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A description of the Agulhas Retroflection Zone

J M Holford

1990

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INSTITUTE OF OCEANOGRAPHIC SCIENCES
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ABSTRACT

CTD and SeaSoar data collected or *RRS Discovery* Cruise 165A have been studied. The main features shown are the retroflection of the Agulhas current and a warm core eddy of Agulhas origin. A surface layer of very light water was found to be carried along in the current core. Volume transports of this water around the retroflection were calculated but variations along the current from upstream proved too great to allow definite conclusions about mixing rates around the retroflection to be drawn. The current cannot be viewed as a steady stream with a constant volume flow across all sections.

KEYWORDS

Agulhas Current, Retroflection, Eddies, Water Mass Analysis

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1. INTRODUCTION

The Agulhas current flows down the coast of southern Africa as a strong western boundary current, lying along the continental shelf break. As the shelf widens into the Agulhas Bank the current begins to meander and boundary phenomena evolve (see Lutjeharms, Catzel and Valentine (1989)). Beyond the tip of Africa it begins a sharp turn back on itself i.e. it retroflects, flowing back into the Indian Ocean as the Agulhas Return current. The exact location of the retroflection changes periodically as the loop of the current intersects itself further upstream, spawning an eddy. For recent descriptions, see Gordon, Lutjeharms and Grundlingh (1987) and Lutjeharms and Ballegooyen (1988). The dominant forces involved in the retroflection are thought to be the current inertia and the existence of potential vorticity gradients, created by vortex stretching and advection into regions with differing Coriolis parameter (f), see De Ruijter (1982) and Ou and De Ruijter (1986). The Agulhas retroflection zone displays a very high level of mesoscale activity, including the production of several different eddy types (see Lutjeharms and Valentine (1988) and Lutjeharms (1989)). It is this, together with the region's role as a connection between the Indian and Atlantic Oceans that make this an important area for study.

RRS Discovery Cruise 165A (28 February - 25 March 1987, Principle Scientist Dr J Luyten) covered the region of the Agulhas retroflection, the main survey area lying within 15°-27°E, 36°-43°S. Among the data collected were 10 CTD casts and 3700 km of SeaSoar sections published in Read, Pollard and Smithers (1987). From this data, together with the ship's electromagnetic (EM) log recording of surface currents, a description of the main water types and dynamics of the region was made. In an attempt to evaluate the amount of mixing that occurs between the fast-flowing current and surrounding water masses, the evolution of a very light surface layer of water carried along in the core was studied.

2. WATER MASS ANALYSIS OF CRUISE REGION

Cruise tracks along which SeaSoar data were collected and the positions of the ten CTD casts made are shown in Fig. 1. Also shown are the distances covered by the twenty (roughly twelve-hour) data files. Fig. 2 displays the surface current velocities as recorded by the ship's electromagnetic log over most of the cruise region. From T/S (temperature vs salinity) profiles and from studying the depth of and potential temperature on selected density surfaces a picture was built up of the main flows and water masses in the region see Figs. 3a, b). The retroflection was clearly seen, together with a flow of some Agulhas water south out of the region. Also seen were a warm core eddy to the north-west and the edge of another possible eddy to the south-west.

2.1 Within Retroflection and Eddy

Surface water within the retroflection was found to be a very homogeneous type of Subtropical Surface Water (SSW), here labelled A, with slight changes in the length of SeaSoar T/S profiles due to density surfaces sloping downward towards the retroflection centre. This sloping of isopycnals was also seen down to around 1500 dbar in the CTD casts within the retroflection (stns. 63-67). Deeper water masses corresponded to South Indian Central Water (SICW) over North Atlantic Deep Water (NADW). The salinity minimum of about 34.4 ppt lay at around 1250 dbar pressure. A deep surface mixed layer was present near the retroflection centre (approximately 100 m deep at stn. 64) which shallowed towards the edges. The two CTD stations on the southern side (stns 65, 67) showed intrusions of cooler, fresher very oxygen-rich water around 1200 dbar depth and generally more stepped T/S profiles.

Water within the north-west eddy, exemplified by stn. 69, was similar to that within the retroflection but had a very deep (approximately 130 m) surface mixed layer (water type A' in Fig. 3). Moving away from the eddy centre, both SeaSoar tracks produced a similar series of stepped T/S profiles corresponding to a layer of fairly homogeneous water (E) underlying a thin surface layer in which both temperature and salinity changed rapidly with depth (F). Such stepped profiles have previously been noticed, see Duncan (1968).

2.2 Surrounding Water

Outside the retroflection and eddy, CTD casts at stns. 68, 70 and 71 showed colder, less saline water much nearer the surface - the salinity minimum of around 34.4 ppt lay at only 700 dbar pressure. Further north of the Agulhas current (stn. 62) lay Tropical Thermocline Water (TTW) above SICW.

Most of the exterior region consisted of a homogenous water type with a nearly linear T/S profile (D). However, a wide flow of Agulhas water separated from the southernmost point of the retroflection and the water east of this was very different. Here the coldest surface temperatures (13°C) were found and the T/S profiles were again stepped, as around the eddy, although the upper water type (F) seemed to represent a deeper layer. Water type E could have been the cooler continuation of types D or A, although the latter seems physically unlikely. This corner showed little correlation between the initial crossing of the region and the later, more detailed survey (8 days apart) suggesting that these variations on small spatial scales changed considerably in that time.

Density surfaces sloped markedly around the retroflection and the warm core eddy and also began to dip down at distrun = 6540 km in the south-west, suggesting this may have been the edge of another eddy. In all other regions density surfaces were surprisingly level even when temperature and salinity gradients individually were steep.

3. THE AGULHAS CURRENT AROUND THE RETROFLECTION

3.1 Description

Cruise tracks with SeaSoar data crossed the Agulhas several times, from before it retroflected to beyond where some of the water had been drawn off to the south. Furthest upstream, fronts seen in runs 4, 3, 9 and 12/13 were alike in structure and were between not dissimilar water types, showing up most strongly near the surface. By as far downstream as run 11 the ambient water type outside the retroflection had changed and the front could be seen clearly throughout the whole 350 m depth of SeaSoar data. Then, where run 7 crossed the return current, it seemed to have a double structure with an inner transition 20 km from the change to the cooler, more southerly water type. In contrast run 5 crossed a single steep front.

All tracks crossing the Agulhas showed a warm surface cap of constant salinity water (of 35.3 - 4 ppt salinity and between 19-25°C) overlying the front structure. This lay along the current core down to a depth of 30-50 m. Upstream the density surface delimiting this water was typically steeper on the inside with the lightest water near this edge of the jet : this structure was reversed in runs 18, 7, 19/20 and 5. The only two runs which were covered by sufficiently detailed EM log data to resolve the velocity structure across the jet were runs 9 and 5, both of which suggested that current speed and direction were fairly constant across the current core. However in run 9 velocities diverged on either side of the current whereas in run 5 they converged and this characteristic, as well as the changing density structure, was probably due to a change from anticyclonic to cyclonic curvature. Most of the runs across the current showed evidence of additional lighter surface water on the inside of the main jet and, occasionally, outside also. These may be plumes or streamers of water pulled off the core (see Lutjeharms, Catzel and Valentine (1989)).

At the southern-most point of the retroflection, a stream of Agulhas water moved south, crossing runs 15 and 16. A slightly cooler surface cap of water was present across the whole flow. The water type B showed the irregular T/S profile characteristic of that between the retroflection water and that outside. The only other appearance of such a warm surface capping was over the possible eddy feature in the south-west corner of the survey region (on run 11).

3.2 Volume Transport of Surface Light Water

In an attempt to quantify the amount of mixing occurring around the retroflection, the volume transport of water less than a given density (within this light surface core) was calculated for each crossing of the current.

The cross-sectional area A of such water present along each track was calculated from datafiles regridded on density using the trapezium rule, the simplest method of estimating the area between each of the data points (4 km apart). Three values were calculated: those for water with sigtheta <24.0, 24.1 and 24.2 kg/m^3. From the T/S profiles, water satisfying sigtheta <24.2 kg/m^3 seemed, at least at the surface, a good definition of this capping layer. For these surface layers it was assumed that 1 m depth ≡ 1 dbar pressure. On runs 3 and 4 the latter two areas had to be estimated from typical current core shapes as the cruise tracks did not reach as far as the surfacing of these isopycnals. (Hence in the results a possible range of values for the transport is given.) Current speed v and directions Ø from the surface EM log, averaged across the current width if necessary, were assumed to apply throughout the layer (i.e. no vertical shear was assumed). To calculate the volume transport along the current track the ship's heading θ was also required: this was measured by hand from a plot of the cruise track. Then

$$\text{volume transport} = Av\,|\sin(\theta - \varnothing)|$$

For the results, see Table 1. Values are a small fraction of the total transport of the current which is over 100 Sv (see Grundlingh (1980)). Volume transports graphed against distance around the retroflection are shown in Fig. 4.

Ignoring air-sea interaction and assuming the jet was a steady stream with no upstream variation, the volume of light water transported around the retroflection might be expected to decrease downstream as the whole light layer mixed with denser surroundings. Such transport could only increase if, at the same time, very light water from the central jet mixed outwards as well. From Fig. 4, the values seem too disparate for such an explanation. Allowing for air-sea interaction by estimating that heating/cooling effects were extremal at roughly 16.00/4.00 hrs suggested compensating the values as shown on Fig. 4. Even for water masses lying in a strong (westerly) wind belt and with the possibility of cross-current breezes due to disparate surface temperatures (see Jury and Walker (1988)), such corrections can not explain the changes seen.

It seems more likely that the irregular variations in volume transport are due to departures of the upstream jet from a steady stream (or, possibly, because of the formation of eddies or meanders). Such alongstream variations were suggested by the deepening and shallowing of the light layer and by the reappearance downstream of very light water (see, for example, runs 12/13 and 19/20) whilst earlier runs crossed no water lighter than sigtheta = 24.2 kg/m^3 (see run 7). Evidence for such alongstream changes giving daily variability were found upstream off Durban by Pearce (1977). To look for advected features, the synoptic positions of the water masses measured were calculated, assuming an average current speed of 1.4 ms^{-1} and measuring the approximate distance along the current path. Relative to a point at distance xo downstream at time to,

synoptic distance downstream of water measured at x_i, $t_i = (x_i - x_o) - (t_i - t_o) \times (1.4)$

(positive downstream). See table 2 for values calculated relative to the water mass of run 4. This placed runs 18, 19/20 and 12/13 adjacently (all possibly high values) and also runs 5 and 7 (with no very light water) together, further downstream than the rest. Hence a jet pulsed in character could explain some of the variation. The very high values of run 12/13 could be due to the peak of an internal tide feature or an eddy. The assumption of no vertical shear may also be invalid. Waveforms propagating alongstream could not be responsible for changes in volume transport unless they involved longitudinal components.

Despite the variations, there was a general downward trend of volume transports around the retroflection, especially if the large peaks from run 12/13 were ignored.

4. CONCLUSIONS

The data from cruise 165A showed the Agulhas current undergoing a clearly defined retroflection at around 20°E, 40°S. A stream of Agulhas water flowed south from roughly this point and the coldest water was found only east of this flow. A warm core eddy comprising water similar to that within the Agulhas retroflection was centred around 16°E, 38°S.

The structure of the Agulhas front between water within the retroflection and the surrounding water masses changed little throughout the region. A capping of warm constant salinity water was found to lie in the high speed core above the front. The structure within the core and the surface velocities around it seemed to depend on whether the jet was curving cyclonically or anticyclonically.

A study was made of the volume transport of water lighter than a given density within this jet. In general, values decreased round the retroflection, suggesting mixing with the surrounding water but conclusive results as to the rate were prevented by large alongstream variations.

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TABLE 1

SeaSoar run	Agulhas core (sigtheta <24.2 kg/m^3)					Volume transport SV		
	Distrun km	Time day/HHMM	Lowest depth m	Current Speed knots	Lowest density kg/m^3	Sigtheta <24.0 kg/m^3	Sigtheta <24.1 kg/m^3	Sigtheta <24.2 kg/m^3
4	4628 - 4664	41/0152 - 41/0429	46.1	+ 2.89	23.785	1.56	2.12 - 2.28	2.36 - 2.54
3	4584 - 4628	40/2204 - 41/0152	50.6	2.89	23.736	1.76	2.50 - 2.73	2.74 - 3.04
9	5624 - 5644	44/1118 - 44/1237	39.5	3.26	23.979	0.63	0.96	1.16
12/13	6840 - 6992	49/0806 - 49/1823	58.4	≠ 1.48	23.670	2.38	3.98	4.82
				1.62				
18	7992 - 8040	52/1859 - 52/2133	48.2	3.4	23.862	0.72	1.06	1.63
11	6700 - 6724	48/2220 - 48/2351	33.6	3.25	23.967	0.40	0.94	1.25
7					24.267			
19/20	8124 - 8172	53/0206 - 53/0448	72.1	2.7	23.862	0.30	1.00	1.48
5					24.327			

\+ Current velocities from 3 as SATFIXES too sparse in 4

≠ Values for two halves of the run

TABLE 2

SeaSoar run	Distance around retroflection km	Synoptic distance downstream km
4	0	0
3	0	10
9	210	-200
12/13	430	-590
18	540	-880
11	560	-390
7	640	380
19/20	670	-790
5	690	680

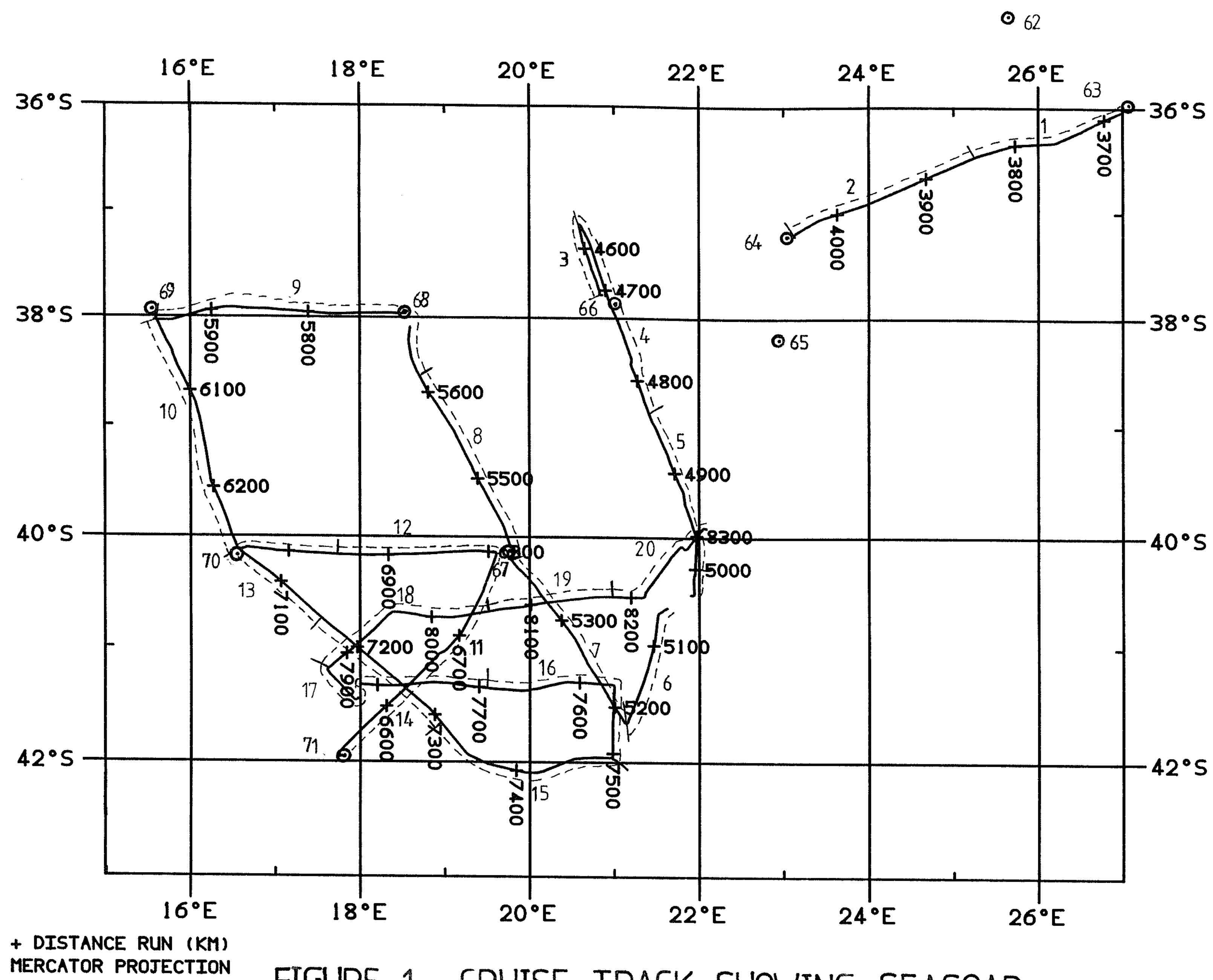


FIGURE 1 CRUISE TRACK SHOWING SEASOAR DATA FILES AND CTD STATIONS (CIRCLED)

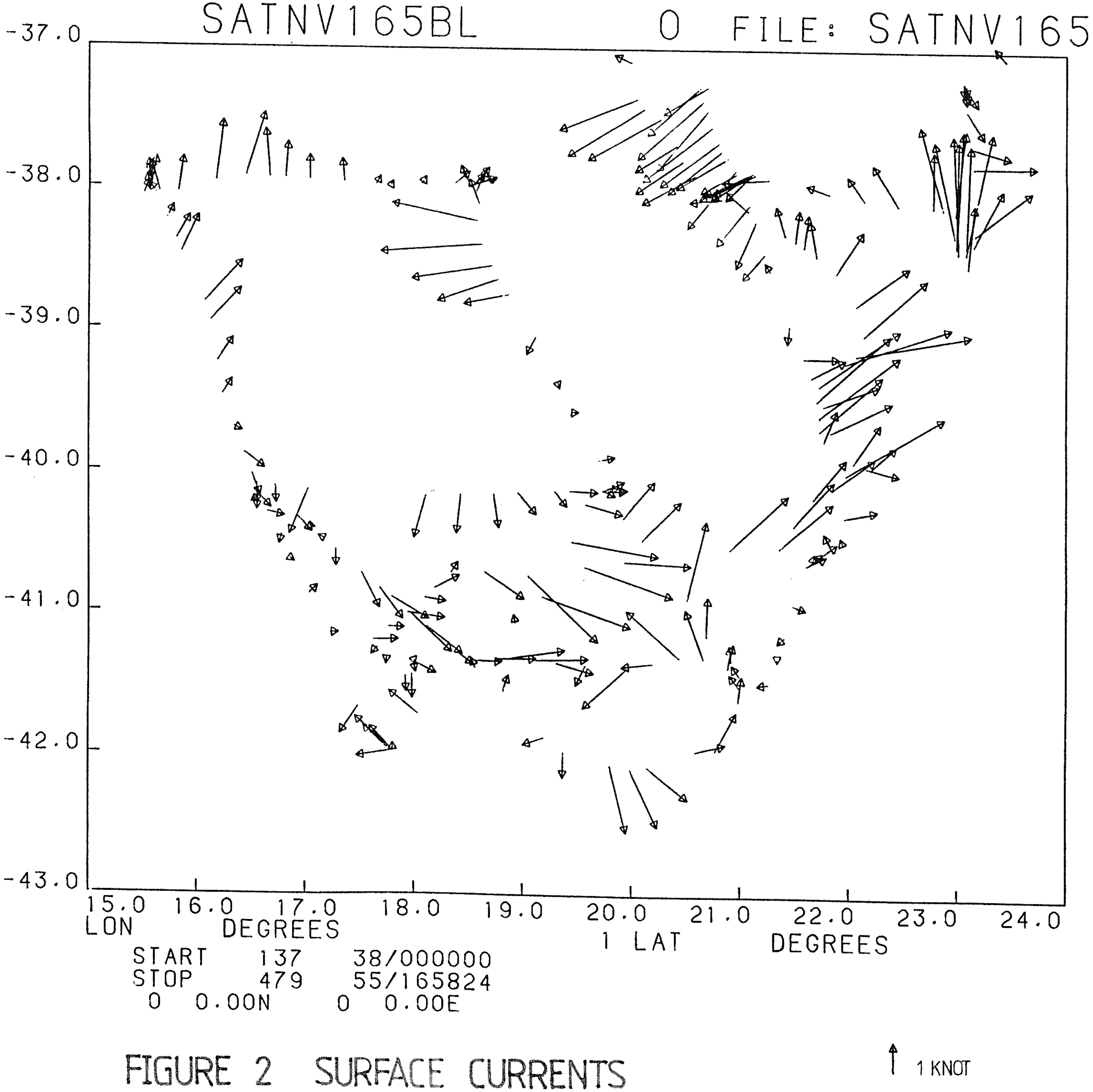


FIGURE 2 SURFACE CURRENTS

FROM READ, POLLARD AND SMITHERS (1987)

FIGURE 3a WATER MASS REGIONS

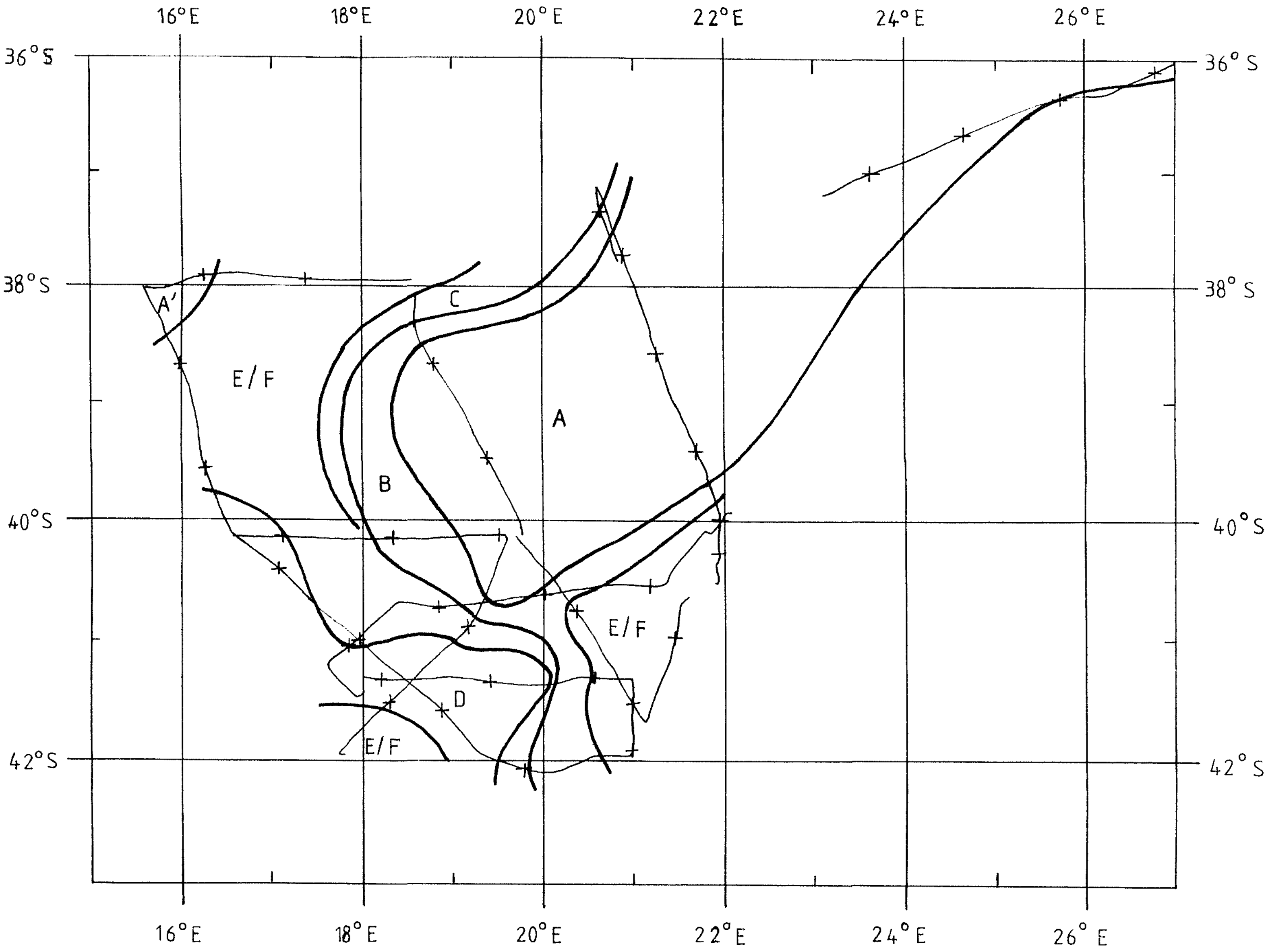
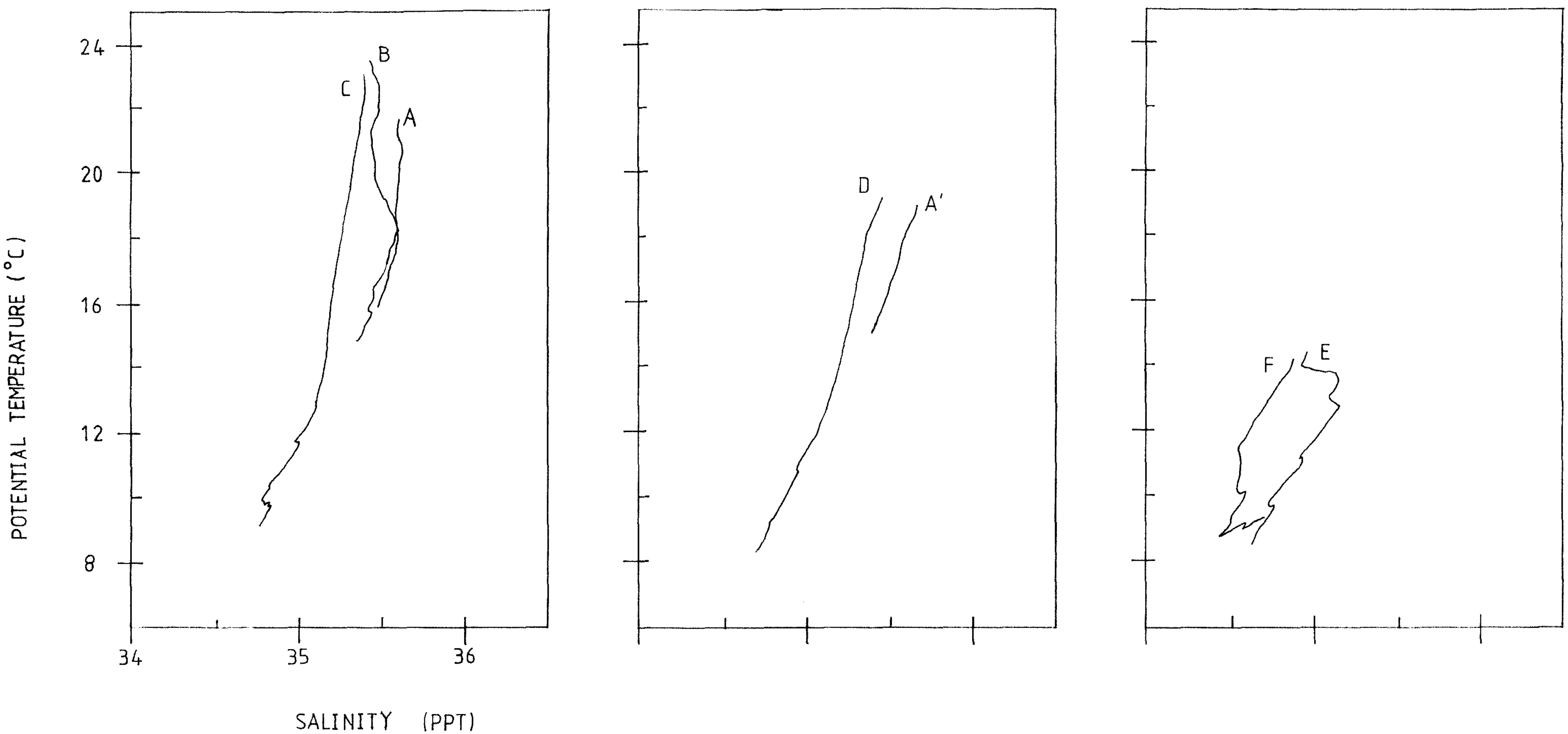


FIGURE 3b TYPICAL T/S PROFILES



AT DISTRUN

A 5488
B 6868
C 5660

A' 5940
D 7796

E 5116
F 4980

FIGURE 4 VOLUME TRANSPORT OF THE AGULHAS CORE