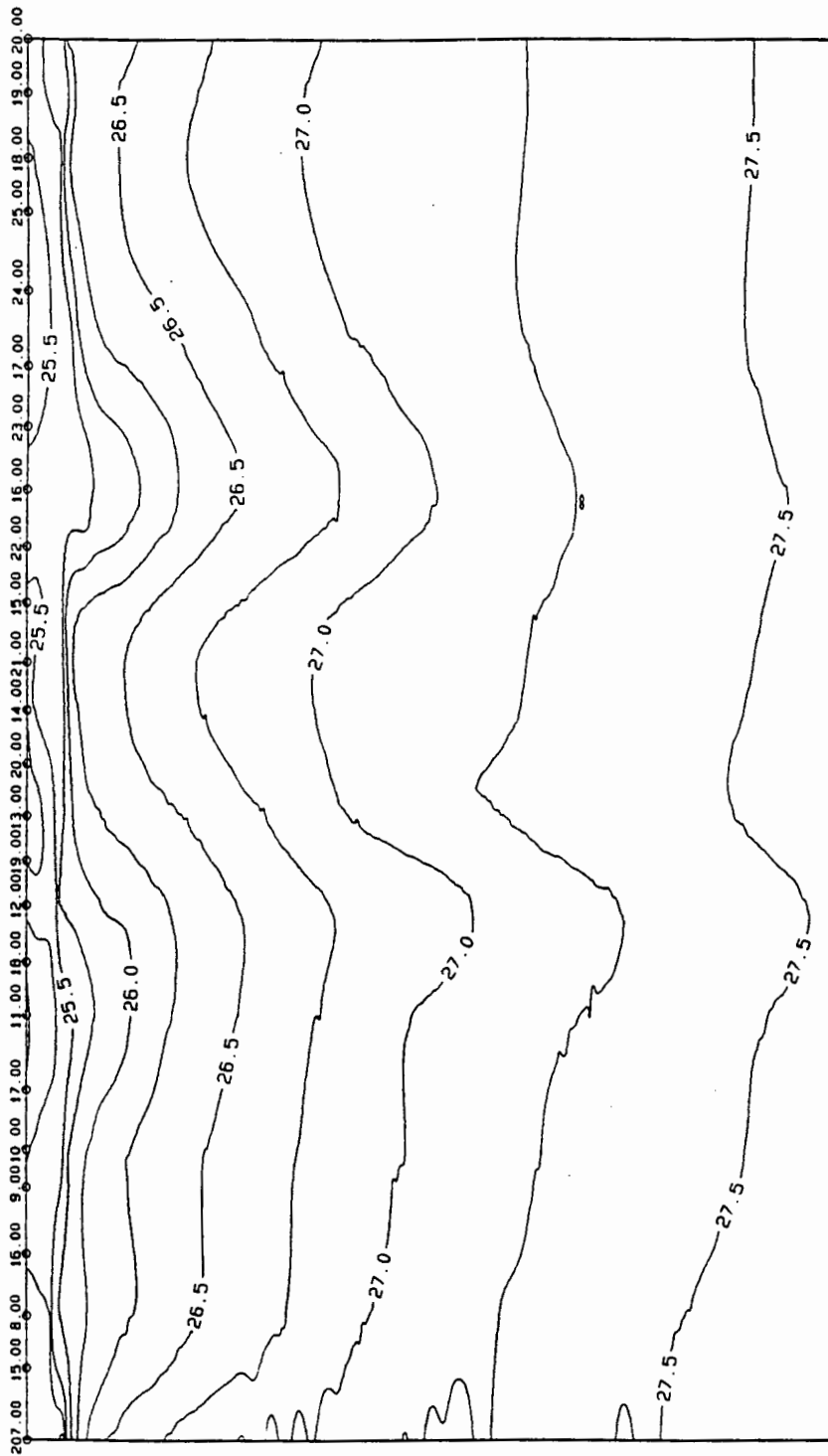
S207220.PTP

SECTION 4: Full-depth section of potential temperature (°C) versus pressure (db).

SECTION 4: Full-depth section of salinity (psu) versus pressure (db).

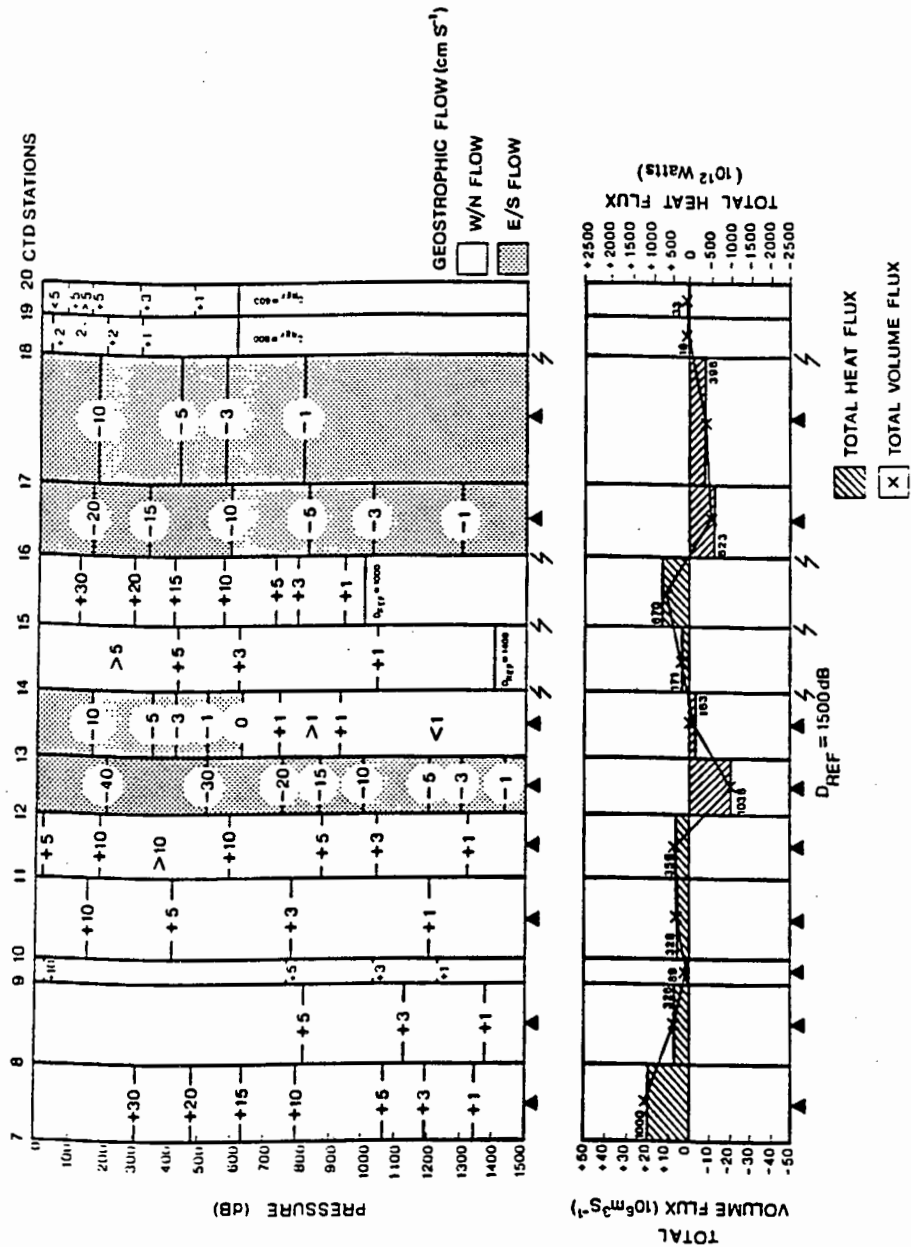


S207220 . SAL



S207220.pdn

SECTION 4: Full-depth section of potential density (kg.m^{-3}) versus pressure (db).

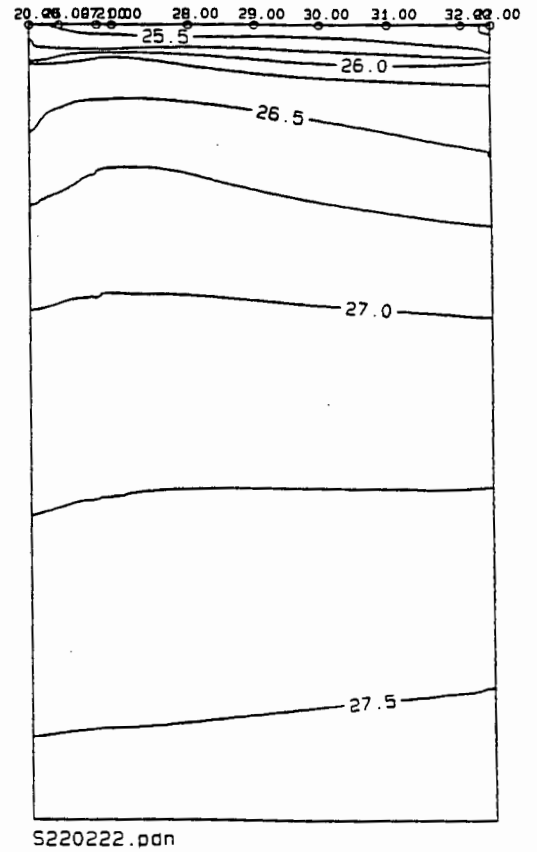
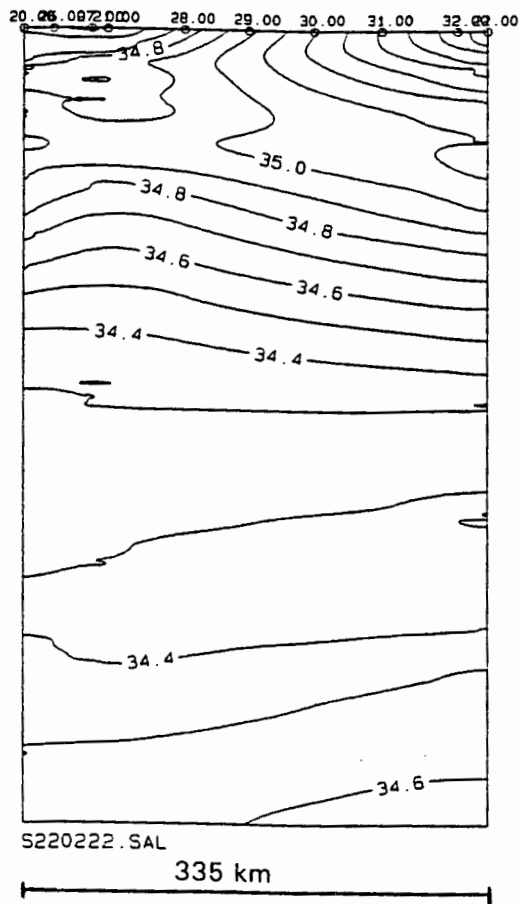
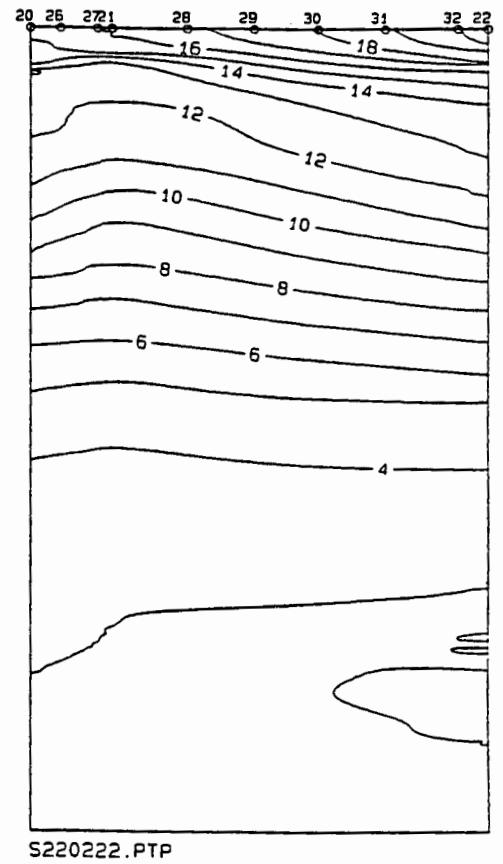
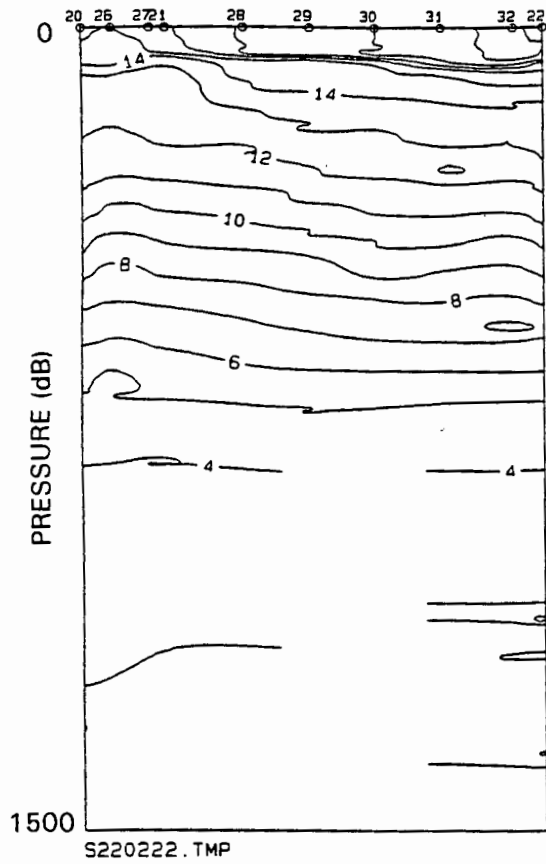


SECTION 4: Full-depth sections of geostrophic velocity (cm.s^{-1}) versus pressure (db), total geostrophic volume transport ($10^6 \text{ m}^3 \text{ s}^{-1}$) and total geostrophic heat flux (10^{12} Watts), referenced to 1500 db.

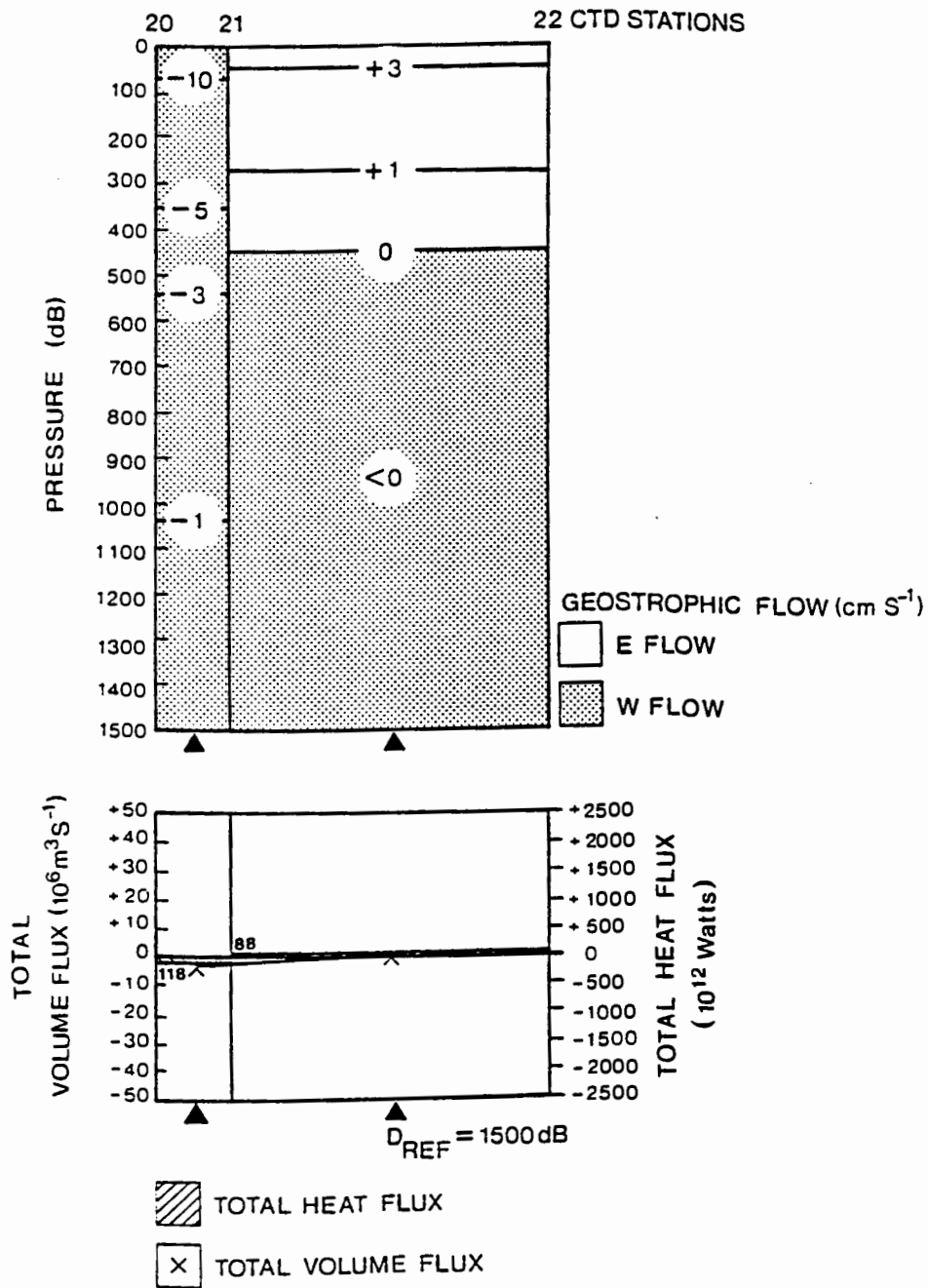
Addendum 2

Temperature, Potential Temperature, Salinity and Potential Density, Geostrophic Velocity and Volume and Heat Flux Sections of the *SCARC*.

SECTION 5



SECTION 5: Full-depth sections of temperature (°C), potential temperature (°C), salinity (psu) and potential density (kg.m⁻³) versus pressure (db).

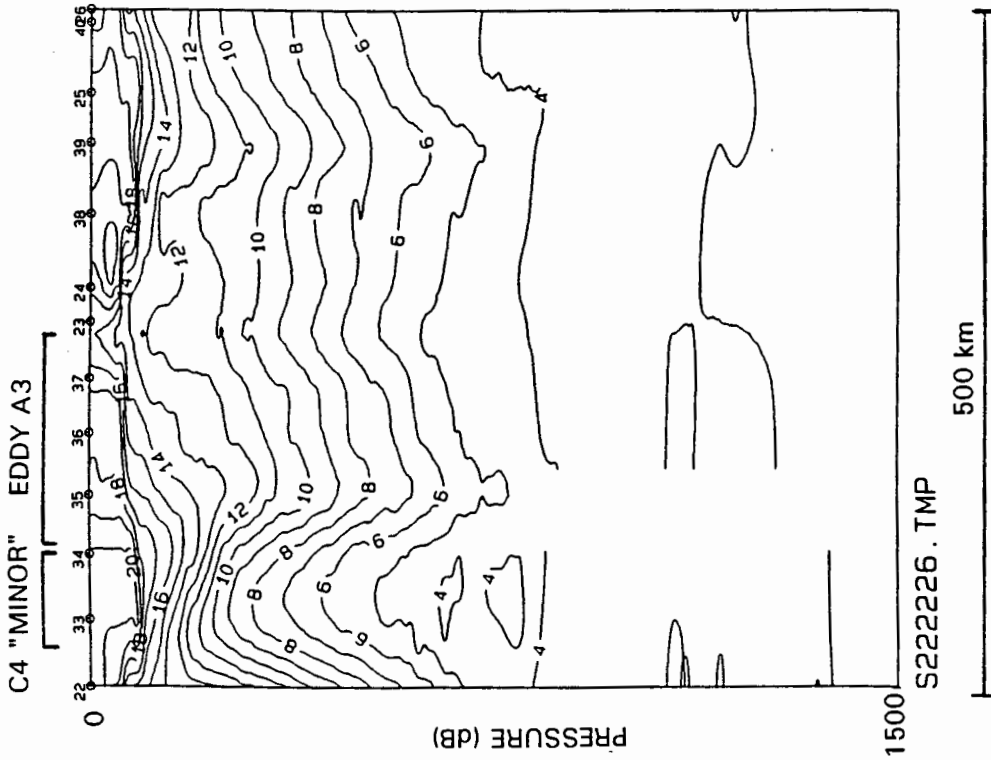


SECTION 5: Full-depth sections of geostrophic velocity (cm.s^{-1}) versus pressure (db), total geostrophic volume transport ($10^6 \text{m}^3 \text{s}^{-1}$) and total geostrophic heat flux (10^{12}Watts), referenced to 1500 db.

Addendum 2

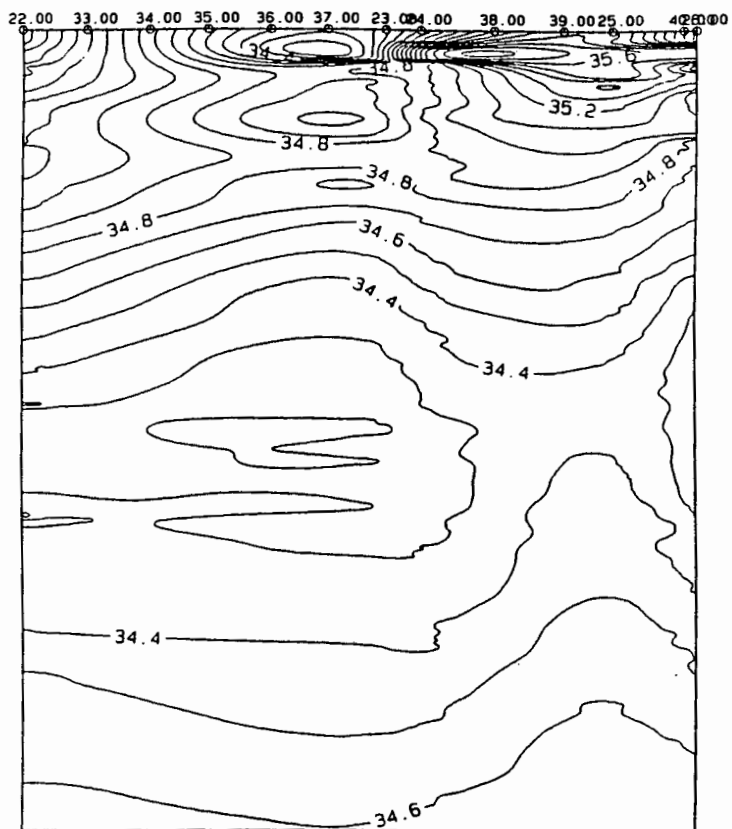
Temperature, Potential Temperature, Salinity and Potential Density, Geostrophic Velocity and Volume and Heat Flux Sections of the *SCARC*.

SECTION 6

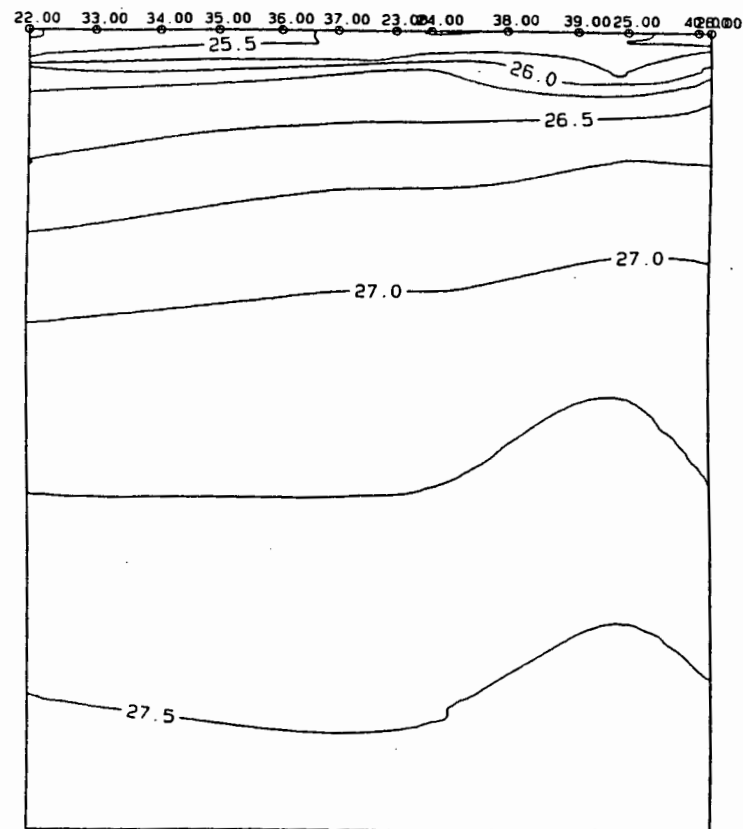


SECTION 6: Full-depth sections of temperature ($^{\circ}\text{C}$) and potential temperature ($^{\circ}\text{C}$) versus pressure (db).

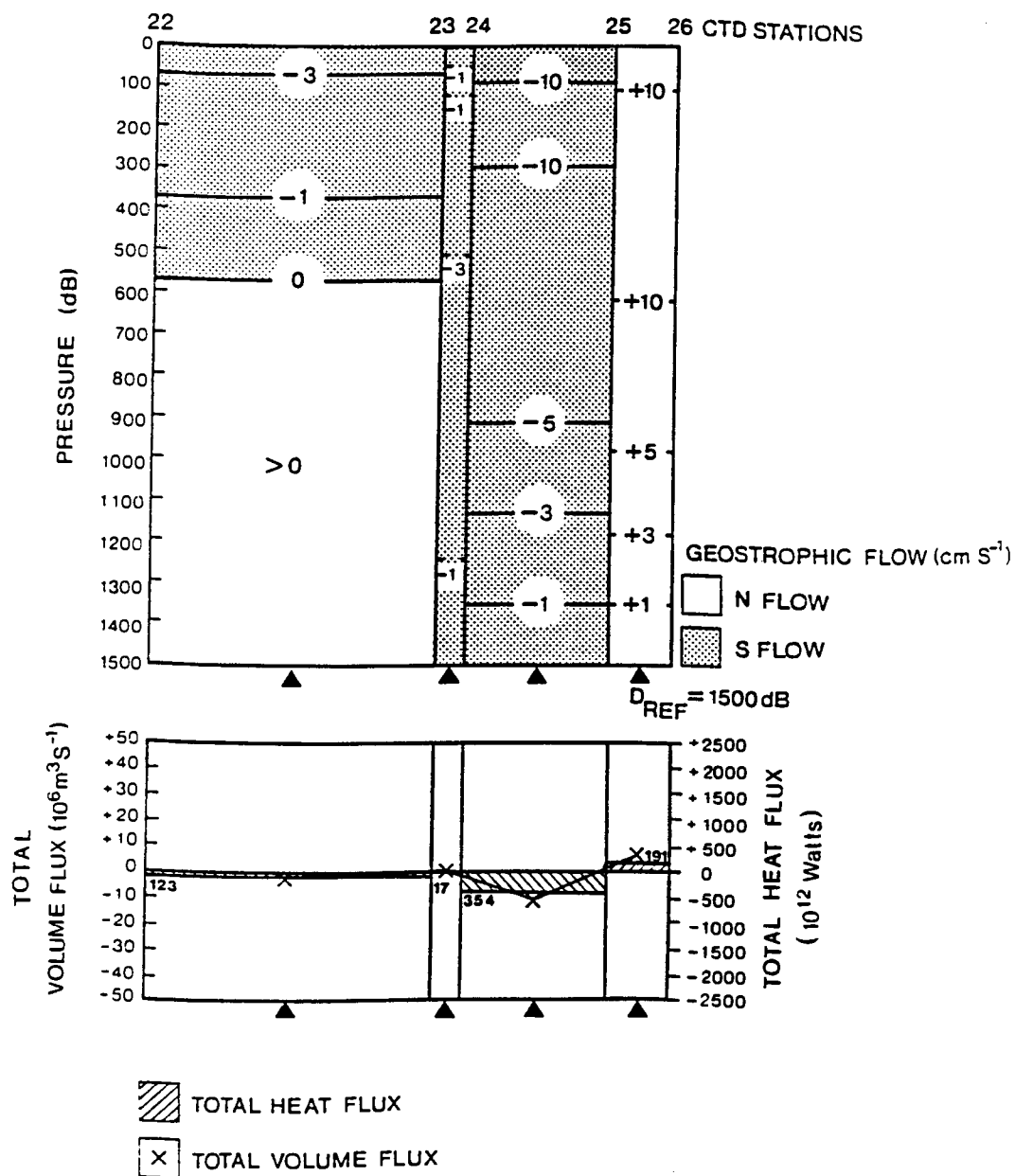
SECTION 6: Full-depth sections of salinity (psu) and potential density ($\text{kg}\cdot\text{m}^{-3}$) versus pressure (db).



S222226.SAL



S222226.pdn

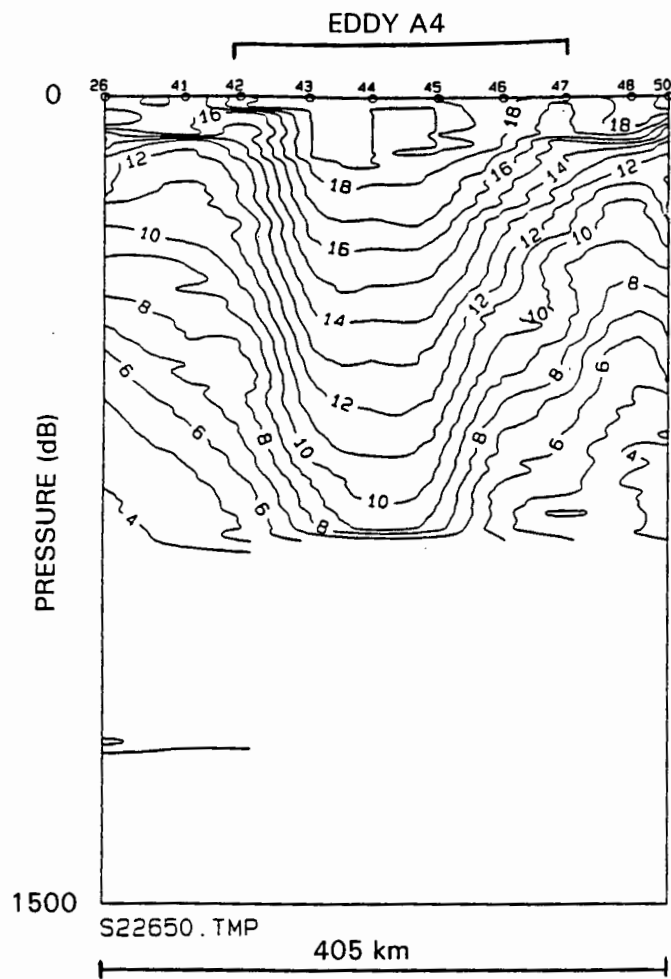


SECTION 6: Full-depth sections of geostrophic velocity (cm.s^{-1}) versus pressure (db), total geostrophic volume transport ($10^6 \text{ m}^3 \text{ s}^{-1}$) and total geostrophic heat flux (10^{12} Watts), referenced to 1500 db.

Addendum 2

Temperature Section of the *SCARC*.

SECTION 7

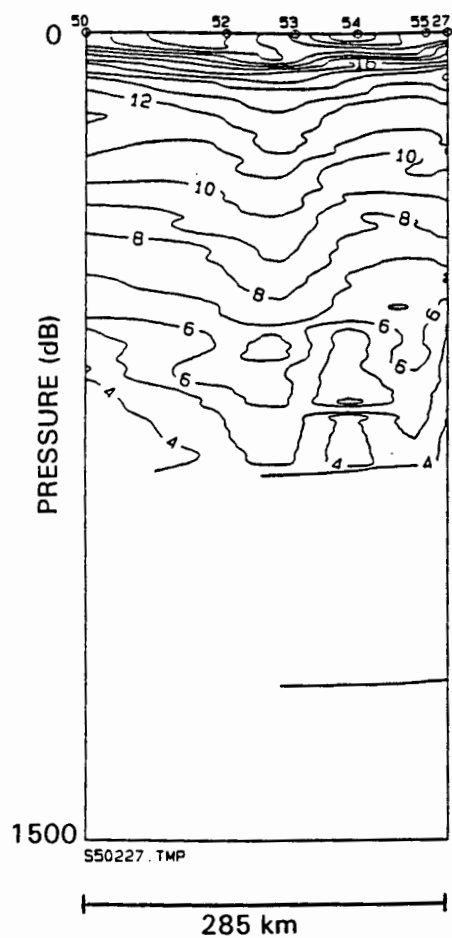


SECTION 7: Full-depth section of temperature ($^{\circ}\text{C}$) versus pressure (db).

Addendum 2

Temperature Section of the *SCARC*.

SECTION 8

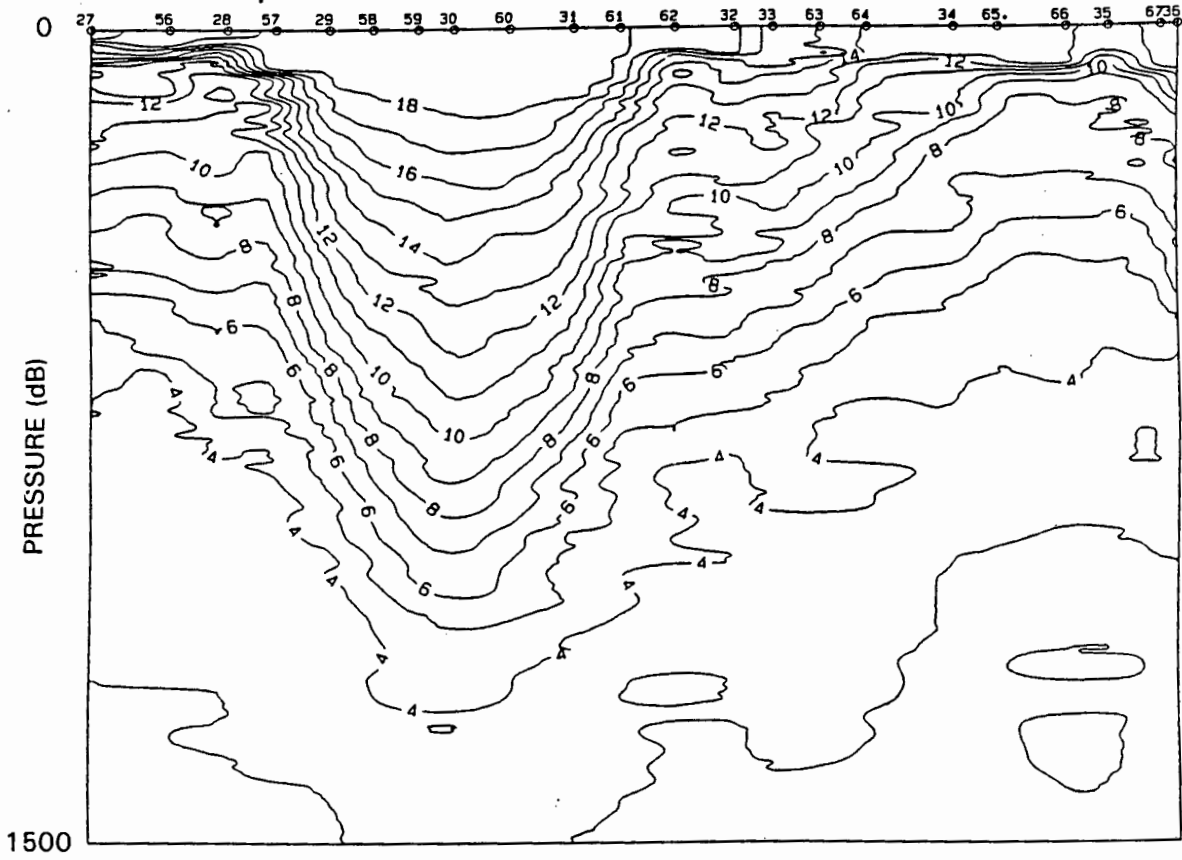


SECTION 8: Full-depth section of temperature (°C) versus pressure (db).

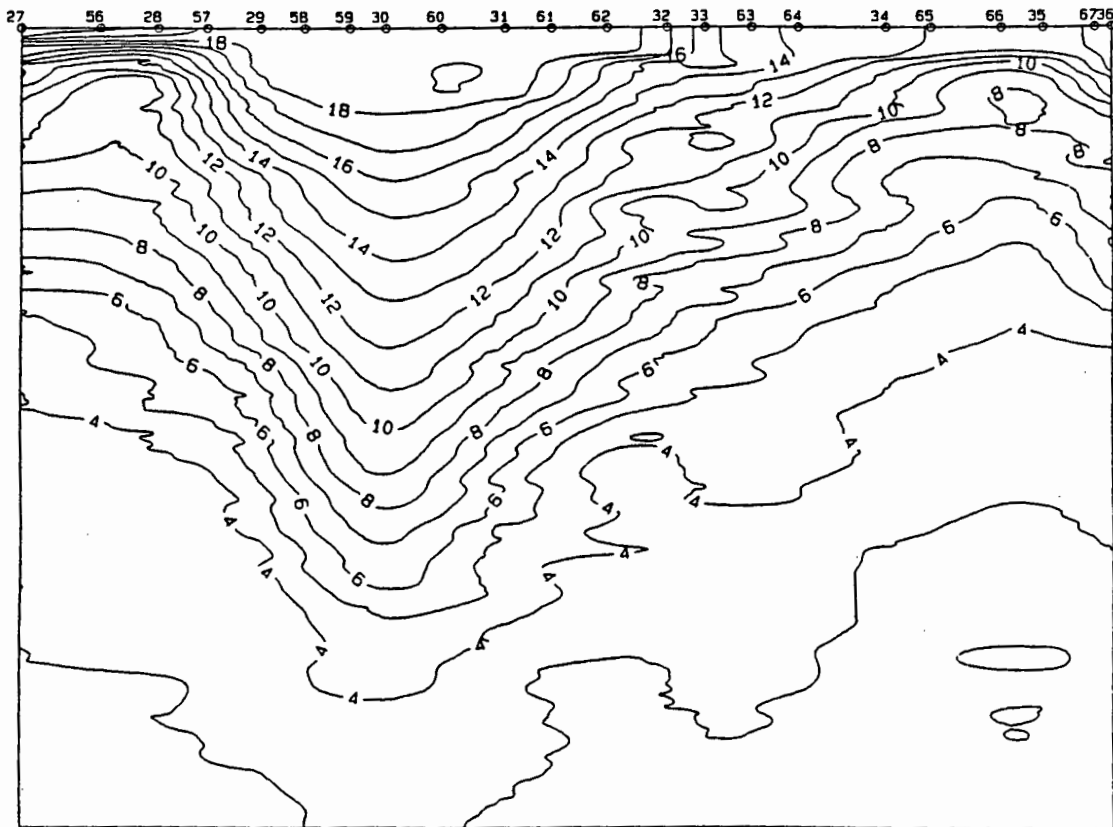
Addendum 2

Temperature, Potential Temperature, Salinity and Potential Density, Geostrophic Velocity and Volume and Heat Flux Sections of the *SCARC*.

SECTION 9



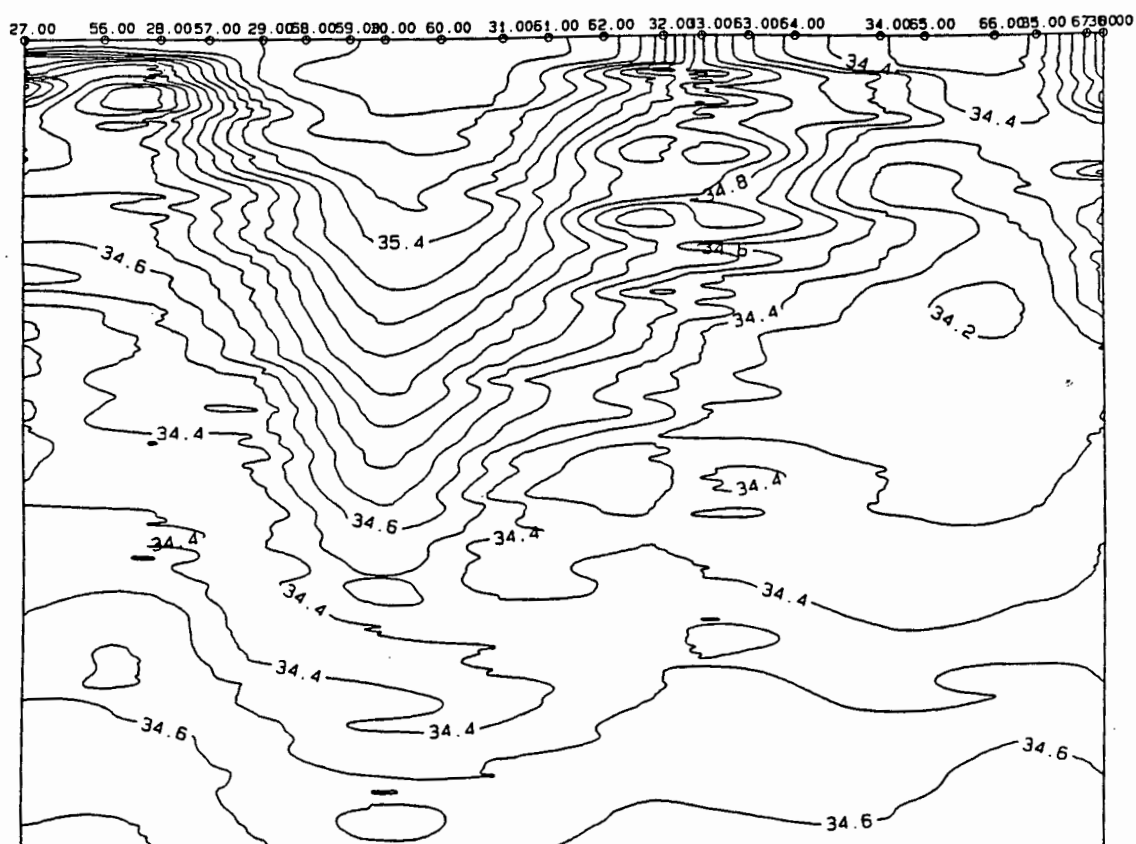
S227236.TMP



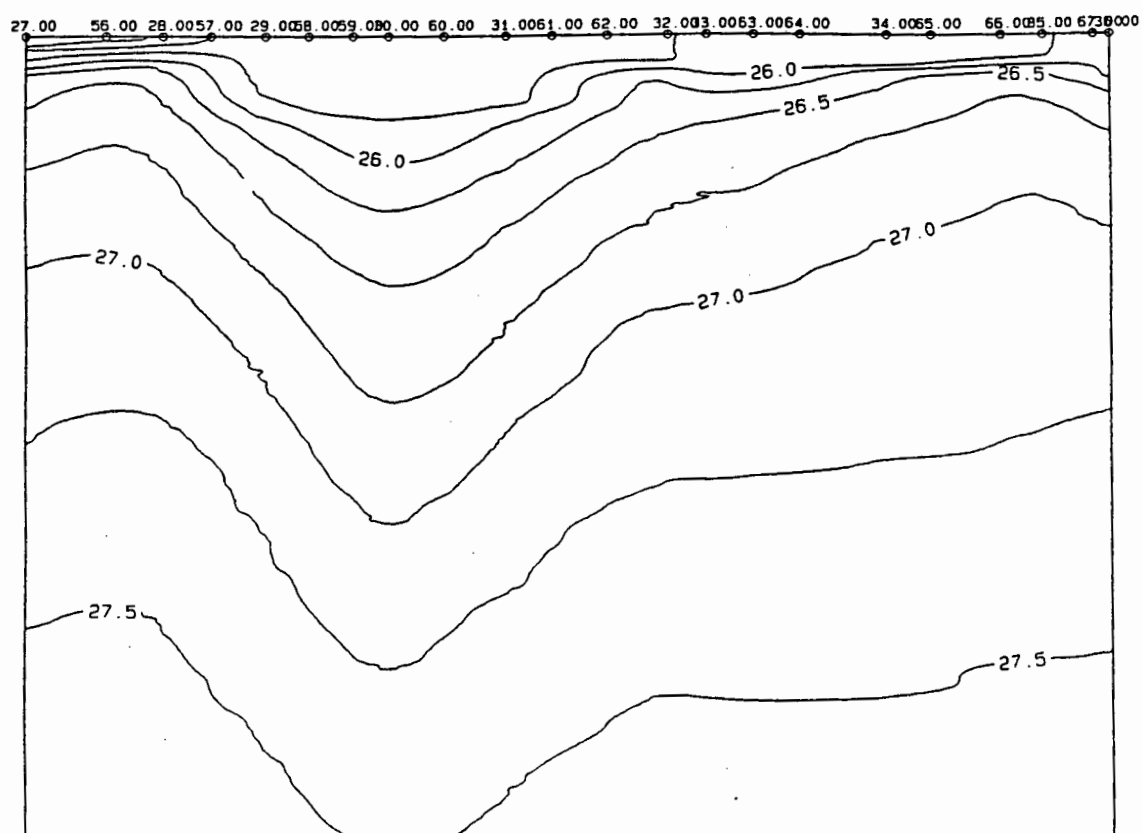
S227236.PTP

790 km

SECTION 9: Full-depth sections of temperature ($^{\circ}\text{C}$) and potential temperature ($^{\circ}\text{C}$) versus pressure (db).

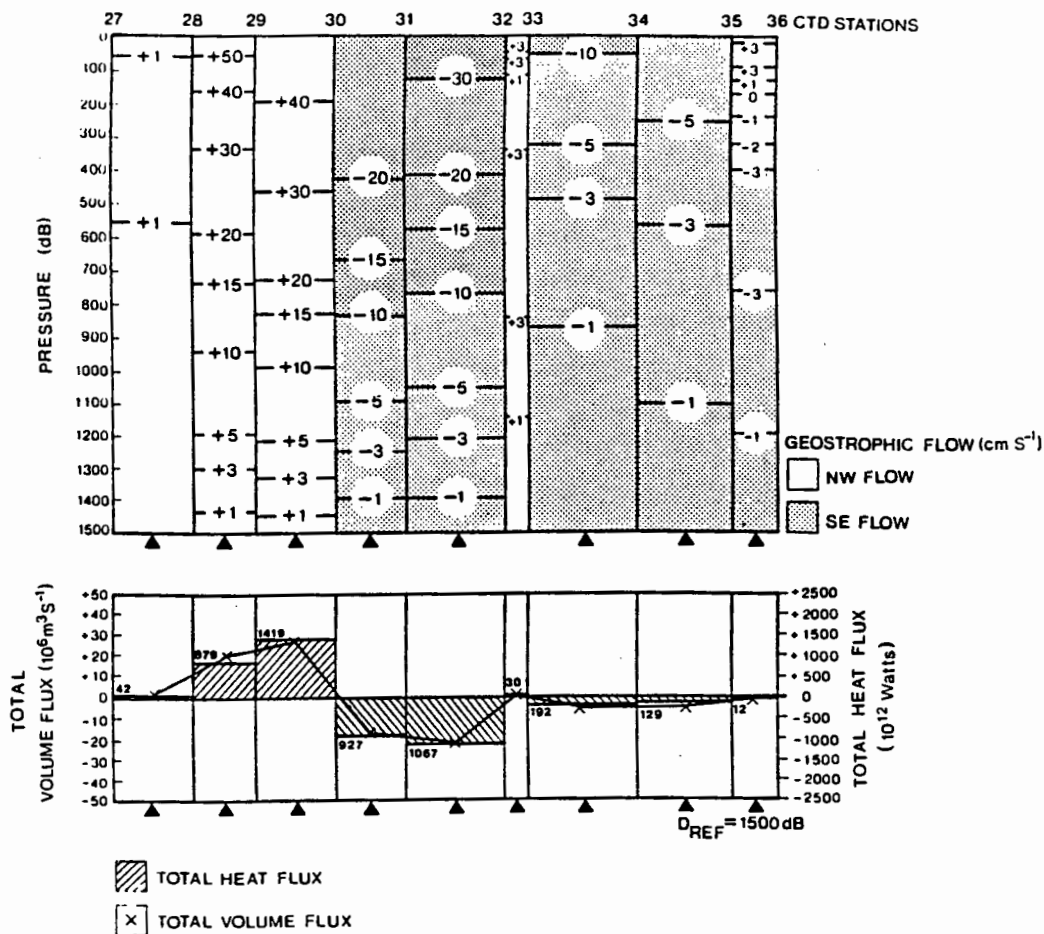


S227236.SAL



S227236.pdn

SECTION 9: Full-depth sections of salinity (psu) and potential density (kg.m^{-3}) versus pressure (db).

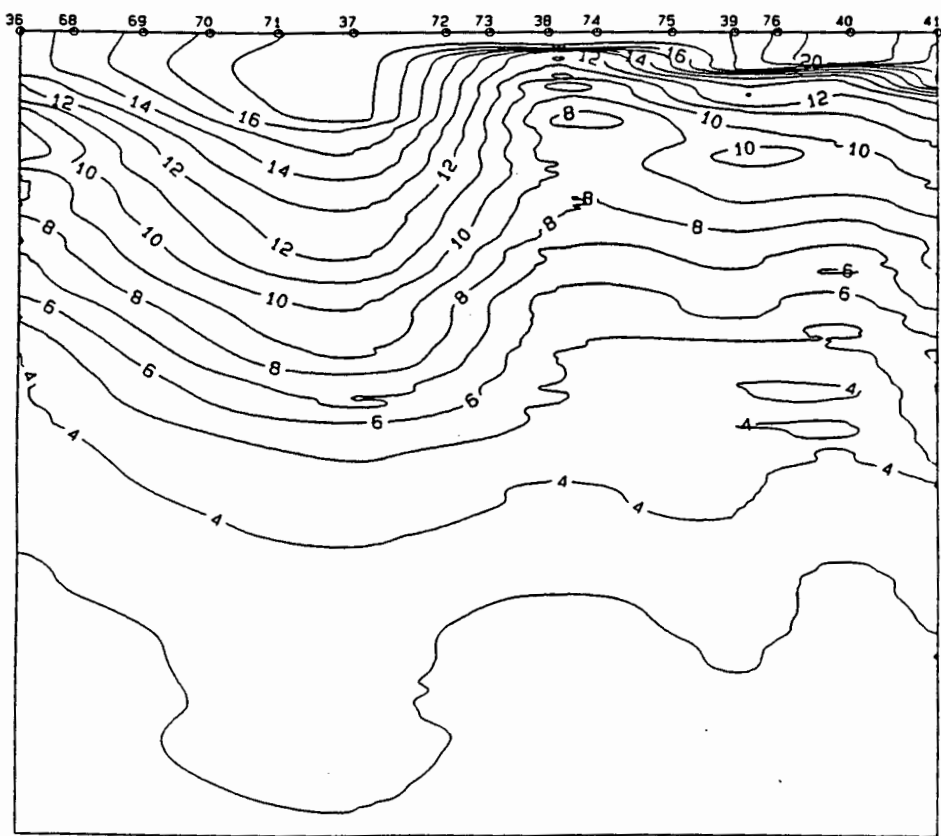
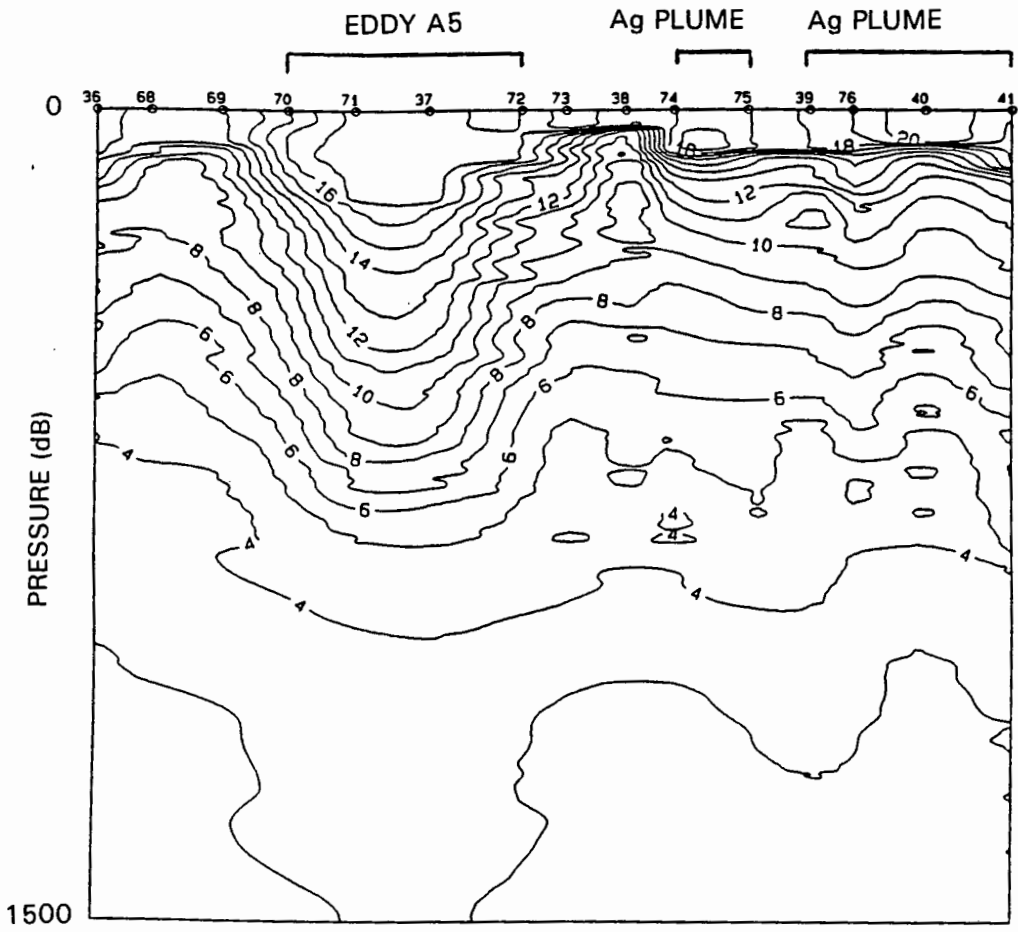


SECTION 9: Full-depth sections of geostrophic velocity (cm.s^{-1}) versus pressure (db), total geostrophic volume transport ($10^6 \text{m}^3.\text{s}^{-1}$) and total geostrophic heat flux (10^{12} Watts), referenced to 1500 db.

Addendum 2

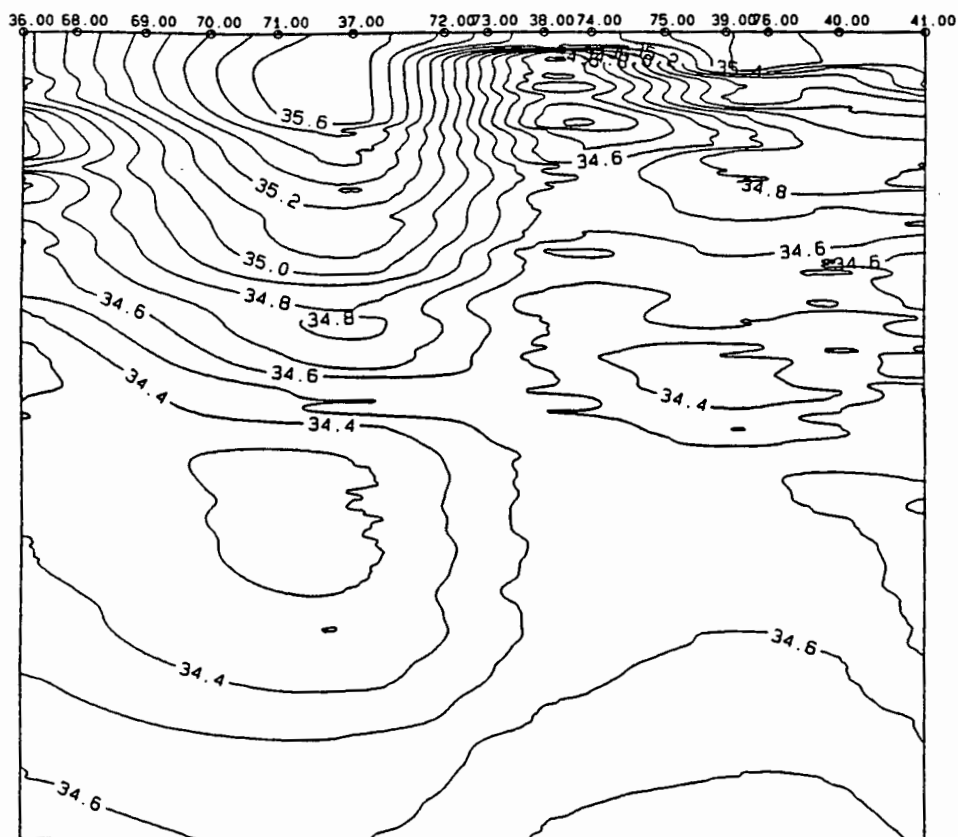
Temperature, Potential Temperature, Salinity and Potential Density, Geostrophic Velocity and Volume and Heat Flux Sections of the *SCARC*.

SECTION 10

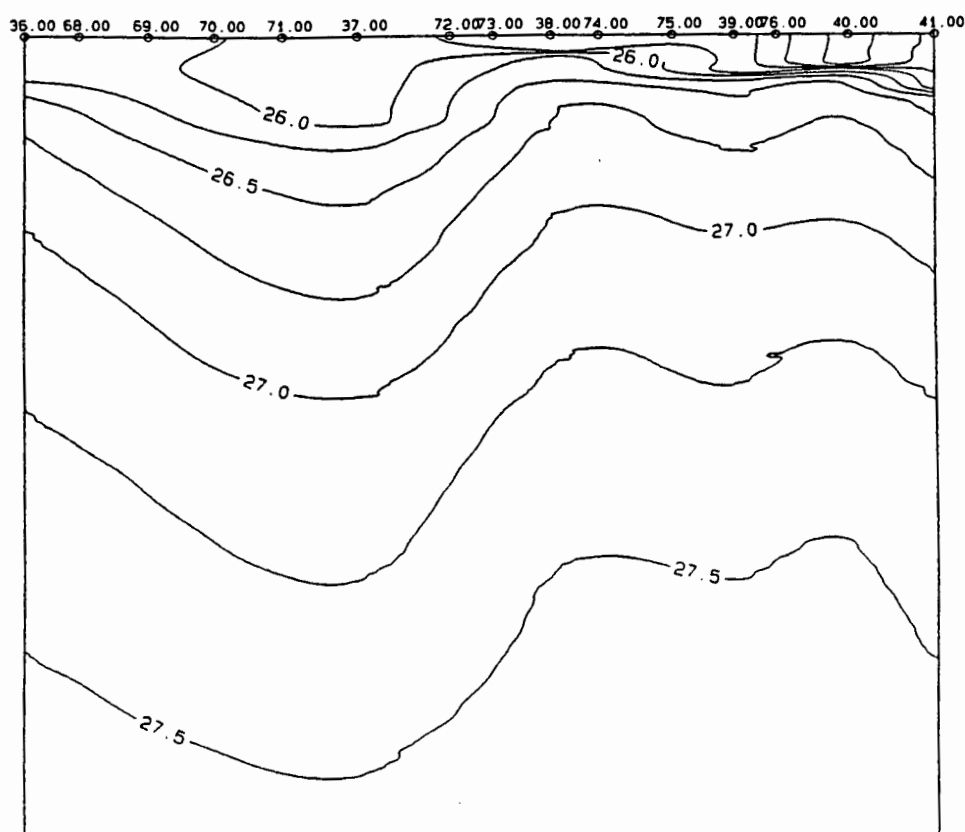


660 km

SECTION 10: Full-depth sections of temperature ($^{\circ}\text{C}$) and potential temperature ($^{\circ}\text{C}$) versus pressure (db).

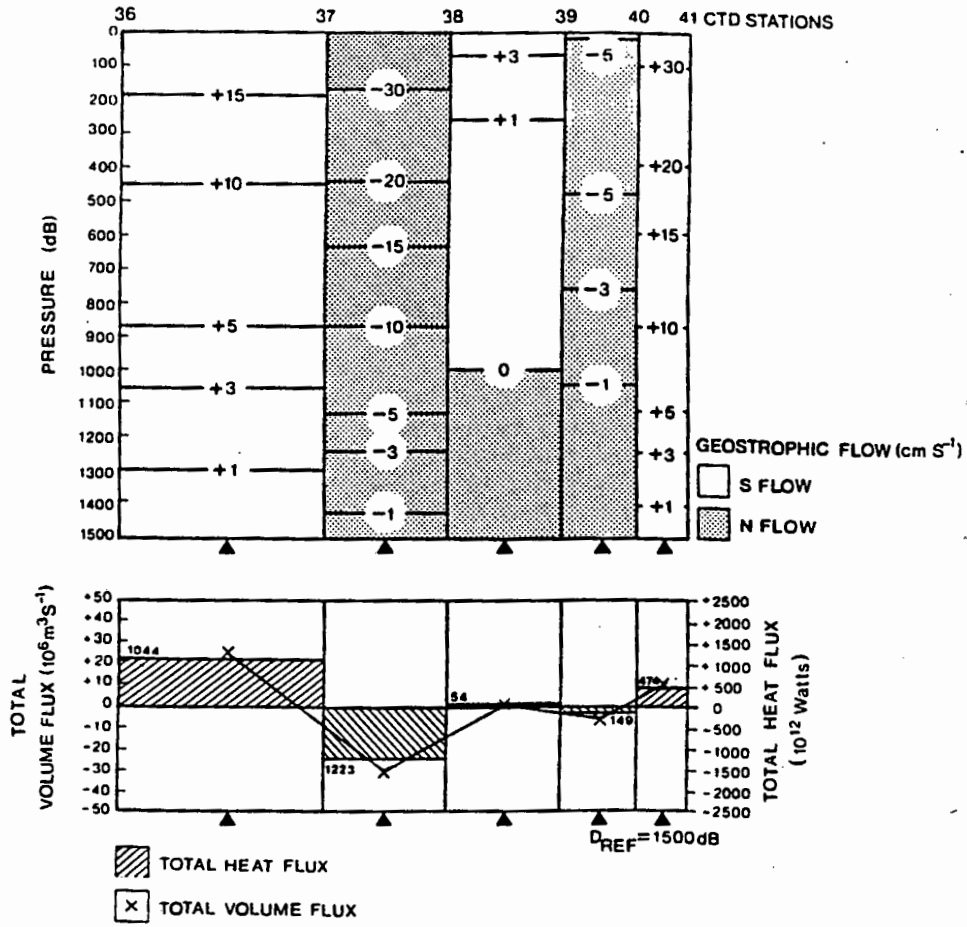


S236241.SAL



S236241.pdn

SECTION 10: Full-depth sections of salinity (psu) and potential density (kg.m^{-3}) versus pressure (db).

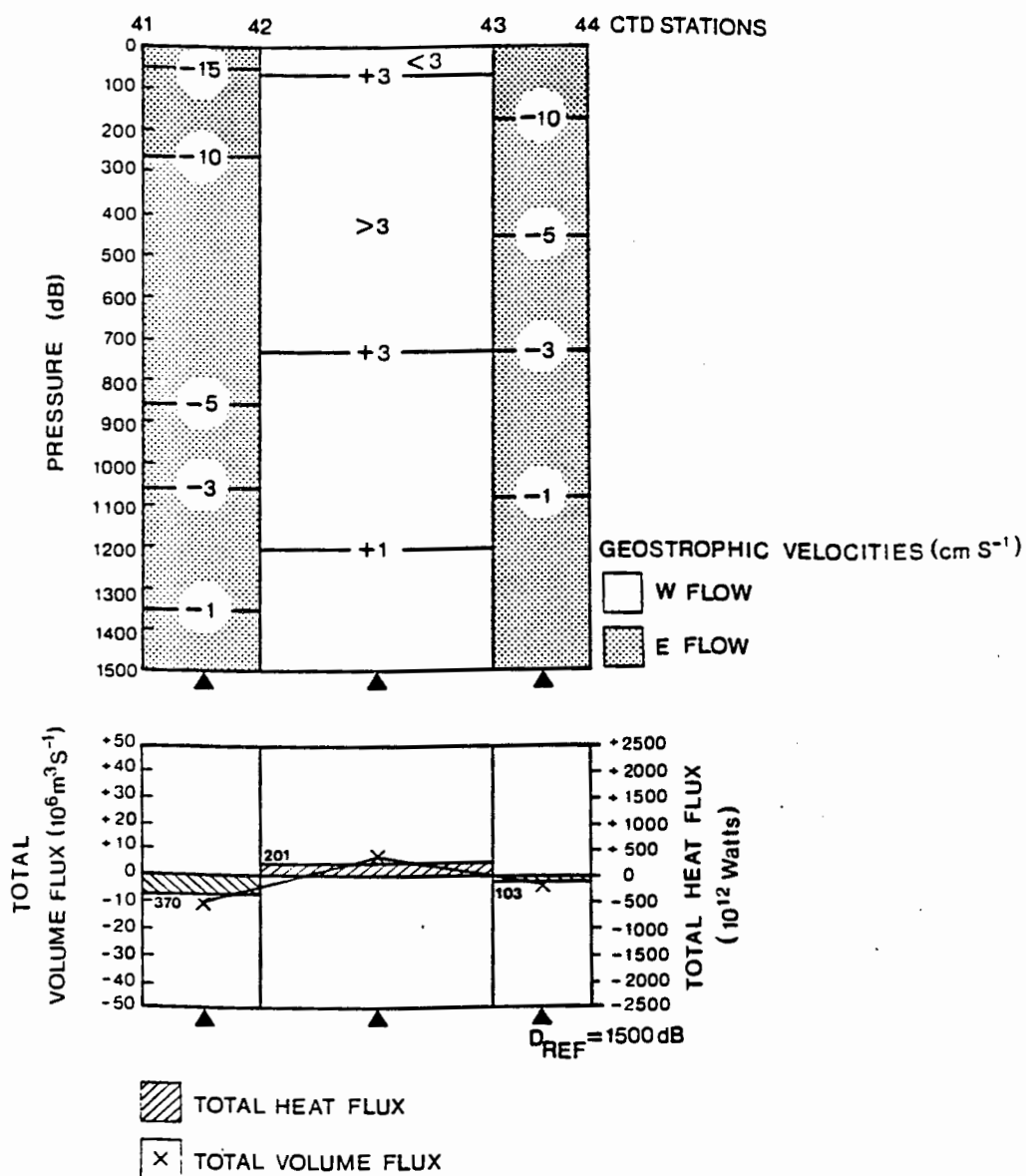


SECTION 10: Full-depth sections of geostrophic velocity (cm.s^{-1}) versus pressure (db), total geostrophic volume transport ($10^6 \text{ m}^3 \text{ s}^{-1}$) and total geostrophic heat flux (10^{12} Watts), referenced to 1500 db.

Addendum 2

Temperature, Potential Temperature, Salinity and Potential Density, Geostrophic Velocity and Volume and Heat Flux Sections of the *SCARC*.

SECTION 11

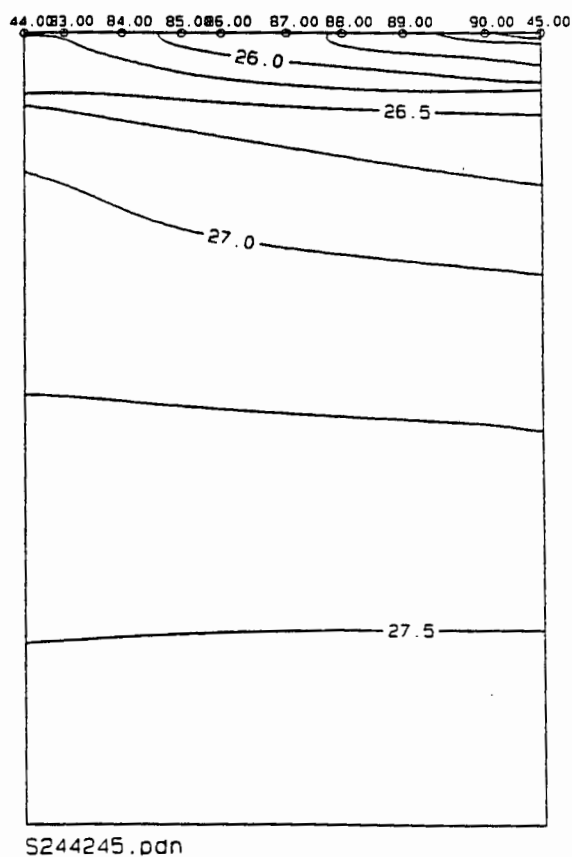
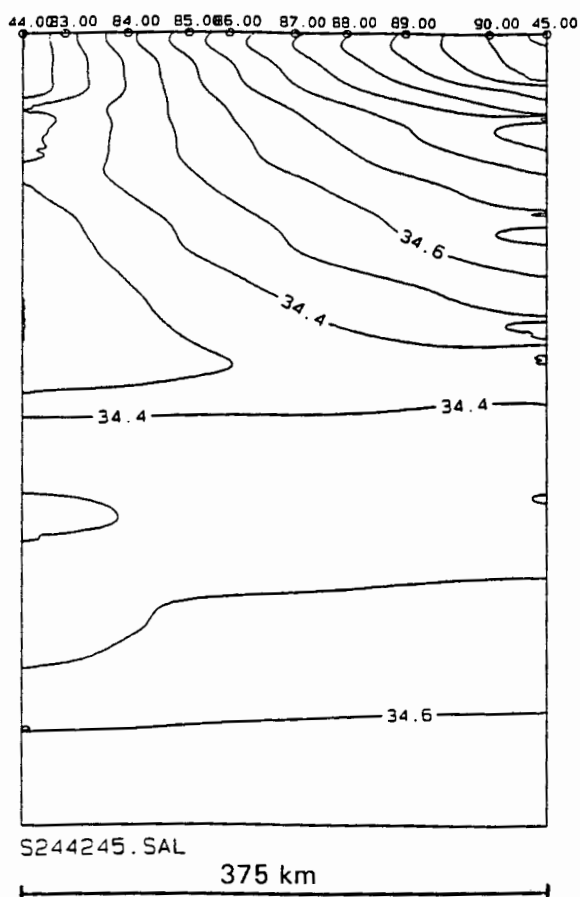
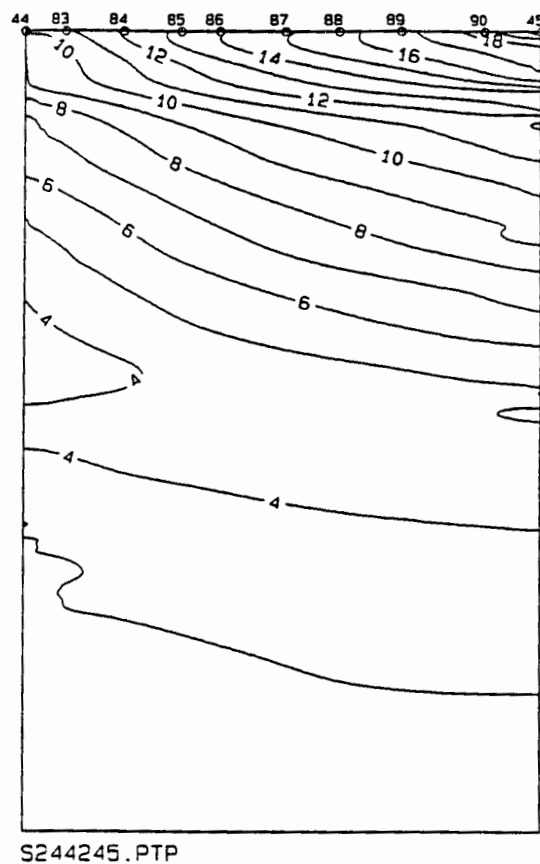
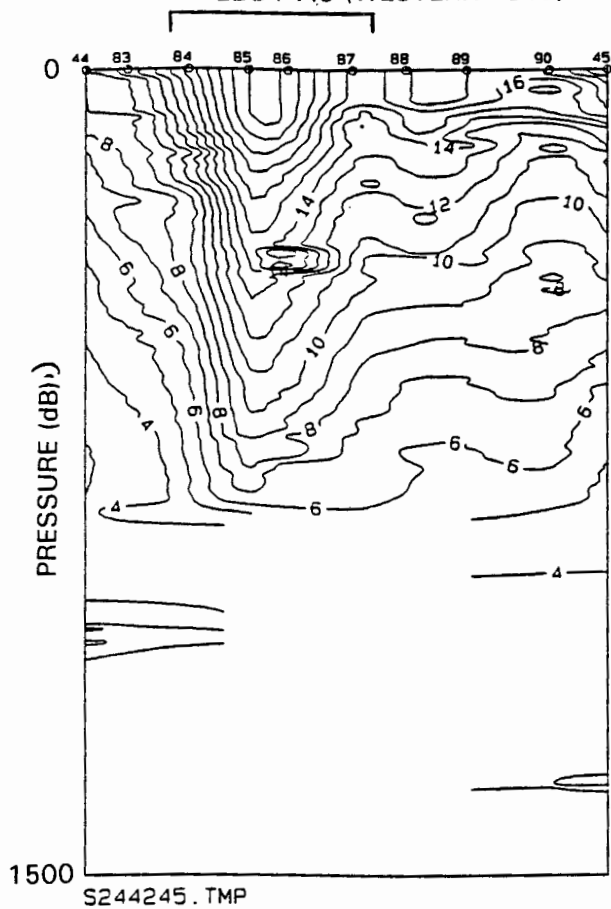


SECTION 11: Full-depth sections of geostrophic velocity (cm.s⁻¹) versus pressure (db), total geostrophic volume transport (10⁶m³.s⁻¹) and total geostrophic heat flux (10¹² Watts), referenced to 1500 db.

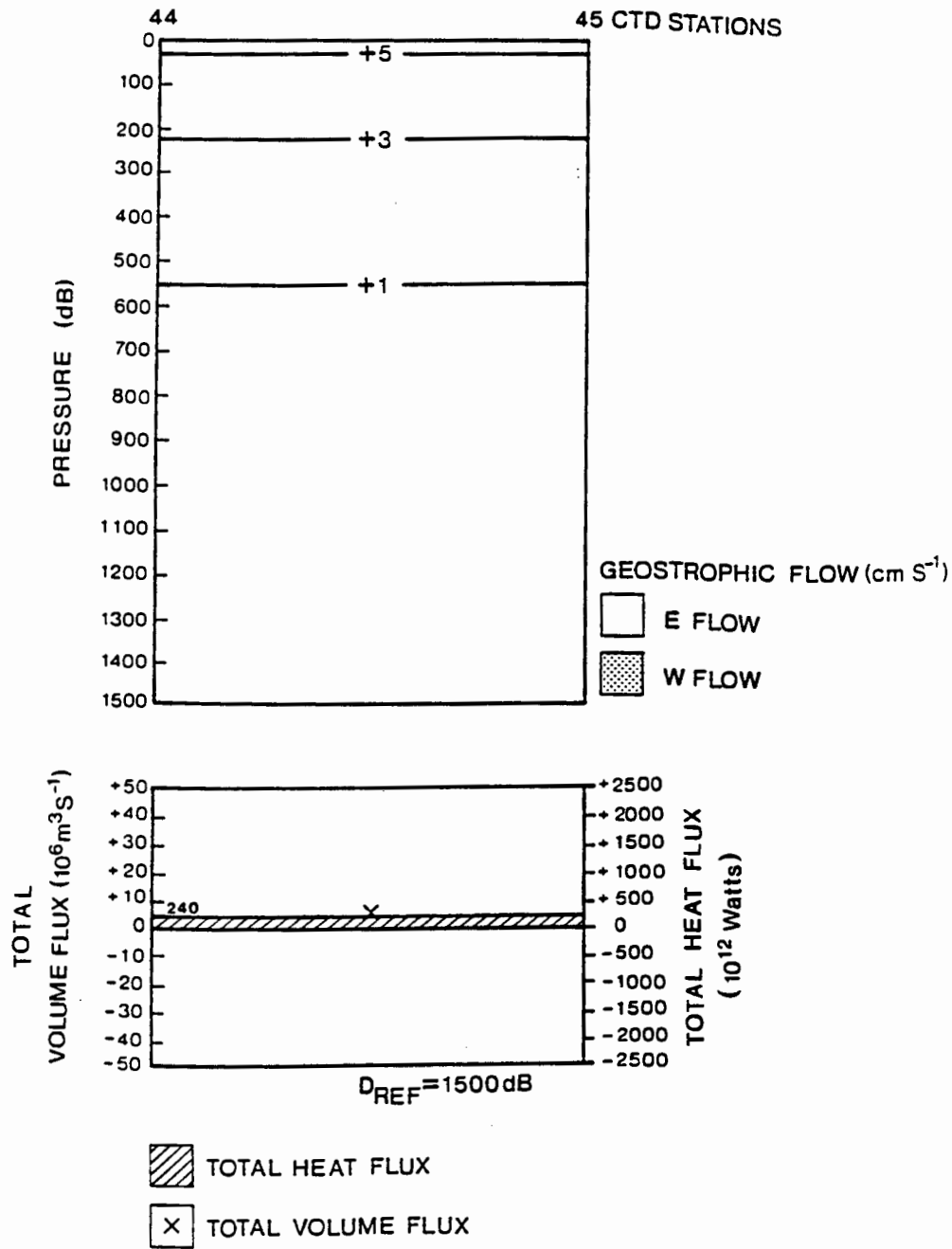
Addendum 2

Temperature, Potential Temperature, Salinity and Potential Density, Geostrophic Velocity and Volume and Heat Flux Sections of the *SCARC*.

SECTION 12



SECTION 12: Full-depth sections of temperature ($^{\circ}\text{C}$), potential temperature ($^{\circ}\text{C}$), salinity (psu) and potential density (kg.m^{-3}) versus pressure (db).

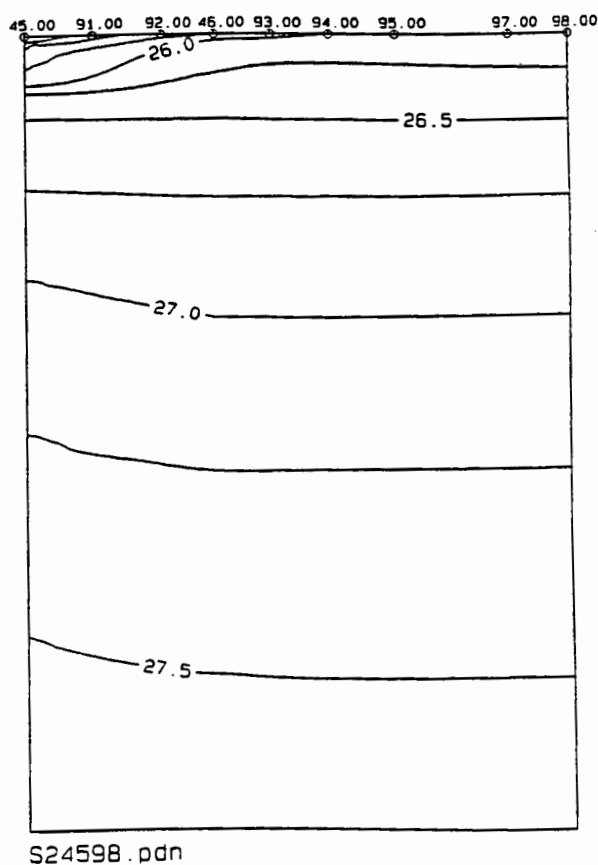
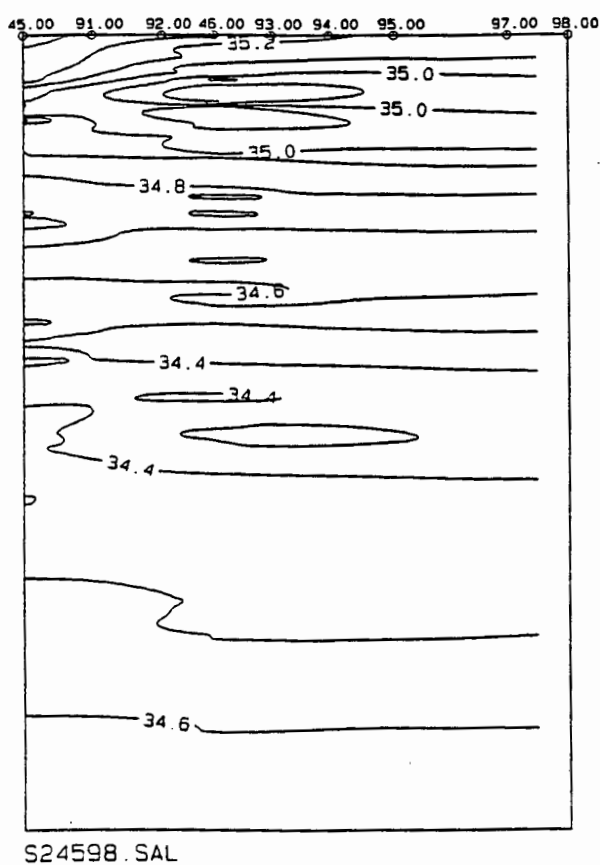
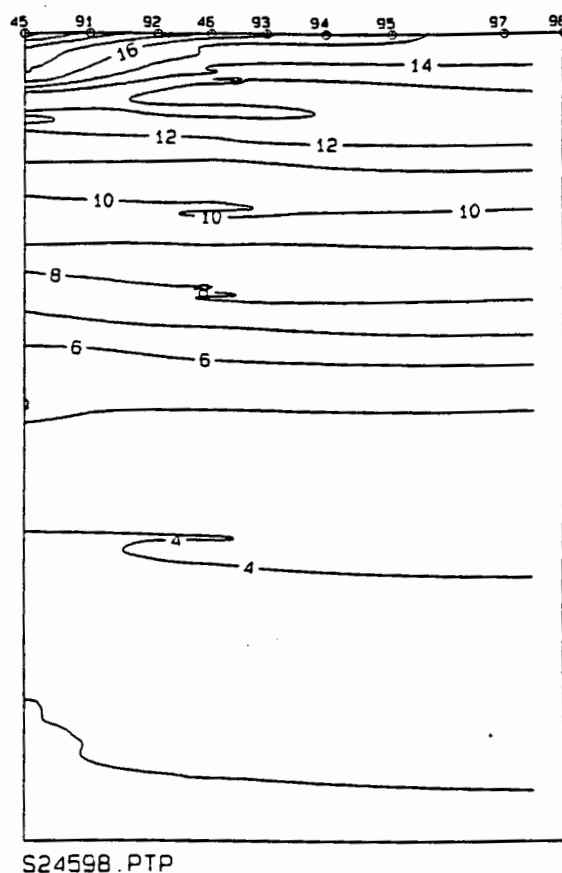
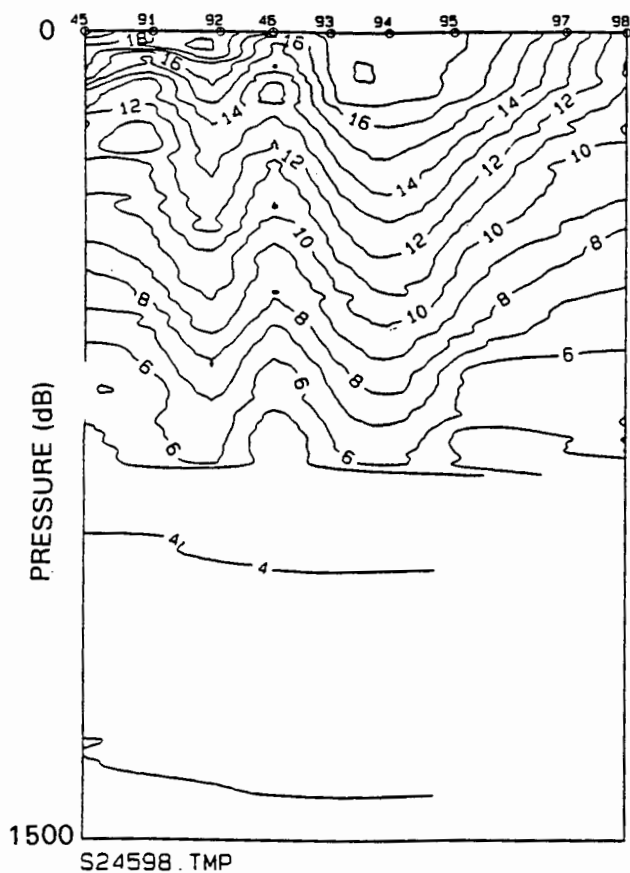


SECTION 12: Full-depth sections of geostrophic velocity (cm.s^{-1}) versus pressure (db), total geostrophic volume transport ($10^6 \text{m}^3 \text{s}^{-1}$) and total geostrophic heat flux (10^{12} Watts), referenced to 1500 db.

Addendum 2

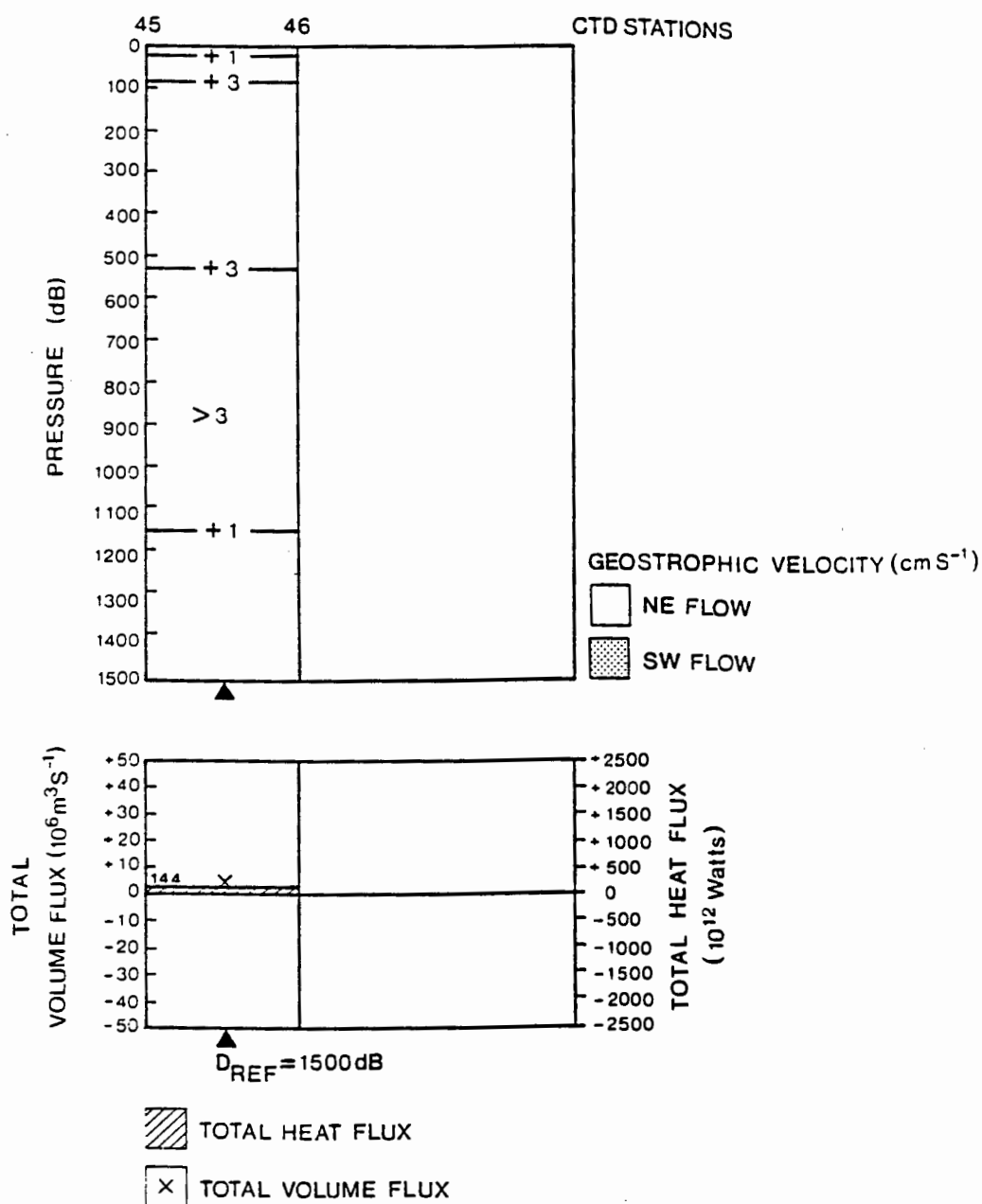
Temperature, Potential Temperature, Salinity and Potential Density, Geostrophic Velocity and Volume and Heat Flux Sections of the *SCARC*.

SECTION 13



395 km

SECTION 13: Full-depth sections of temperature ($^{\circ}\text{C}$), potential temperature ($^{\circ}\text{C}$), salinity (psu) and potential density (kg.m^{-3}) versus pressure (db).

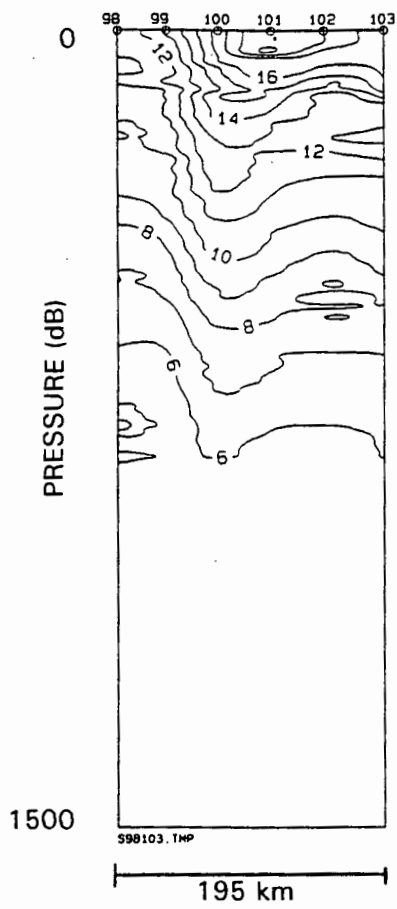


SECTION 13: Full-depth sections of geostrophic velocity (cm.s^{-1}) versus pressure (db), total geostrophic volume transport ($10^6 \text{ m}^3 \text{ s}^{-1}$) and total geostrophic heat flux (10^{12} Watts), referenced to 1500 db.

Addendum 2

Temperature Section of the *SCARC*.

SECTION 14

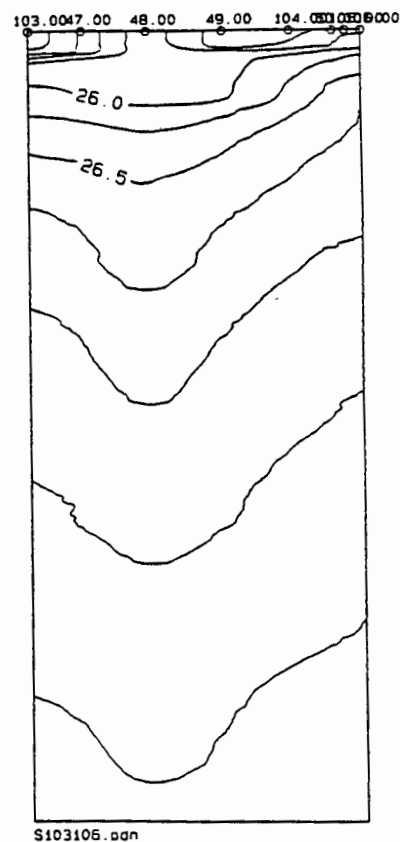
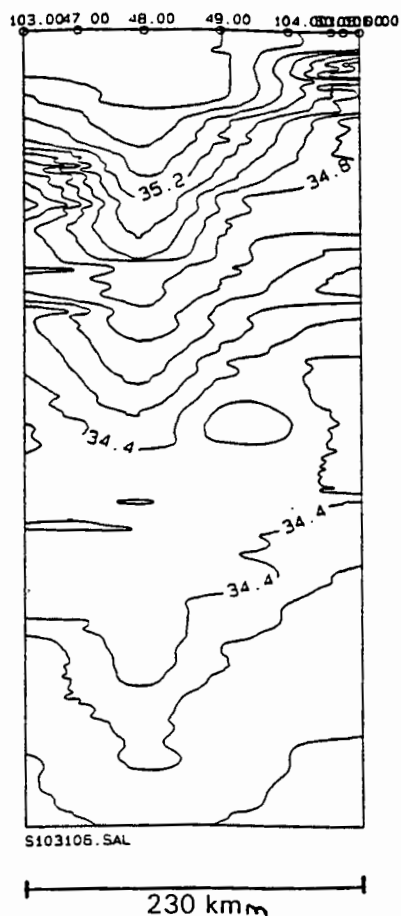
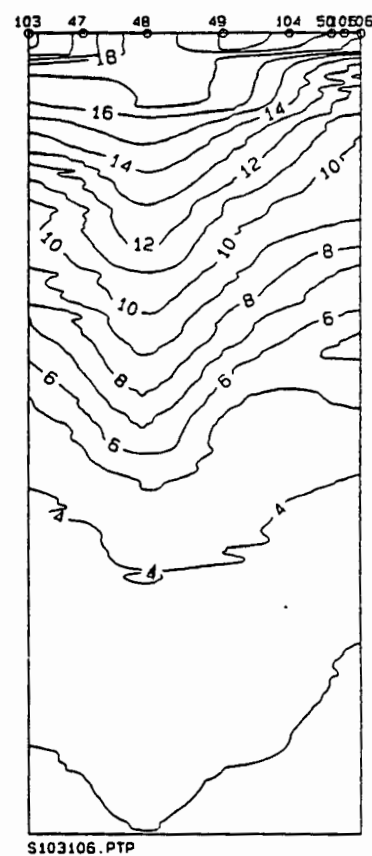
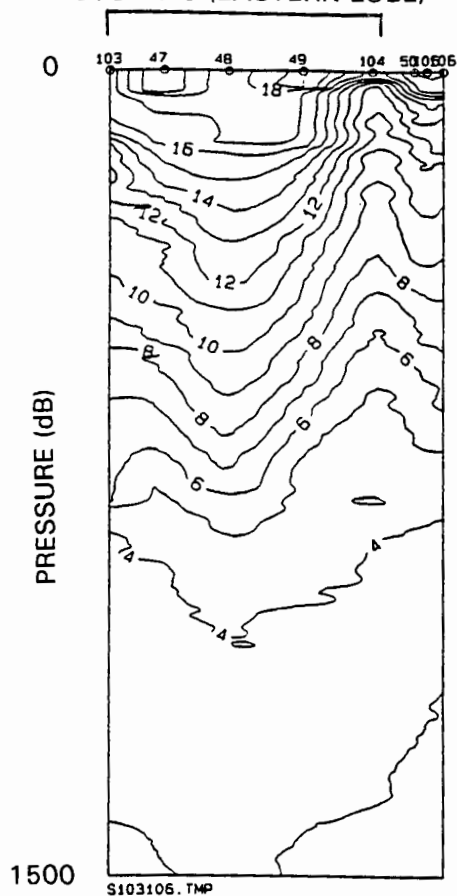


SECTION 14: Full-depth section of temperature (°C) versus pressure (db).

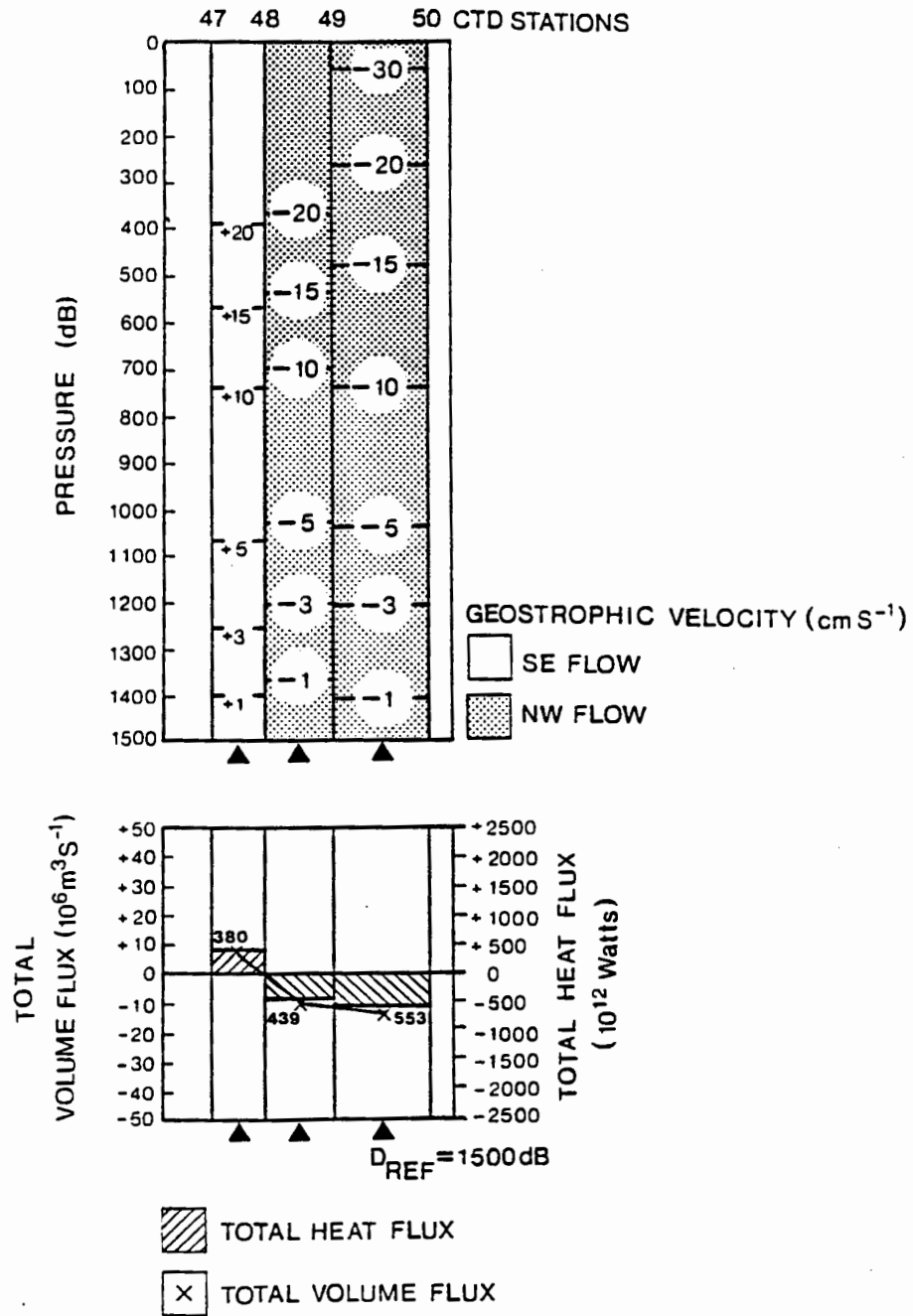
Addendum 2

Temperature, Potential Temperature, Salinity and Potential Density, Geostrophic Velocity and Volume and Heat Flux Sections of the *SCARC*.

SECTION 15



SECTION 15: Full-depth sections of temperature ($^{\circ}\text{C}$), potential temperature ($^{\circ}\text{C}$), salinity (psu) and potential density (kg.m^{-3}) versus pressure (db).

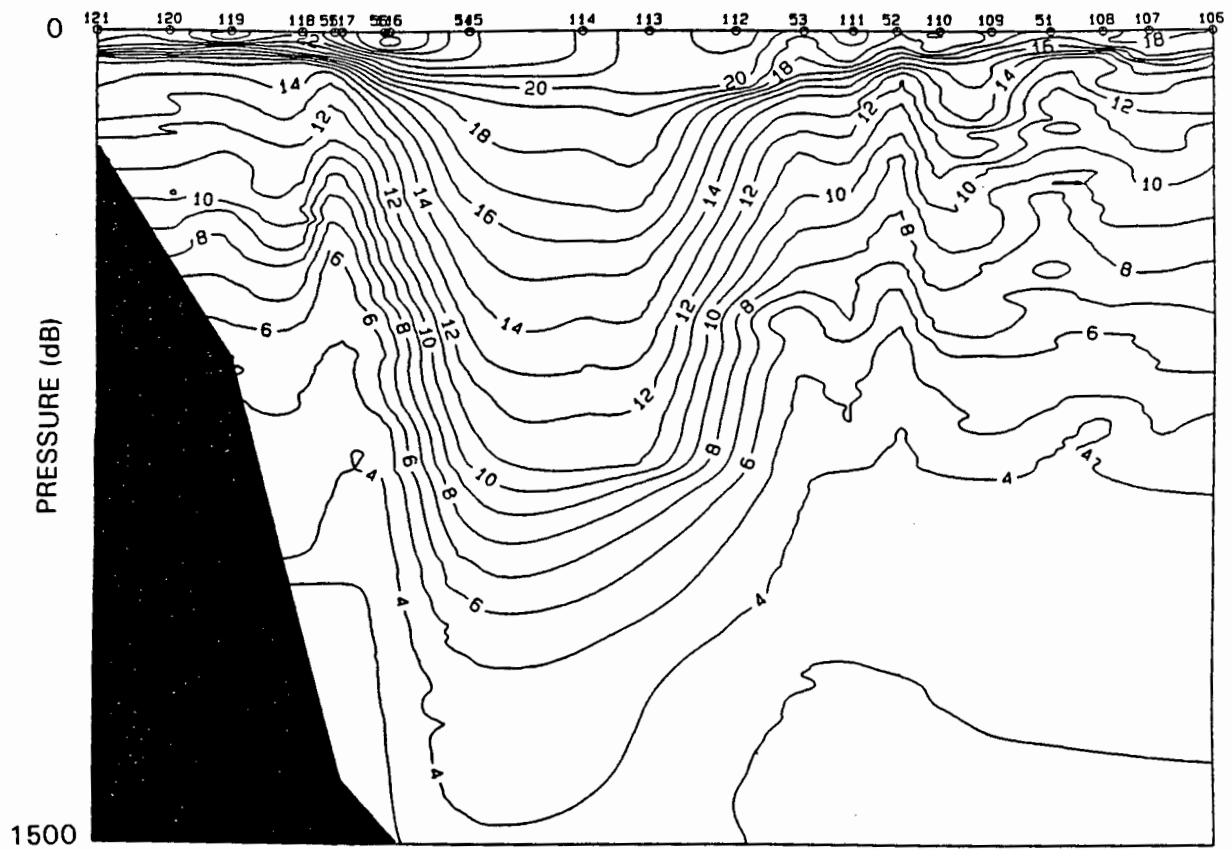


SECTION 15: Full-depth sections of geostrophic velocity (cm.s^{-1}) versus pressure (db), total geostrophic volume transport ($10^6 \text{ m}^3 \text{ s}^{-1}$) and total geostrophic heat flux (10^{12} Watts), referenced to 1500 db.

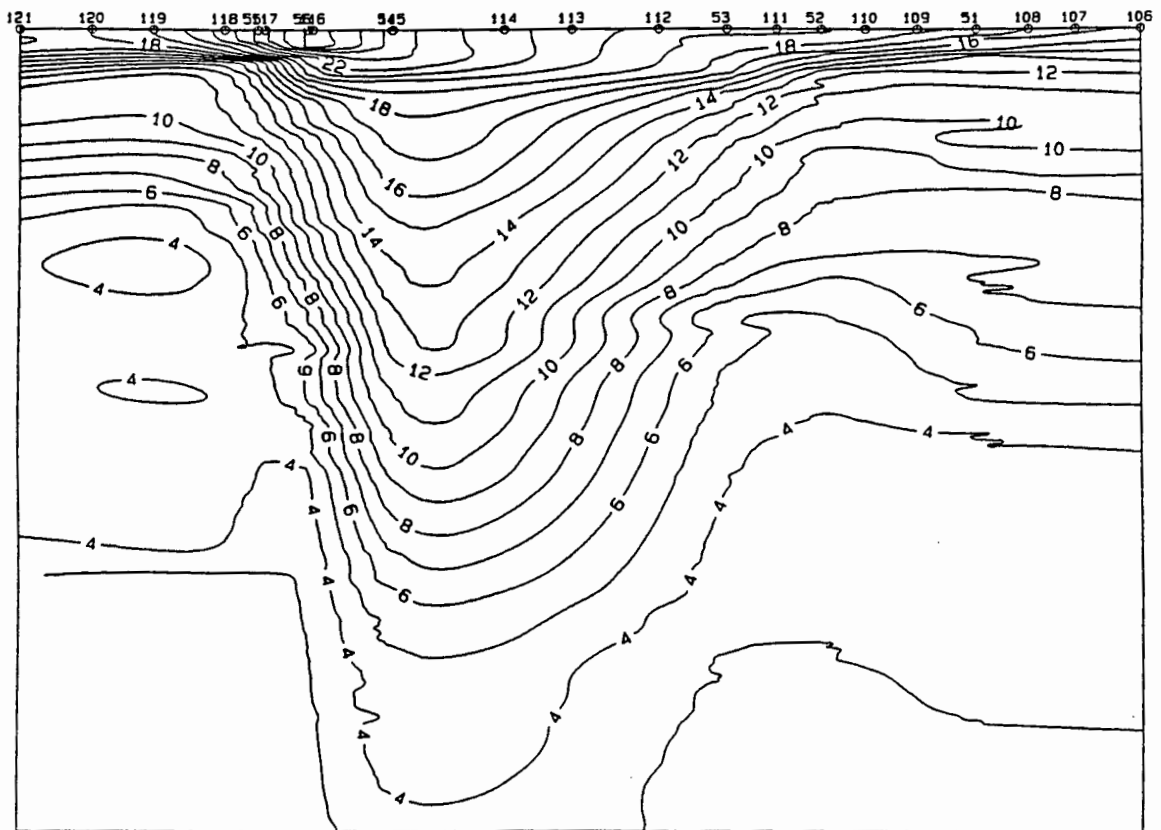
Addendum 2

Temperature, Potential Temperature, Salinity and Potential Density, Geostrophic Velocity and Volume and Heat Flux Sections of the *SCARC*.

SECTION 16



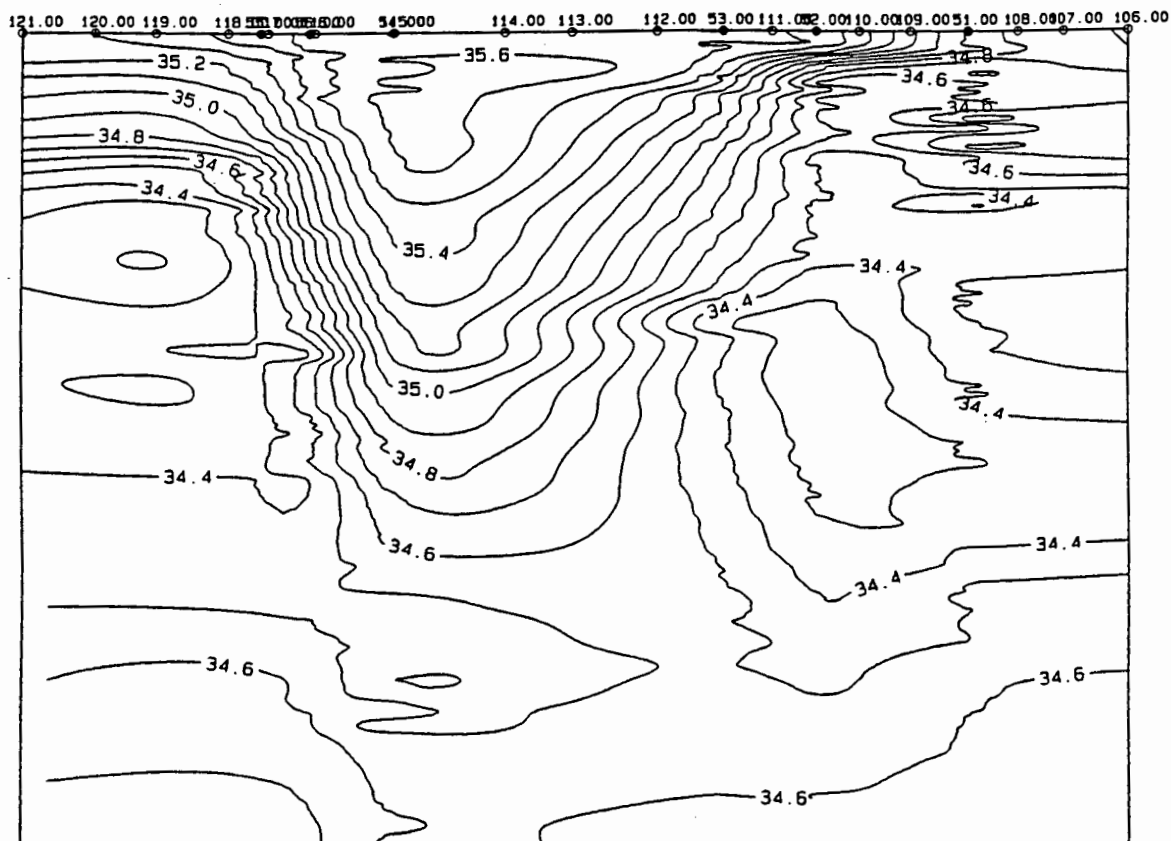
S121106.TMP



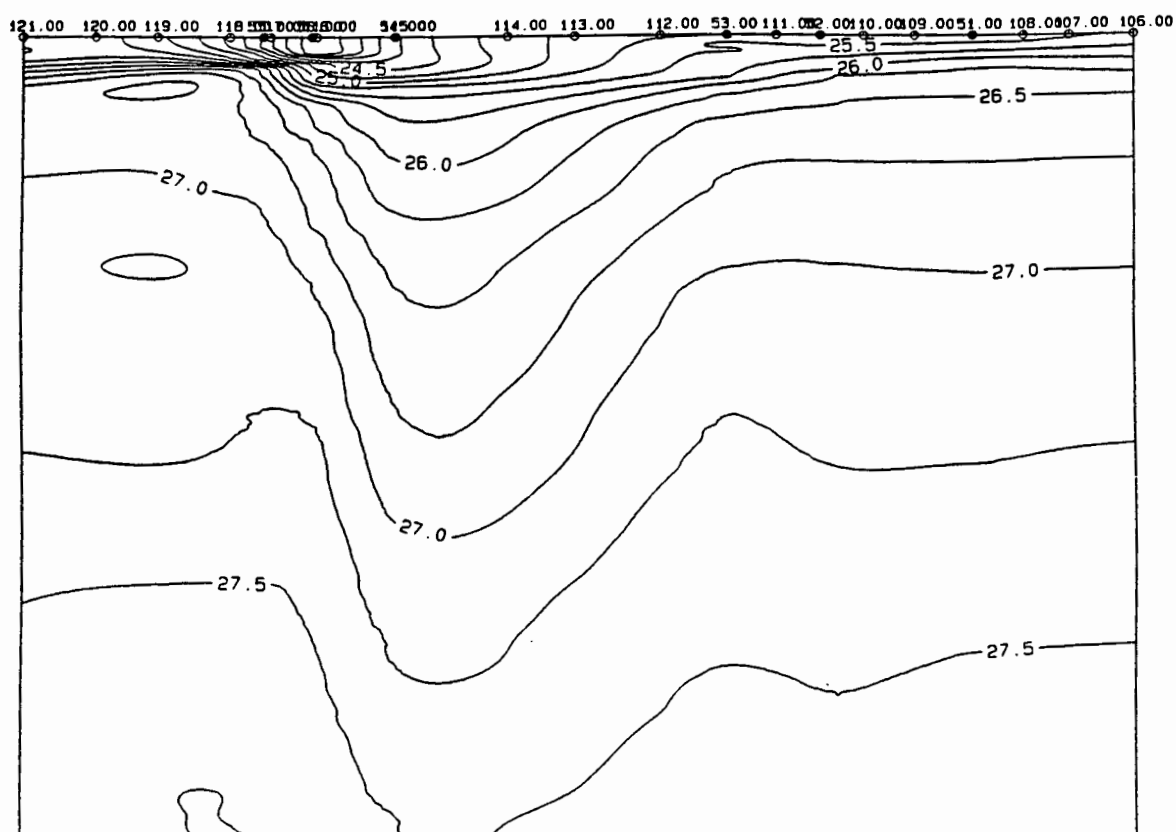
S121106.PTP

830 km

SECTION 16: Full-depth sections of temperature ($^{\circ}\text{C}$) and potential temperature ($^{\circ}\text{C}$) versus pressure (db). The location of the Agulhas Current (AgC), Agulhas Return Current (AgRC) and Agulhas Front (AgF). Open circles denote XBT stations, solid circles denote CTD stations.

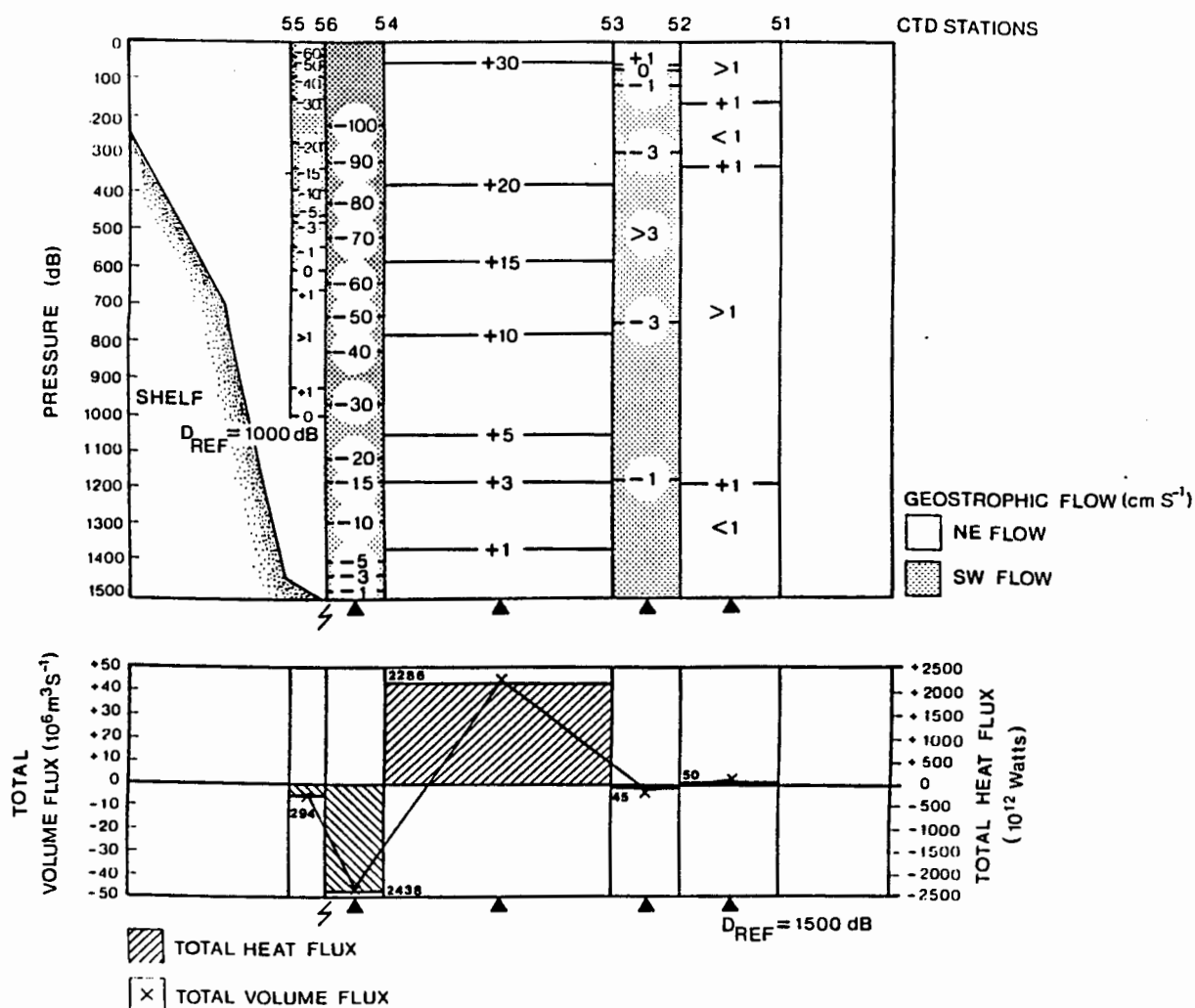


S121106.SAL



S121106.pdn

SECTION 16: Full-depth sections of salinity (psu) and potential density (kg.m^{-3}) versus pressure (db). The location of the Agulhas Current (AgC), Agulhas Return Current (AgRC) and Agulhas Front (AgF). Open circles denote XBT stations, solid circles denote CTD stations.

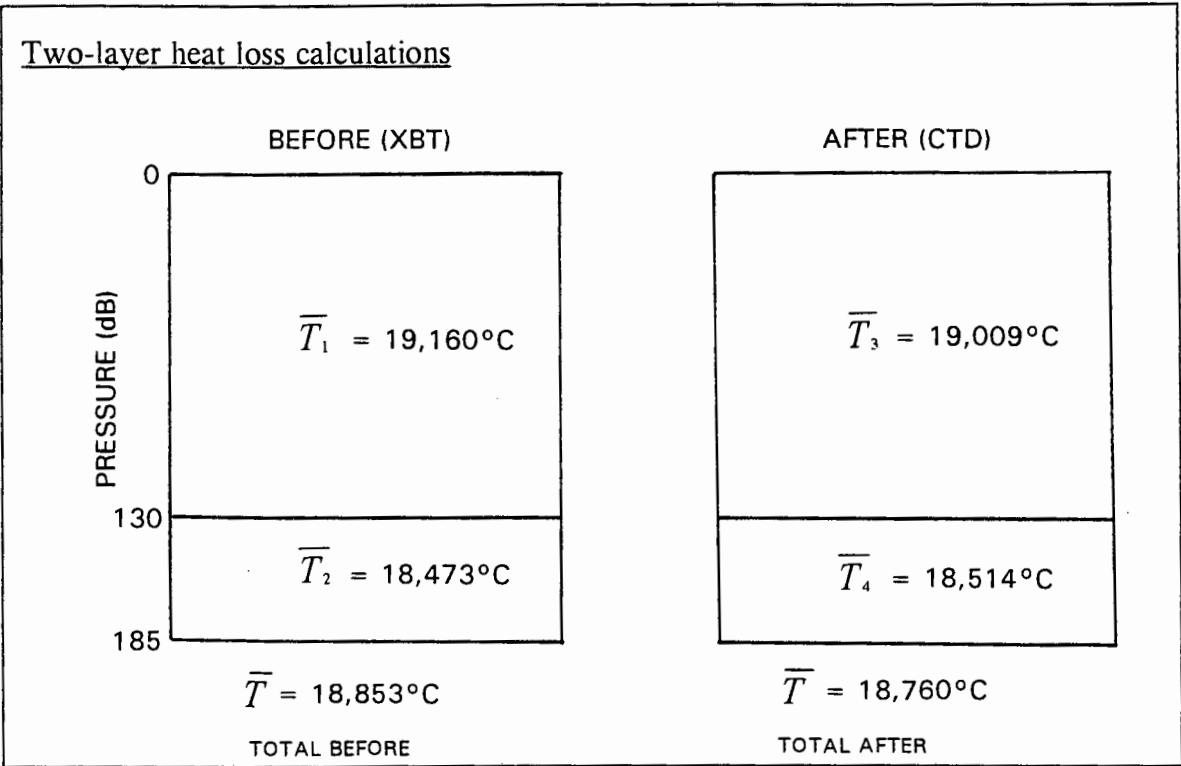


SECTION 16: Full-depth sections of geostrophic velocity (cm.s^{-1}) versus pressure (db), line graphs of total geostrophic volume transport ($10^6 \text{ m}^3 \text{ s}^{-1}$) and bar graphs of total geostrophic heat flux (10^{12} Watts), referenced to 1500 db. Figures in parenthesis are heat flux values in 10^{12} Watts. The location of the Agulhas Current (AgC), Agulhas Return Current (AgRC) and Agulhas Front (AgF). Geostrophic calculations between CTD_055 and CTD_056 are referenced to 1000 db.

Addendum 3

Calculation of the heat fluxes to the atmosphere (and mixed layer modification) associated with Eddy A4

Since two SCARC hydrographic transects of Eddy A4 were executed, an estimation of the modification of the surface mixed layer in the period between the two transects could be done. The mixed layer depth of Eddy A4 deepened from 130 db to 164 db over approximately two days (XBT_044 and CTD_030 respectively). A two-layer model was employed, mixing the water from 130 db to 164 db over two days. The upper layer extends from the surface to 130 db, and the lower layer extends from 130 db to 185 db. 185 db was chosen as the lower boundary based on intercomparisons of Θ/S properties of CTD_030 and the Agulhas input (CTD_054). Increasing the lower boundary to 185 db also allows for mixing in of cooler water from below the thermocline. Assumptions that should be born in mind in this analysis is that an XBT station is compared to a CTD station and that these stations are assumed to represent the centre stations of the vortex. Also, I assume negligible heat loss to the surroundings through lateral mixing. Integrated average temperatures between the two layers are calculated over 1 db resolution over a 1 x 1 m column from the surface to 1500 db. The calculations for this model are shown below.



$$\text{RADIUS OF A4} = (276 \times 10^3 \text{ m}) \div 2 = 1,38 \times 10^5 \text{ m}$$

$$\begin{aligned}\text{Heat Content Before} &= \int_0^{130} \rho C \overline{T_1} dV_1 + \int_{130}^{164} \rho C \overline{T_2} dV_2 \\ &= 7,41 \times 10^{20} \text{ J}\end{aligned}$$

$$\text{Where: } \rho = 1 \times 10^3 \text{ kg.m}^{-3}$$

$$C = 4 \times 10^3 \text{ J.kg}^{-1} \cdot \text{K}$$

Assuming mixing, the new temperature will be $T = 18,879^\circ\text{C}$ ie. a drop in the temperature of the mixed layer by $0,281^\circ\text{C}$

$$\begin{aligned}\text{Heat Content After} &= \int_0^{130} \rho C \overline{T_3} dV_3 + \int_{130}^{164} \rho C \overline{T_4} dV_4 \\ &= 7,37 \times 10^{20} \text{ J}\end{aligned}$$

$$\text{Where: } \rho = 1 \times 10^3 \text{ kg.m}^{-3}$$

$$C = 4 \times 10^3 \text{ J.kg}^{-1} \cdot \text{K}$$

Assuming mixing, the new temperature will be $T = 18,779^\circ\text{C}$ ie. a drop in the temperature of the mixed layer by $0,229^\circ\text{C}$

$$\begin{aligned}\text{So, } \Delta H &= H_{\text{NBT}} - H_{\text{CTD}} \\ &= 3,92 \times 10^{18} \text{ J}\end{aligned}$$

Which is equivalent to a heat flux of $379,606 \text{ W.m}^{-2}$ over the two days.
ie. a drop of temperature due to heat loss to the atmosphere of $0,049^\circ\text{C}$ per day

