

THE AGULHAS CURRENT SYSTEM ABOVE  
THE INTERMEDIATE LEVEL

by

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## ABSTRACT

A first detailed picture of the Agulhas current is obtained from data of the Quasi synoptic Agulhas current cruise of March 1969. Reinterpretation of other hydrographic data was possible in the light of the 1969 cruise and the information obtained from satellite tracked buoys. For the 1969 cruise acceleration potential diagrams on various sigma-t levels are discussed and indicate that certain features in the current are of such a scale (length and time) that only closely spaced synoptic stations will show them.

Of special interest are the following features: two main supplies to the current; a region of dynamical upwelling between East London and Port Elizabeth; the region where the current turns eastward (retroflexion); the interaction with the South East Atlantic ocean; the planetary waves in the Agulhas return current over and east of the Agulhas plateau.

Volume flux calculations (reference 1100m.) show that the two supplies to the Agulhas current could be estimated at 15 sverdrups each. The main part of the current turns back into the South West Indian ocean. An amount of roughly 5 sverdrups was lost into the South East Atlantic. Property distributions although difficult to interpret, were used to construct the acceleration potential diagrams as the contouring of these diagrams was not always obvious.

For a more detailed discussion of the combined data the current system was divided into areas. These areas are: Source area (including the inflow south of Durban and the countercurrent at Durban; Dynamical upwelling region; Mixing and retroflexion area; Planetary wave region. The areas can be found in figure 11.

The lack of data in the source area to the south and south west of Madagascar has been improved by satellite buoy 1116. The anticyclonic sweep of this buoy into the southern part of the Mozambique Channel could subsequently be supported

somewhat by various hydrographic data. The buoy revealed that an inflow from the east south of Durban can flow down from the south western corner of the Mozambique Channel. The "classical" source for the Agulhas current flows down the coast of Southern Africa. Both inflows were evident in the 1969 cruise but a gap existed between the northern part of the 1969 cruise and the south western part of the Mozambique Channel. To couple these two areas Warren's (1963) inertial jet model was applied. The result was that two pathways did seem to exist. Preference to an inshore pathway was given to jets starting in water shallower than 650m. Jets starting in water deeper than 700m. initially tended to flow south along the Mozambique Ridge, after which they meandered westward. These tracks could represent an inflow from the east. An attempt was then made to contour the sparse data according to the jet tracks (and buoy 1116). This was not always successful.

Various data sources showed that the inflow south of Durban could range from 10-30 sverdrups. It is suggested that this inflow may be a factor influencing the formation of a counter-current at Durban and an anticyclonic eddy formed on the seaward side of the current (over the northern end of the Natal Valley).

The occurrence of severe upwelling (dynamical) between East London and Port Elizabeth has been investigated. No clear explanation for this remarkable feature could be found.

Maximum westward penetration of the Agulhas current was obtained from buoy 1210 which retroflected at  $13^{\circ}$  E. From hydrographic cruises (1969, 1964) it seemed that the main current retroflects further east (respectively  $18^{\circ}$  E,  $21^{\circ}$  E).

A division line running from Cape Town to  $40^{\circ}$  S,  $10^{\circ}$  E. has been introduced. This line runs roughly over the Cape Rise and separates the retroflexion area from the start of the Benguela current regime. The area to the north of this line

was dominated by a large anticyclonic circulation (180 nm. diameter) in March 1969. The outside part of this circulation entered between stations 46-63 (fig.9) and seemed to supply some convergence water. This inflow might be the supply to the Benguela current and the upwelling region of the South West coast of South Africa. To the south west of the 1969 cruise data the area was studied with the 1964 Schmidt Ott cruise. The streamline pattern of this cruise is compared with that of a Taylor column. Formation of eddies separating from the Agulhas current in the retroflexion area is discussed.

Planetary wave formation in the Agulhas return current is discussed. Cyclonic eddy formation within the northern loops of these waves was evident from different data (1969 cruise, buoy 1210). It is argued that these eddies might drift north east (similar to the gulf stream) into the source area. This would explain the eddies found in the source region on several occasions. When these eddies drift through the high salinity band in the South West Indian ocean formation of central water may take place.

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## CHAPTER A

### INTRODUCTION AND CURRENT NAME DEFINITIONS

The purpose of this thesis is to study the Agulhas current system, above the intermediate level, by using mainly synoptic hydrographic data.

The Agulhas current system has been studied by a considerable number of workers, such as Bang (1970), Darbyshire (1964, 1972), Dietrich (1935), Duncan (1970), Harris (1967, 1970, 1972), Lutjeharms (1976), Orren (1966, 1963). These workers often had to deal with non synoptic widely spaced stations. This made study difficult as the data showed a considerable variability of the current system.

The quasi synoptic Agulhas current project of March 1969, covered a large part of the Agulhas current system with closely spaced stations. This cruise has not yet been studied in detail and will form the basis of this thesis.

To get a better understanding of the 1969 cruise, and to discuss certain areas within the system in more detail, other hydrographic data were used. All data used have been studied previously but could now be looked at again in the light of the evidence obtained from:

- a. Nimbus VI satellite tracked buoys (Gründlingh 1976, 1977)
- b. The 1969 Agulhas current project.

The source area (fig. 11) was given special attention. This was possible because of:

- a. The evidence obtained from the satellite buoy tracks
- b. The evidence obtained from the application of Warren's (1963) inertial jet model in the western part of the source area.

In the study emphasis has been placed upon the following features:

- a. Two supply paths to the Agulhas current
- b. Dynamical upwelling occurring between East London and Port Elizabeth
- c. Retroflexion of the current and interaction of the current with the South Atlantic ocean
- d. Planetary waves over and east of the Agulhas plateau.

For the sake of clarity it is useful to define the names for the different currents within the whole Agulhas current system.

Agulhas current system: This includes the southern part of the Mozambique channel (south of  $20^{\circ}$  S.), the Agulhas current, Agulhas return current and area of interaction with South East Atlantic ocean. Its eastern boundary will be defined as  $45^{\circ}$  E. because the recycling between Agulhas current and Agulhas return current seems to take place west of  $45^{\circ}$  E.

Agulhas current: Western boundary current flowing south west from Durban (in older work from southern entrance of the Mozambique Channel) to the area of retroflexion approximately south of the Cape of Good Hope.

Agulhas return current: (eastward current). After retroflexion the Agulhas current flows eastward roughly along  $40^{\circ}$  S. thus contributing to a bigger contrast in properties along the subtropical convergence. Equatorward branches of the Agulhas return current are often included in the Agulhas return current.

Counter current: Inshore of the Agulhas current a counter current is present especially in the neighbourhood of Durban.

Offshore Counter current: On the seaward side of the Agulhas current a current flowing in the opposite direction to the Agulhas current can be present roughly between Port Elizabeth and Durban.

Continental Shelf edge jet: (Good Hope jet) (Bang 1973). This is a current flowing north along the continental shelf break off the south west coast of South Africa.

South equatorial current as a source: Some workers mention the south equatorial current as the source of the Agulhas current. They then refer to both the Mozambique current and the East Madagascar current (which both originate from the south equatorial current).

Mozambique current: Current originating from the south equatorial current running south along the western side of the Mozambique Channel.

East Madagascar current: Current flowing south along the east coast of Madagascar (A western boundary current) originating from the south equatorial current.

## CHAPTER B

### LITERATURE REVIEW

The literature of the South West Indian ocean has been reviewed extensively by Lutjeharms (1971). This review will concentrate on the Agulhas current. The discussion will be divided into two parts. The first part will deal with the most important papers on the large scale circulation in the South West Indian ocean. The second part will deal with papers that discuss a specific area important in the large scale circulation of the Agulhas current and some of the recent experiments.

#### I. LARGE SCALE CIRCULATION IN SOUTH WEST INDIAN OCEAN

The first effort to establish surface currents round South Africa was made by J. Rennell (1820)<sup>1832</sup>. Rennell concluded that the main part of the Agulhas current returned into the Indian ocean and that the remaining part flowed into the "southern connecting" current (Benguela Current) as shown in his surface current chart. He calculated surface currents by using ship's drift information (made possible by the introduction of the chronometer in navigation).

The early oceanographers (L. Möller (1921), B. Michaelis (1923), H. Peach (1926), A. Merz (1925), Willimzik (1929)) were all concerned with surface properties. The knowledge of the surface currents in those days was very well illustrated by the streamline charts of Merz (1925) (fig. 1) and Willimzik (1929) (fig. 2). Although these charts are constructed for mean conditions, since there were almost no synoptic data available, the following features should be noted. From Merz's chart the retroflexion of the Agulhas current east of 20° E. is obvious. The stationary points at longitudes 26° E. and 32° E. coincide remarkably well with the eddies established with certainty by the satellite tracked buoy 1210 (see fig. 19) deployed in 1975. Willimzik's chart (fig. 2)

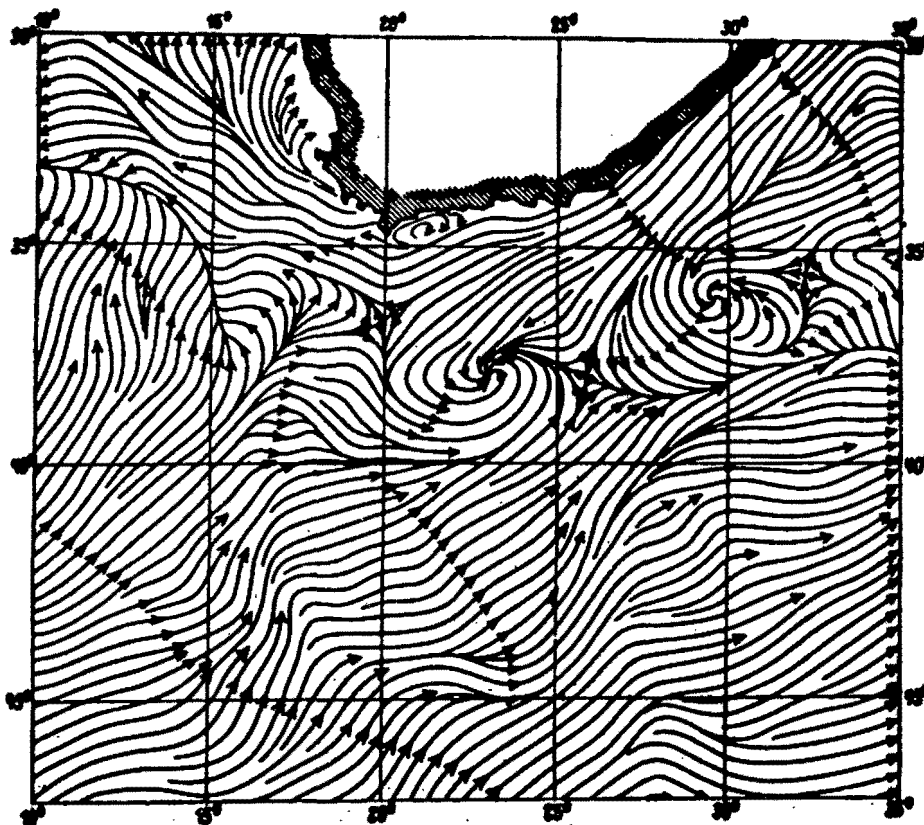


Fig. 1.

Stream lines south of Africa for May (according to Merz) (1925)

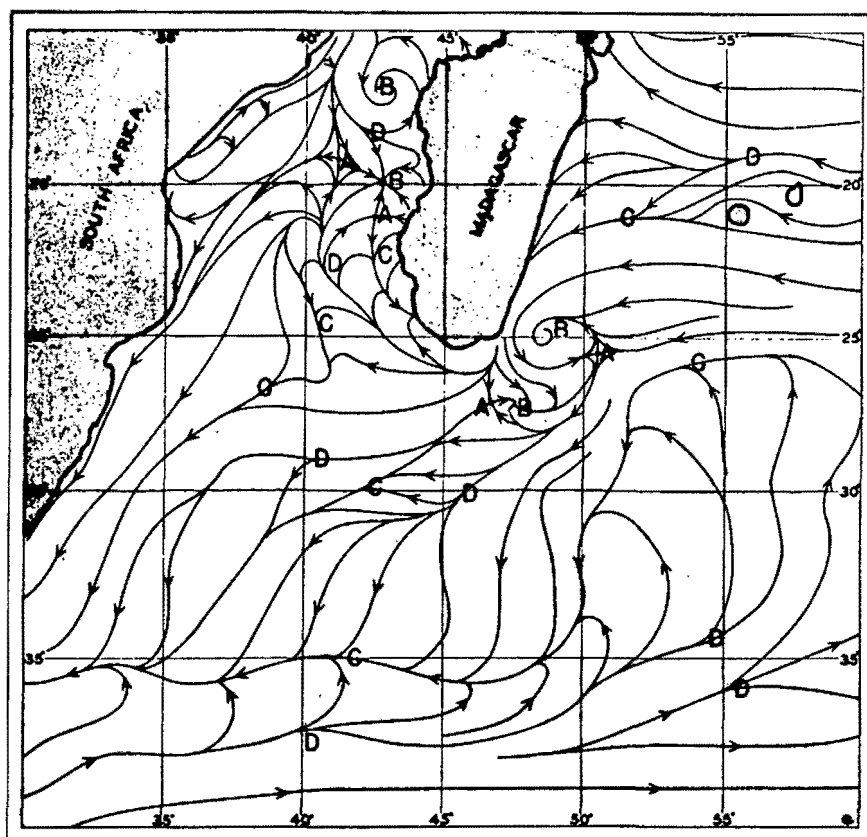


Fig. 2.

Stream lines of the surface currents off south eastern Africa  
in July (after Willimzik) (1929)

shows the complicated situation in the Mozambique Channel (Mozambique current partly turning back at  $18^{\circ}$  S. and partly flowing along the African coast to join the Agulhas current) and the anticyclonic tendency of the East Madagascar current as it reaches the southern tip of Madagascar.

The first extensive work including deep water current circulation in the southern part of the Agulhas current was done by G. Dietrich (1935). His work shows dynamic topography charts using the 1000 db. level as a reference level (fig. 3) and velocity distribution in the vertical sections. Using this information he calculated volume discharge through the different sections, showing the strong decrease as the Agulhas current rounds the Cape. The main contribution of his work was to confirm the retroflexion of the Agulhas current and consequently the small contribution to the South East Atlantic ocean. The work was based upon data of 11 deep sea cruises (GAZELLE (1874), VALDIVIA (1898), GAUSS (1901, 1903), PLANET (1906), MOWE (1912, 1913), METEOR (1925, 1926), DISCOVERY II (1930)). Despite the great number of cruises the stations were too far apart to enable Dietrich to make a more detailed study of the area. Problems must have arisen due to the fact that the data were not synoptic. These difficulties were recognised by Dietrich. In his summary Dietrich clearly states the complex nature of the current which can be seen from the following quotation:

"A few observations establish without doubt that deep disturbances can be present in the system. Because of the fact that the measurements are random nothing can be said about their cause, dimension or time dependency. Two different types of disturbances can be established. The first can be observed in the Agulhas current and are caused by a pulsation of the current; the other occurs in the antarctic watermass and is evidently due, analogous to atmospheric phenomena, to isolated eddies which have separated from the convergence".

A.J. Clowes (1950) made a study of the area between  $20^{\circ}$  and  $40^{\circ}$  S. and  $5^{\circ}$  W. and  $45^{\circ}$  E. using the data from DISCOVERY and METEOR (1925-1927) expeditions. In his work he describes water



masses and currents of the surface and subsurface layers. A detailed description is made of T-S relationships, particularly in the linear parts of the curves. The outstanding feature is the huge anticyclonic circulation south and east of South Africa, consisting not only of the subtropical surface layer but also of the antarctic intermediate current which flows in the same direction as the surface layer in this area. It is considered from a study of the sigma-t charts that Agulhas water does not round the Cape of Good Hope but mixes considerably with South Atlantic water.

M. Darbyshire (1966) divides surface waters near Southern Africa into two distinct water masses (subtropical and Agulhas water). One of her conclusions (not supported by Orren and Shannon (1967)) is that Agulhas water can be identified off the coast of South West Africa in summer.

J. Darbyshire (1964) made a study of the Natal cruises, 1962-1963 (April-July-October 1962 and January 1963). From these synoptic cruises he drew the following conclusions. The results showed up very clearly the current's seasonal variations and its connection with the equatorial current and the west wind drift. The relatively large temperature gradient inshore of the Agulhas current was related to an Agulhas convergence (Fukase 1962). The small effect of local winds on the main current system was shown. It was considered that the cooler water to the north of the current had not been upwelled by wind action but had been displaced by the southern and south westerly movement of the warm water. This cooler water had a higher temperature at the surface and different T-S characteristic from the central water upwelled in the Benguela current area. A number of eddies were found inside the current itself.

An attempt at establishing the large ocean circulation, with drift cards was made by the South African Division of Sea Fisheries in 1965-1966. The most probable current paths have been assumed, depending upon the time elapsed between deployment and recovery of the drift cards. The results for

the South Indian ocean are shown in fig. 4.

Notable results are: Penetration of the East Madagascar current into the Mozambique Channel (D5741); the anticlockwise recirculation east of Southern Africa (A9378, D5724); the penetration into the Benguela system (E7022).

Orren (1963, 1967) has done extensive work on the water masses in the Indian ocean. From T-S data he concludes that Mozambique and Agulhas currents have their origin in equatorial water. A large eddy is established off Port St. Johns and seems to be an outlying part of the Mozambique current. Current measurements calculation by using the ship's drift are done by Orren and presented here in fig. 5. Orren's schematic presentation of the definition of the different surface water masses is shown in fig. 6.

A dividing line between the Benguela current system and the mixing area of Agulhas and Atlantic waters has been defined by Shannon (1966) as latitude  $34^{\circ}30'S$ . He found the steep slopes of isohalines of the Agulhas bank an indication for strong currents down to 1000m or more. He derived circulation charts for the three water masses (surface, central, antarctic water) and concluded that they have the same circulation characteristics.

The first study on the Agulhas current system as a whole was made by Duncan (1970 Ph.D. thesis). He also claimed a large seasonal dependency of the system in agreement with Darbyshire (1964). He argued that an accurate flow pattern could be obtained using 1000db. as a reference level. The following conclusions were drawn by Duncan. Little exchange takes place between the great subtropical gyres of the Atlantic and Indian oceans, although between spring and autumn anticyclonic eddies of Indian ocean origin entered the Atlantic flow. Three large permanent anticyclonic eddies were established; one in the Madagascar Channel, one to the east of Madagascar, and one forming part of the Agulhas current itself, recycling as much as one third of the total flow. The average geostrophic

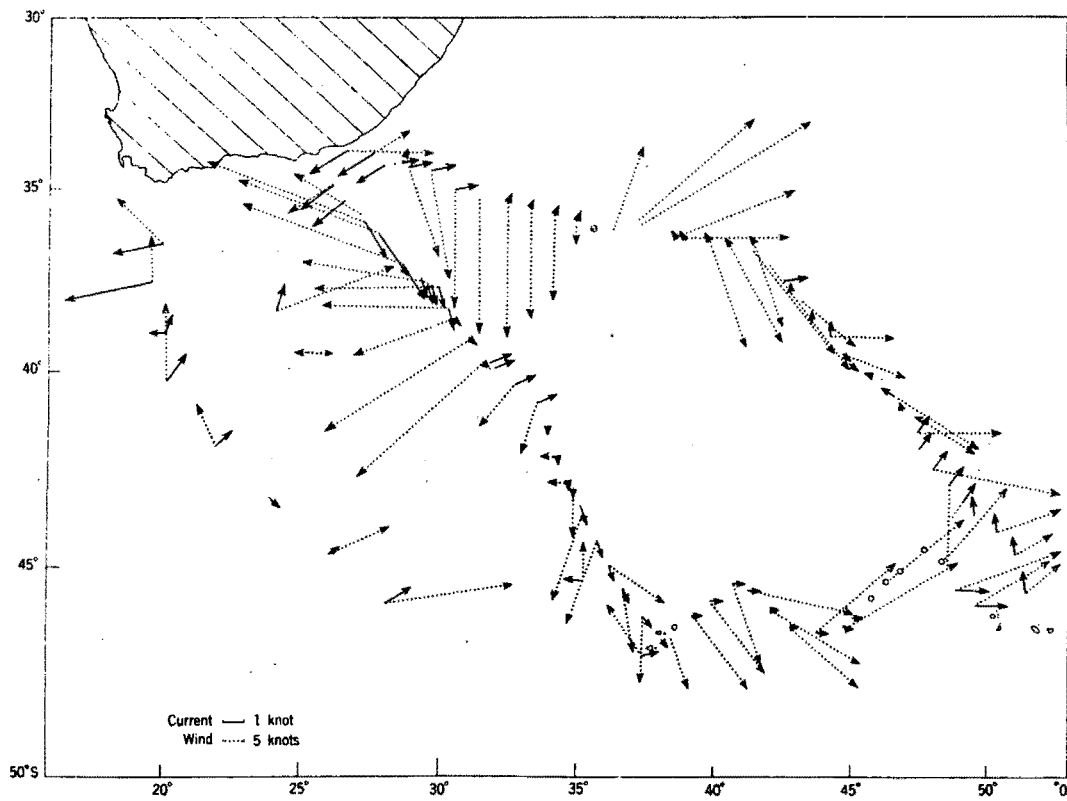


Fig. 5.

Surface currents (unbroken line) and wind vectors (dotted line) in the South West Indian ocean (July 1962) according to Orren 1966).

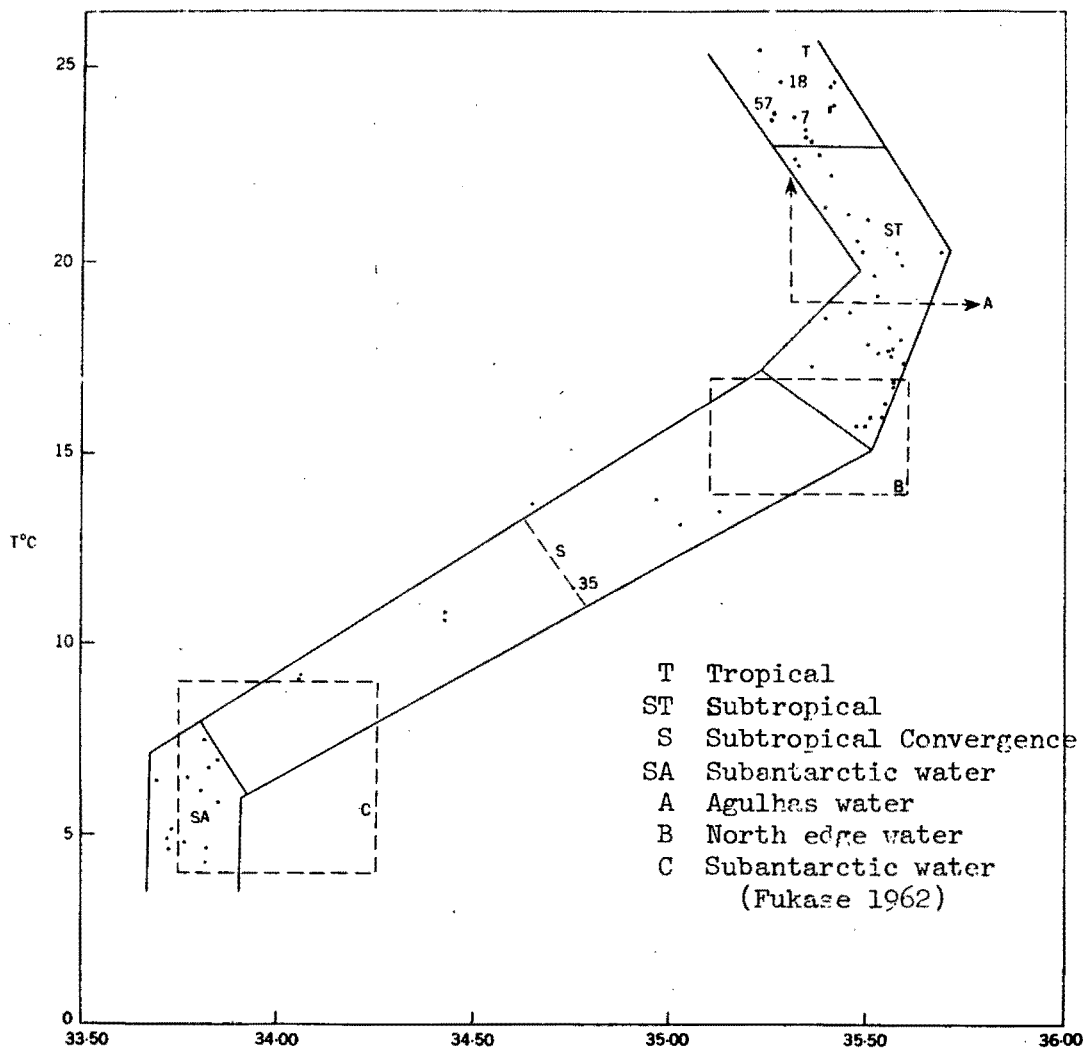


Fig. 6.

Surface T-S Relationships in the South-West Indian Ocean (Orren 1966).

transport of the Agulhas current was estimated at 64 sverdrups in the Southern Hemisphere's summer and at 85 sverdrups in winter. The south equatorial current supplied 46 sverdrups to the Agulhas current in winter but only two thirds of that amount in summer. Some tropical surface water rounded the southern tip of Madagascar in all seasons. The greatest flow of this water mass into the northern end of the Mozambique Channel takes place during winter. Subtropical surface water enters the Agulhas current system only past the southern tip of Madagascar, with greatest quantities in winter. Antarctic intermediate water, characterised by salinities less than  $34.6\text{‰}$ , does not extend north of Madagascar so that this water mass enters the Agulhas current only past the southern tip of the island. The high salinity Red Sea water enters the Agulhas current only through the Madagascar Channel, in quantities sufficient to distribute most of the excess salt into the Northern Indian ocean from the Red Sea.

Lutjeharms (1976) presents the part of his M.Sc. thesis (1971) concerned with the Agulhas current system. He concluded that the concept of a large South West Indian ocean gyre is justified, causing a large measure of Agulhas water recirculation, and that this gyre is probably a permanent feature at most depths, but more intensely so at greater depths. From this work done for the northeast monsoon season it would appear that the Agulhas current had different sources at different depths. At and near the sea surface the Mozambique and South Madagascar current acted as tributaries while at greater depths there was no more continuous flow through the Mozambique Channel and the Agulhas current derived its northern supply from east of Madagascar only.

A first deep-sea co-operative survey was undertaken in South African waters in 1969. This three ship synoptic cruise had been partly studied by Bang (1970). From a detailed surface temperature diagram the following observations and conclusions were made. A major cyclonic eddy centred at  $37^{\circ}\text{S}$ ,

27°E. and characterized by surface currents of up to 6 knots. The eddy extended to a depth of at least 1600m. A narrow strip of cold (14°-20°C) water was located immediately adjacent to the northern boundary of the current (first mentioned by Darbyshire (1964) and emphasises a divergent characteristic (previously called Agulhas convergence, Fukase 1962) of what is otherwise a strongly convergent but eddy-prone system. Another very interesting discovery by Bang (1973) is a Continental Shelf jet off the south west coast of South Africa. Bang (1976) concludes the jet is a feature of the South Atlantic wind driven circulation and that at the shelf edge high speeds extend right down to the bottom. He states that the jet is a warm transport mechanism, transporting South Atlantic, not west wind drift water. It is anticipated that the jet will weaken rapidly with decreasing latitude due to vorticity conservation factors; the more "normal" boundary geometry further north and the rather different local wind regime of Lüderitz.

## II. AREAS WITHIN THE AGULHAS CURRENT SYSTEM

### The Mozambique Channel, Sources of the Agulhas Current.

The situation in the Mozambique Channel was studied by Menaché with a number of cruises (1957, 1960, 1962). With respect to this study the most important result was obtained in 1957 when Menaché showed that the Mozambique current turned back at the southern entrance of the Mozambique Channel and thus making a small if any contribution to the Agulhas current. This result was remarkable because one generally assumed up to now that the Agulhas current was more or less a continuation of the Mozambique current supplemented by the south equatorial current rounding the southern tip of Madagascar.

Soares (1975) made some volume flux calculations in his thesis on the Mozambique Channel. For the COMMANDANT ROBERT GIRAUD 1960 cruise he calculated a transport of 15 sverdrups towards the south (using a reference level of 1000db) across 20°S. The transport towards the north however was shown to

be 25 sverdrups leaving a net northward transport of 10 sverdrups.

The fascinating problem of the sources of the Agulhas current was again taken up by Harris (1972). Harris (1972) also commented upon the situation in the Mozambique Channel. Using the ALMIRANTE LACERDA cruise (1964) supplemented by the ANTON BRUUN cruise (1964) his findings were broadly in accord with Menaché's (1957) findings in the Mozambique Channel. There was some evidence however of a flow from the Mozambique Channel, of Mozambique current water, very close to the African Continent (in depths less than 1000m). This work revealed the presence of a front extending from between Port St. Johns and Durban to the northern end of the Mozambique Channel. This front was demarcated by contrasting properties between water of the Mozambique current and water entering the system from the east. Water from the east has two main sources, the south equatorial current passing south of Madagascar and the Agulhas return current recycled west of the Madagascar ridge. Along the front a series of deep anticyclonic vortices were identified. The most marked of these was a vortex off Durban. With the help of transport, sigma-t curves it is argued that a new water mass might have formed due to the mixing of the denser recycled water from the south with lighter south equatorial current water. Some figures are reproduced below summarising the sources of water of the Agulhas current at Durban (according to Harris).

	Transport in Sverdrups
1. South equatorial water passing south of Cape St. Mary and entering the current directly or indirectly in the Mozambique Channel	35
2. Mozambique current through the narrows (Cape St. Andrew)	10
3. Agulhas return current - recycled west of the Madagascar ridge	15
4. Agulhas current recycled in vortex off Durban	12

Harris remarks upon the paucity of data just south of Madagascar (as does Lutjeharms (1971) and Duncan (1970)). He also commented upon the importance of synoptic data as he feels that the variability is so large that non-synoptic data would lead to severe difficulties in interpretation.

The data gap south of Madagascar had been partly investigated by Bang (1977). Twenty sverdrups seemed to round Cape St. Mary mainly in the subsurface layer.

A big effort has been made in an attempt to explain the phenomena of an inshore counter current off Durban. Pearce (1976) has recently discussed the results obtained from several cruises. Attempts to correlate the counter current with wind systems have been successful, but there are anomalies which have not been explained.

#### Planetary Waves over the East of the Agulhas Plateau.

The deflections of the eastward current over the Agulhas plateau, commented upon by several workers, were first investigated theoretically by Harris (1970). Using Porter and Rattray's (1964) mathematical model for barotropic zonal eastward flow over meridionally orientated topographical features, he showed that poleward excursions of planetary waves between the Agulhas plateau and Madagascar ridge can be very large. He noted that for the velocity of the barotropic current (he assumed 10cm/s) the Agulhas plateau is about half a wave length wide and the distance separating the plateau, the extension of the Mozambique ridge and Madagascar ridge is of the order of a wave length (fig. 7). Both of these facts would contribute to resonance effects and lead one to expect large amplitude planetary waves. In the same paper Harris commented upon equatorward branching from the Agulhas return current, in the region of  $40^{\circ}$  E. to  $60^{\circ}$  E, suggesting recirculation towards the south equatorial current. This branching might be partly caused by the extensions of the Mozambique and Madagascar ridges.

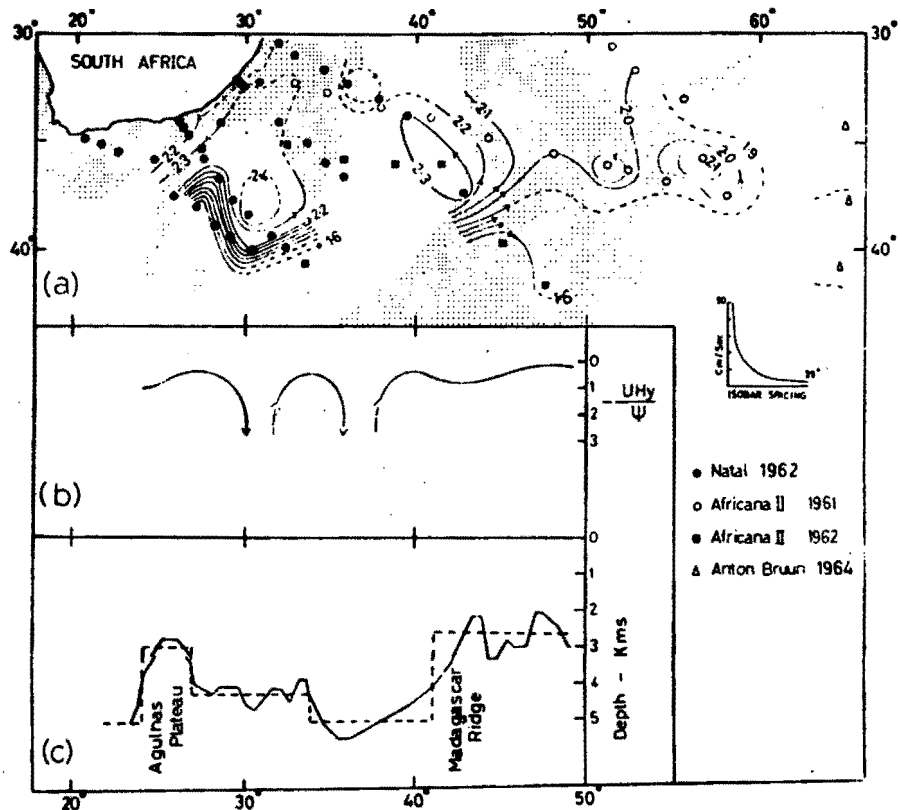


Fig. 7.

- (a) Dynamic topography of the surface with reference to the 1500 db. level for June and July for selected stations. Shading indicates approximate position of water depths of 3000 and 4000 m.
- (b) Normalized stream function of theoretical barotropic flow
- (c) Approximate bottom profile along latitude  $39^{\circ}$  S. Dashed line shows simplified profile used in the calculations

Note: Horizontal scales for (a), (b) and (c) are the same.

(after Harris, 1970).

Further theoretical work has been done by Darbyshire (1972). Using Warren's (1963) inertial jet model he concluded that: the existence of a small bottom current (4cm/s) would enable the Agulhas current to proceed round the Cape. When the stream is at its highest, however, the bottom current may be insufficient to do this and the stream can, under some conditions, double back without becoming unstable and then there is a true return current. There is, however, all the year round a strong eastward current to the south of the Agulhas current but most of the time this is fed only slightly by the Agulhas Current and it originates outside the Agulhas current system area. Again with a small bottom current and the same order of magnitude as with the Agulhas current, this eastward current is deflected round the Agulhas plateau. Darbyshire's calculations were done with a desk computer confining him to a limited number of track calculations.

#### Recent Experiments.

The recent experiments in Agulhas current research have been done with the aid of satellite tracked buoys. Gründlingh (1976) discussed the track of buoy 1116 (fig. 19). He commented upon the existence of synoptic scale cyclonic gyres of which the first direct current measurements were included in his study. He postulates that the eddies originate somewhere on the Madagascar ridge (fig. 10). In another paper Gründlingh (1977) discussed the track of buoy 1210 (see fig. 19). In his analysis he suggested a secondary eastward return at  $39^{\circ}$  S,  $15^{\circ}$  E). Another feature discussed was formed over the Agulhas plateau. Two 400km. northward excursions from the main axis of the Agulhas return current were observed at the Agulhas plateau and the southerly tip of the Mozambique ridge. Each excursion revealed a strong cyclonic eddy of approximately 200km. in diameter. Gründlingh used Warren's (1963) inertial jet model to simulate these northward excursions. This was only partly successful.

CHAPTER C.REASONS FOR THIS STUDY.

From the literature review it is clear that a lot of uncertainties and contradictions about certain aspects of the Agulhas current system exist. In particular, the sources, the interaction with the South Atlantic ocean, the scale and effect of the planetary waves over and east of the Agulhas plateau, the eddy-like structures and the time-dependency of the current are not yet understood. The recent tracks of satellite buoys (and satellite infrared images now being studied at the University of Cape Town) have contributed towards a better understanding of the current system but on the other hand have also raised many new questions. This recent evidence has made clear that the time dependency and the scale of certain features of the current is such that only synoptic and closely spaced hydrographic data are really useful.

The detailed "synoptic", Agulhas current cruise of 1969 which had not yet been fully studied forms a unique opportunity to study the current in the light of this new evidence. The 1969 cruise will therefore form the basis of this thesis. The new evidence has made it possible to look at old data under a new light. In some cases recontouring of old diagrams was possible and thus contributed to support the arguments.

CHAPTER D.

DATA SOURCES.

a. The main data source for this study is the Agulhas current project of March 1969. This 3-ship project constitutes the first deep-sea co-operative survey undertaken in South African waters. Station positions and numbers can be found in fig. 8. The 3-ships concerned were R.S. AFRICANA II of the Division of Sea Fisheries, R.V. THOMAS B. DAVIE of the University of Cape Town, and R.V. MEIRING NAUDE of the National Physical Research Laboratory. The cruise was completed in 15 days (6th-25th March), (Bang and Pearce 1970, \_\_\_\_\_ 1969).

Other Hydrographic Data Used:

- b. S.A.S. NATAL cruises in the South West Indian ocean during the SCOR International Indian ocean expedition. (April 1962; June/July 1962; October 1962; January 1963). (Shipley and Zoutendyk 1964).
- c. COMMANDANT ROBERT GIRAUD cruises in the Mozambique Channel. (October/November 1957; July/September 1960) (Menaché 1963, \_\_\_\_\_ 1960).
- d. N.H. ALMIRANTE LACERDA cruise in the Mozambique Channel (September/October 1964, \_\_\_\_\_ 1967).
- e. R.V. ANTON BRUUN cruise in the southern end and south of the Mozambique Channel during the International Indian ocean expedition (August/September 1964, \_\_\_\_\_ 1965).
- f. R.S. AFRICANA II cruise in the Schmidt Ott seamount area (March 1964) (South African Division of Sea Fisheries) (Visser 1969).

Other Data Used Consists of:

- g. NIMBUS VI satellite tracked buoys, 1116, 1210, 1120 all deployed in the Agulhas current system in 1975 (Gründlingh 1976, 1977).

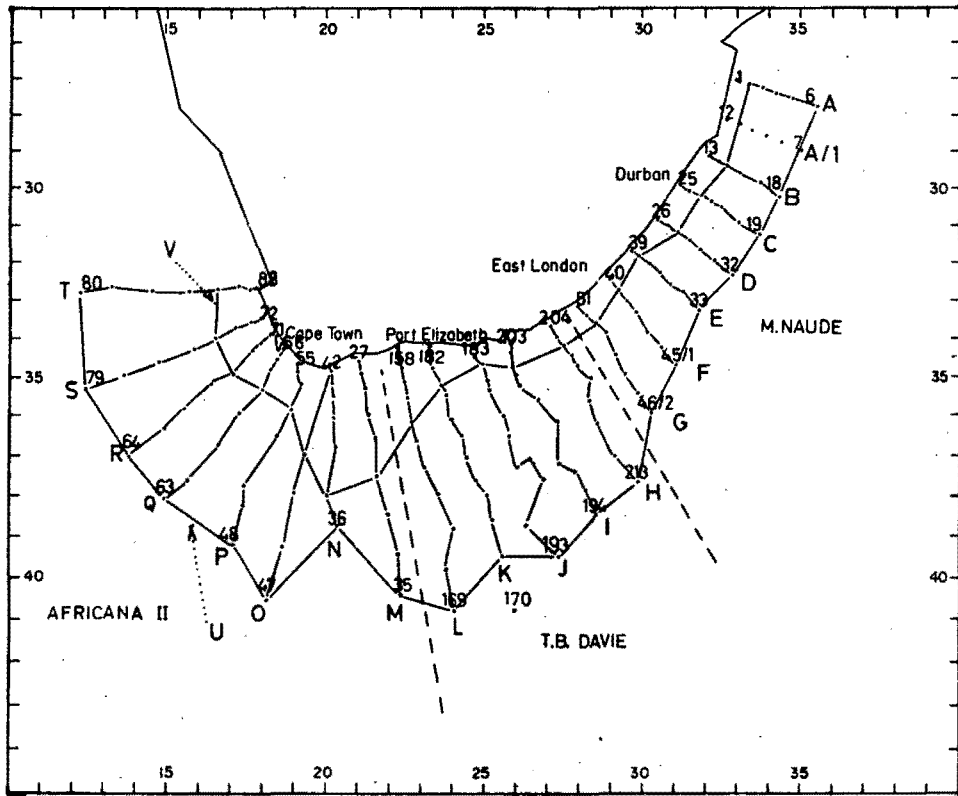


Fig. 8.

Agulhas current project March 1969. Station positions, numbers and section letters.

No salinities were obtained at line A/1  
 Sections U and V are roughly parallel to the coast.

h. SOFEX (Southern Ocean Float Experiment) buoy 776 deployed in 1976 (Harris and Stavropoulos 1977).

i. NOAA 4 and 5 satellite infrared images. These images have only been recently received and are now studied at the University of Cape Town, (Harris, Legeckis, van Foreest 1977). To support certain arguments in this thesis the images will be mentioned briefly.

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## CHAPTER E.

### METHODS USED AND PROBLEMS INVOLVED.

#### (a) General

The hydrographic data were processed with standard computer programs to give property values on selected sigma-t levels, the depth of these sigma-t values and acceleration potentials. This enables one to study the distribution of properties on a sigma-t level together with the flow pattern obtained from the acceleration potentials. Property distributions were often "patchy" and therefore difficult to interpret and not always helpful. Due to the sampling depth limitation of the MEIRING NAUDE, the data of the 1969 Agulhas current project will not be studied beyond the salinity minimum. The Red Sea water will not be discussed.

The 1969 cruise consists of 20 sections, normal to the coast, numbered A, . . . ., T. For the volume flux calculations the areas in between the sections have been divided into boxes. For this division two sections, U and V, have been introduced running more or less parallel to the coast (see fig. 8). Section V is characterised by the fact that the bottom topography within the section is deeper than the reference level (1100m) chosen. A box is now defined as the volume of water closed off by two sections, the reference level, the surface, the relevant part of section U and the continent. Boxes will be numbered after the sections (i.e. the first box to the north east of Durban is box A, the last box to the north west of Cape Town is box S (see fig. 8)). Every box is subdivided into an offshore and inshore box by section V. The offshore boxes are now free of bottom topography penetrations.

#### (b) Volume Flux Calculations

Volume flux calculations will be made in particular for the 1969 cruise. For these calculations a computer program

derived by Lutjeharms (1971) will be used. The program is based upon Witte-Margules' equation. The advantage of Witte-Margules' equation over the dynamic method is that one can use stations in water shallower than the reference level chosen by just setting the velocity at the sea floor equal to zero. Witte-Margules' equation states:

$$\tan j = -f(\rho_1 v_1 - \rho_2 v_2) / g(\rho_1 - \rho_2).$$

where  $j$  is the slope of the density interface between water masses with densities  $\rho_1, \rho_2$ .  $v_1$  is the velocity of the water mass with density  $\rho_1$  and  $v_2$  is the velocity of the water mass with density  $\rho_2$ .  $f$  is the coriolis parameter and  $g$  the acceleration of gravity. Calling  $\rho_1 - \rho_2 = \Delta\rho$  and replacing  $\rho_1$  and  $\rho_2$  by the mean density we get

$$v_1 - v_2 = g \Delta\rho \tan j / f \rho.$$

The essential assumptions made are:

1. No frictional forces.
2. No accelerations.
3. No vertical motion.

Applying Witte-Margules' equation one has to deal with a section in which one has drawn the sigma-t levels. An interval of 0.2 sigma-t will be used. Applying the formula to a sigma-t level (e.g. 26.0) the velocity of the layer of water above this level (between 26.0 - 25.8) relative to the velocity of the layer of water underneath that level (between 26.0 - 26.2) will be found. This can be interpreted as the relative velocity of the sigma-t level 25.9 to the sigma-t level 26.1. Thus to get the knowledge of the absolute velocity it is necessary to choose a level of no motion.

### (c) Level of No Motion

The 1969 Agulhas current project aimed at sampling to a depth of 1500 metres. The ships AFRICANA II and T.B. DAVIE were sufficiently equipped to sample down to this depth. The MEIRING NAUDE however, although with modern equipment, was limited to a sampling depth of approximately 1000 metres.

For the data from the AFRICANA II and the T.B. DAVIE it is possible to fix the level of no motion, for the volume flux calculations, at a depth of 1500m. using the 27.6  $\sigma_t$  level. But as study of the 1969 cruise as a whole is ofcourse preferred, the limitations for the level of no motion is made by the sampling depth of the MEIRING NAUDE. Therefore the choice for the volume flux calculations fell upon the 27.2  $\sigma_t$  level which was fixed at a depth of 1100m. For the acceleration potential calculations a reference depth of 1000 metres was used. The difference in reference level between the acceleration potential calculations and the volume flux calculations is caused by the fact that for the volume flux calculations the often considerable slope on the 27.2 level had to be flattened out completely. The 1100m. depth line seemed to be a reasonable choice throughout the 1969 cruise. For all other cruises studied the same reference level was usually chosen to make comparison with the 1969 cruise possible. The validity of the reference level will be discussed in Chapter G2. Duncan (1970) derived a factor of 2.66 to convert transports calculated using the 1000 db. level as a level of no motion into transports relative to the 2500 db. level.

(d) Difficulties concerning Volume Flux Calculations

Problems arise with the drawing of the  $\sigma_t$  sections. Due to the very steeply sloping  $\sigma_t$  levels in the Agulhas current and the few samples taken close to the continental boundary it was difficult to find the intersection point of the  $\sigma_t$  levels with the continental boundary. As a start the levels were drawn intersecting the boundary at a place in agreement with the general picture of the section. This method often left a wide range of possibilities for shifting the intersection points up or down, resulting in considerable transport differences. The offshore boxes (see definition at the start of Chapter E) free of bottom topography penetrations must balance (continuity) independent of the choice of the reference level. One must bear in mind that

this balance is artificially created by the application of Witte-Margules' equation and is by no means an indication that the choice of the reference level is correct. The inshore boxes create different problems however. Because the intersection points of the  $\sigma_t$  levels with the continent are not known, discrepancies will generally arise in these boxes (water cannot be supplied through the continent). The intersection points were adjusted within reasonable limits until the best possible balance was accomplished. (see Table II Chapter F3). The discrepancies that arise in the inshore boxes are, besides due to extrapolation difficulties, due to the limitations of Witte-Margules' equation. The discrepancies might therefore indicate vertical motion, acceleration of the current etc. (i.e. not in geostrophic balance). Density inversions occurring at some stations (e.g. station 27) in the main current complicated the situation. Better balances were created by smoothening out the density depth curves.

(e) The Free Inertial Jet Model

The model used was developed by Warren (1963). In his study the current is regarded as a narrow filament of rapidly flowing water that moves through a region of geostrophic flow. Across the filament the pressure gradient is much larger than that characteristic of the open ocean. At each edge of the filament the pressure gradient joins smoothly to the open ocean value without the help of a solid boundary. It is in this sense that the current is considered to be free. It is the total change of vorticity of the current that is the matter of interest and consists of three terms. One is due to planetary vorticity, a second is due to vortex stretching and shrinking, and a third is due to changes in the curvature of the path along which the water flows. Each of these terms, because of the assumed thickness of the current, is a function of the downstream distance only. The essential assumptions made are:

- (1) the motion is steady
- (2) friction and density variations are neglected
- (3) relative vorticity  $\left(\frac{dc}{dz} + \frac{c}{z}\right)$  is expressed as  $KC$ ,  
where  $K$  is the curvature and  $C$  the current velocity.

Since velocities are small outside the stream the shear makes only a negligible contribution to the total vorticity transport.

- (4) the bottom current, which is responsible in this model for vortex stretching and shrinking, is assumed not to be displaced laterally very much from the vertically averaged current.

If one treats the velocity structure as known, a given change in latitude and depth under the current produces a fixed change in curvature which leads to a differential equation for the path of the current. The equation is:

$$1. \frac{d^2y}{dx^2} \left(1 + \left(\frac{dy}{dx}\right)^2\right)^{-3/2} + \left(\left(\beta v - f_0 T D_y\right)/M\right)y - \left(f_0 T D_x/M\right)x = 0$$

where  $f_0$  is the inertial frequency at the starting point;

$\beta = \frac{df}{dy}$  is the B plane approximation.

$V$  is the integrated volume transport across a section of the stream.

$M$  is the integrated momentum transport and  $T$  is the transport across unit depth near the bottom. The depth  $D$  is given by

$$D = D_x x + D_y y$$

Warren solved the equation analytically for the Gulf-stream and obtained reasonable results for the mean current path.

Niiler and Robinson (1967) used the equation in a slightly different form:

$$2. \frac{d^2y}{dx^2} \left(1 + \left(\frac{dy}{dx}\right)^2\right)^{-3/2} - c_0 + \beta v (y - y_0)/M + f_0 T (D - D_0)M = 0$$

and solved it numerically using the Runge-Kutta method.

( $c_0$  is initial curvature,  $D_0$  depth at the starting point and

D depth at a point (x,y)). Godfrey and Robinson (1971) applied the jet model in form 2 to the East Australian current. Although there is no obvious relationship between the features of dynamic topography and bottom topography the results gave an insight in the eddy formation which is a marked feature of the East Australian current.

As will be seen later the Agulhas current seems to have a remarkable response to bottom topography (see for example fig. 12). Application of the inertial jet model might therefore be interesting (Darbyshire 1972).

The model will be used here to investigate the source area. Use of the model here is justified by the velocity section (fig. 9) reproduced from Harris (1972). The results will be discussed in Chapter G1.

For the computations a computer program was developed. The co-ordinate system used has the origin in the sea-surface, x is positive east, y positive south, z positive down. In this co-ordinate system equation 2 takes the form;

(a) for eastward motion:

$$\frac{d^2y}{dx^2} = \left(1 + \left(\frac{dy}{dx}\right)^2\right)^{3/2} \left(c_0 - \frac{\beta v}{M}(y-y_0) + \frac{\rho T}{M}(D-D_0)\right)$$

(b) for westward motion:

$$\frac{d^2y}{dx^2} = -\left(1 + \left(\frac{dy}{dx}\right)^2\right)^{3/2} \left(c_0 - \frac{\beta v}{M}(y-y_0) + \frac{\rho T}{M}(D-D_0)\right)$$

A ten by ten nautical mile grid was used. The depths were taken from the bathymetry chart shown in fig. 10.

(f) Presentation

Volume flux diagrams and acceleration potential diagrams are presented superimposed on the bottom topography. The bottom topography is a photographic reproduction of a three dimensional plaster model (Marine Geology Department, University

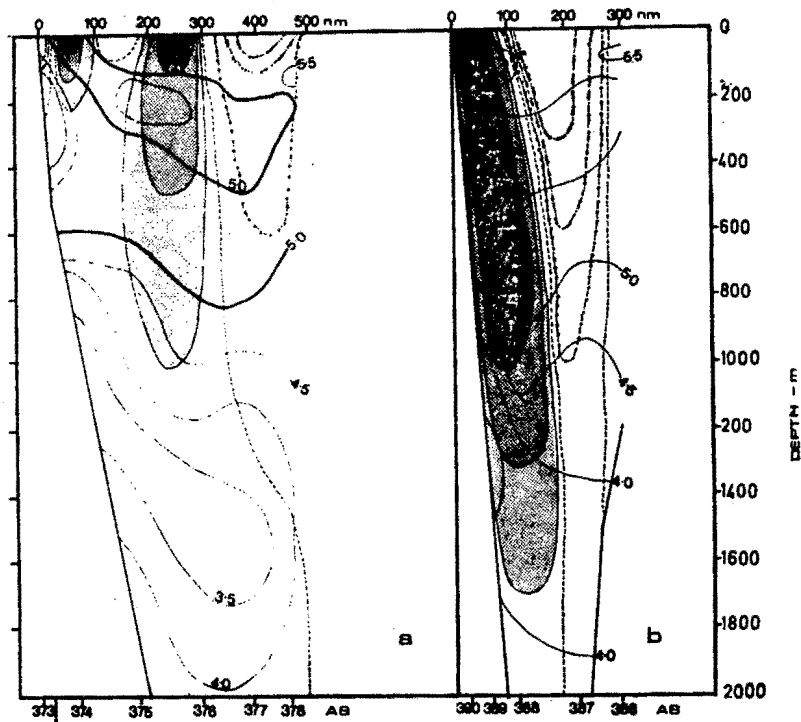


Fig. 9.

Velocity and oxygen (ml/l.) contours on sections (a) between Lourenco Marques and The Walters Shoal, (b) across the Agulhas current and the offshore counter current off Durban. (ANTON BRUUN 1964). Shaded currents are southgoing.

dark shaded	15 $\text{cm/s}$
medium shaded	10-15 $\text{cm/s}$
light shaded	5-10 $\text{cm/s}$

Note that the current axis of the Agulhas current (fig. b) is parallel to the Continental Shelf slope. (after Harris 1972).

of Cape Town). For the actual depths and names of ridges, seamounts, etc., one is referred to fig. 10. The tracks generated from the inertial jet model will also be presented on the bottom topography. Use of one scale throughout the thesis has been made in order to facilitate comparison of different diagrams.



Fig. 10.

Bathymetry around Southern Africa.  
 Superposition of a 3 dimensional model photograph on the bathymetry map after Simpson. (June 1974).

## CHAPTER F1.

### FLOW PATTERN OF THE 1969 AGULHAS CURRENT PROJECT

In this chapter the acceleration potential diagrams (fig. 12, 13, 14) of the 1969 cruise will be discussed. For a more detailed discussion together with other data reference will be made to the relevant chapters. Three sigma-t levels, 25.60, 26.40, 26.80, have been selected for presentation here. The 25.60 level is chosen because it is the level closest to the surface without actually cutting the surface. The 26.80 level was the deepest level possible for the MEIRING NAUDE data without losing too many stations. The 26.40 level an arbitrary level in between. The first thing that should be noted in the acceleration potential diagrams (especially 25.60) is the apparent similarity between isobaths and lines of constant dynamic height. This is especially clear in areas where the bottom topography gradients are large, such as along the east coast of South Africa, from Durban to the southern part of the Agulhas bank, and along the northern half of the Agulhas plateau. Another remarkable feature is the anti-cyclonic eddy structure in between Agulhas and Agulhas return current.

The following is a more detailed description of the 25.60 acceleration potential diagram.

Two supplies for the Agulhas current are evident. The first flowing down from the north is joined by a second flowing in from the east, just south of Durban. The flow from the north is fast and narrow (20 dyn.cm. drop across 30 nm.), compared with the inflow from the east (15 dyn.cm. drop across 150 nm.). Inshore of the supply from the north some cyclonic return motion seems to take place, while on the seaward side of this supply anticyclonic movement takes place. (This will later be related to an eddy off Durban).

Convergence of the supplies takes place approximately at station line D (fig. 8). The area to the north of line D is named source area (fig. 11) and will be discussed further in Chapter G1, together with other relevant data.

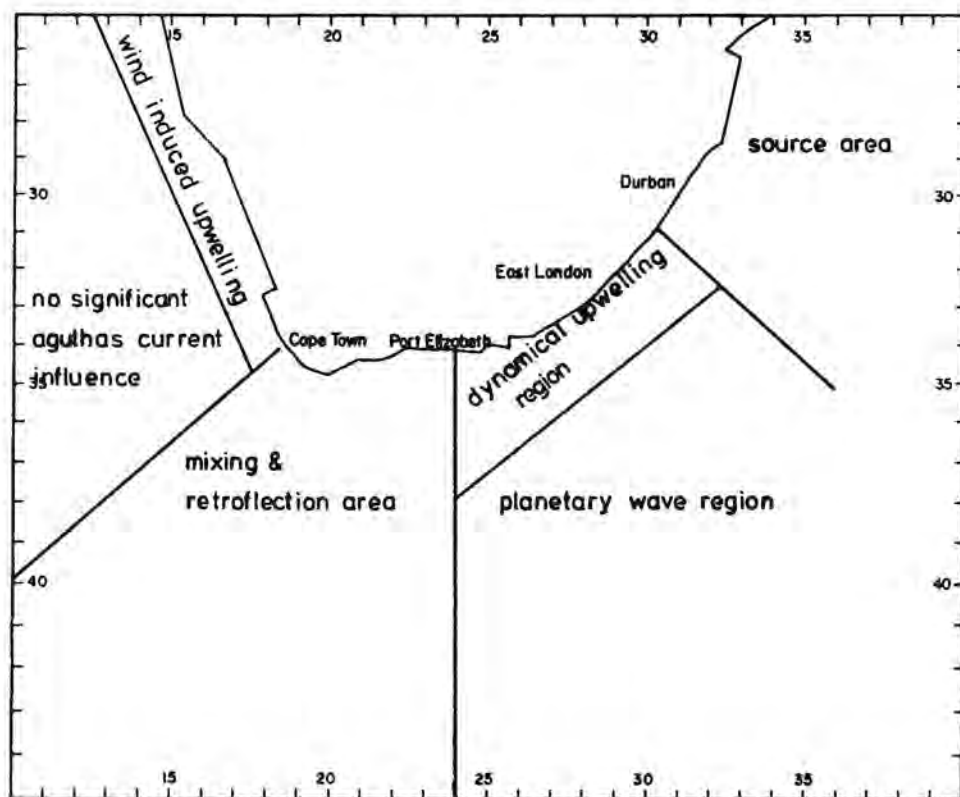


Fig. 11.

Schematic presentation of the different areas within the Agulhas current system.

Source Area - see Chapter G (Source Area)

Dynamic upwelling region - see Chapter H (Area between East London and Port Elizabeth)

Mixing and retroflection area - see Chapter I (Mixing Area)

Planetary wave region - see Chapter J (Agulhas Return Current)

South of line D the Agulhas current is fully developed, and flows very close inshore to the latitude of East London. Severe upwelling is encountered at station lines G and H, as can be seen from the corresponding sigma-t sections (fig. 16). The outside part of the current seems to leave the coast. The 1.80 dyn.metre line is directed southward to join with Agulhas return current just east of the Agulhas plateau. The lines inshore of the 1.80 dyn.metre line tend to run southward as well, but recover again to form a loop between East London and Port Elizabeth. The dynamic high region south east of East London probably plays an important role in the turning offshore and the inflow from the east. A more detailed discussion of the area is given in Chapter H. The area is referred to as the area between Port Elizabeth and East London, and its boundaries are shown in fig. 11. It is understood to include the dynamic high region south east of East London. The current runs along the continental slope almost to the southern end of the Agulhas bank. A dynamic high region is found exactly over the Davie Seamount ( $36^{\circ} 30' S$ ,  $24^{\circ} 30' E$ ). Unfortunately the Davie Seamount was not shown on the plaster model, as it had not been discovered at the time that the plaster model was constructed. The position of the Davie Seamount can be found in fig. 10.

After leaving the continental slope the current runs over the abyssal plane and gradually turns anticyclonically to form the Agulhas return current. This retroflexion can be explained with the potential vorticity equation: During its flow south, the Agulhas current can compensate its gain in planetary vorticity by moving into deeper water. As the current flows over the abyssal plane, however, no more depth change is possible. The still increasing planetary vorticity can therefore only be compensated by anticyclonic motion resulting in the retroflexion. The limit of penetration south could not be established for the 1969 cruise as it fell outside the data limit. The area west of the Agulhas plateau (west of  $24^{\circ} E$ .) is discussed further in Chapter I. The area will be referred to as a mixing area (fig. 11).

For completeness another division line must be introduced here. The line runs from Cape Town to  $40^{\circ} 0' S$ ,  $10^{\circ} 0' E$ . From other data it can be argued, as discussed in Chapter I, that no "coherent" influence of warm Agulhas water is evident further north west than this line, although patches of warm water may extend further. Due to the choice of the reference level it can not be established from the acceleration potential diagrams whether Agulhas water finds its way into the waters west of South Africa. Volume flux calculations will show that water inshore of the Agulhas current does flow into waters west of South Africa. Property distributions suggest that this water upwelled in the Port Elizabeth/East London region or cold water lifted over the Agulhas bank. Within the retroflection some anticyclonic circulation takes place. The area to the west of South Africa is dominated by a large anticyclonic circulation (180 nm. diameter) and an inflow from the west between station 63 and 64. In this area the influence of the Agulhas current is small. The inflow between stations 63 and 64 was a possible source for the Benguela current, as will be discussed in Chapter I.

After retroflection the Agulhas return current impinges upon the Agulhas plateau and is forced round its northern half. East of the plateau a large amplitude (180 nm.) planetary wave is described. The anticyclonic circulation in the northern part of this wave could have been a separate eddy (the connection between the northern half and the southern part fell just outside the data limit), but property distributions and satellite buoy tracks have supported contouring, as shown here.

Surface currents of 6 knots have been recorded in parts of the return current (Bang, 1970) during the 1969 cruise. The return current is discussed together with other data in Chapter J (Agulhas Return Current).

Coherency or lack of coherency of the flow pattern with depth can be seen in figures 12, 13, 14 and an attempt to illustrate this quantitatively is made in Table I. Note the shallowness of the eddy off Durban (200m).



Fig. 12.

March 1969 Agulhas current project. Acceleration potential on the 25.60 sigma-t level (reference level 1000 db.) (contour interval 0.05 dyn.meter, 1. is omitted).



Fig. 13.

March 1969 Agulhas current project. Acceleration potential on the 26.40 sigma-t level (reference level 1000 db.) (contour interval 0.05 dyn.meter, 1. is omitted).

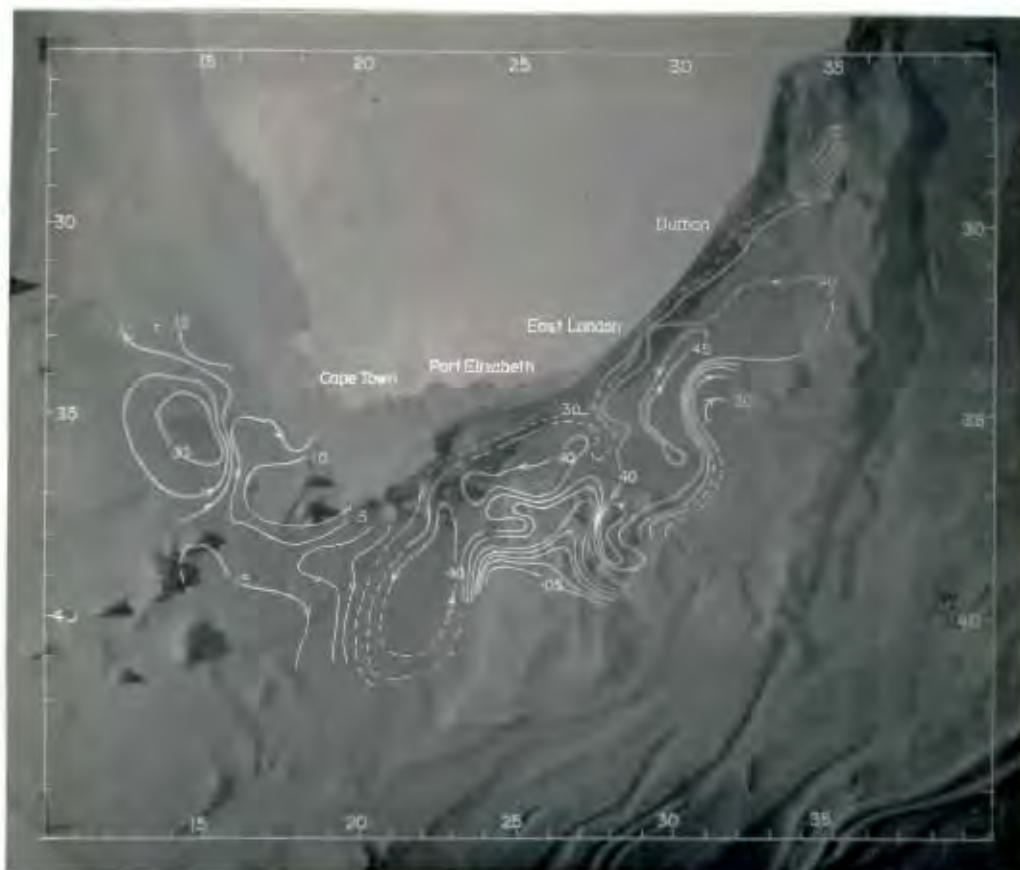


Fig. 14.

March 1969 Agulhas current project. Acceleration potential on the 26.80  $\sigma_{\text{t}}$  level (reference level 1000 db.) (contour interval 0.05 dyn.metres, 1. is omitted)



Fig. 15.

Superposition of buoy tracks (fig. 19) on the 25.60  $\sigma_{\text{t}}$  acceleration potential (fig. 12).

TABLE I

Drop in dynamic height (in units of 5 dyn.cm), across several features in the 1969 cruise, on different sigma<sub>t</sub> levels. For all sigma<sub>t</sub> levels a reference level of 1000 db. was used.

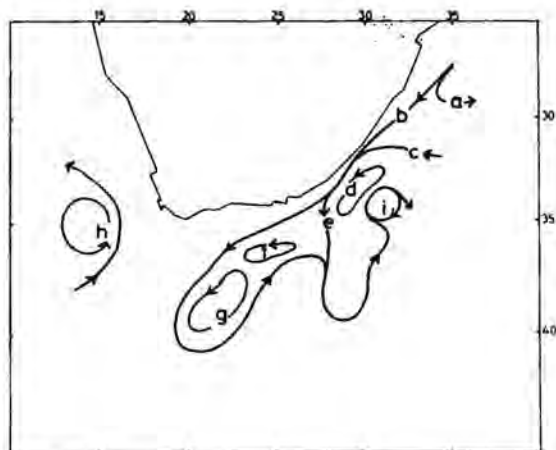
Sigma-t level	a	b	c	d	e	f	g	h	i
25.0	4	3-4	3-4	2	1	2	1	-	6
25.6	2	3-4	3-4	2	1	2	2	4	7
26.2	1	3-4	3-4	1-2	1	2	2	3-4	5
26.4	1	3-4	2-3	1	1	1-2	2	3-4	4-5
26.6	0	4	2	1	0	1	2	3	4-5
26.8	0	2	1	1	1	1	1	2	4

The flux (with reference to 1100m) transported by these features was (fig. 17):

	a	b	c	d	e	f	g	h	i
Flux (sv.)	5	15	15	5	5-10	5	10	5	5-10

The features concerned are:

(Positions can be seen in the adjacent figure).



- a. Eddy off Durban
- b. Contribution to the current from the north at Durban
- c. Inflow from the east just south of Durban
- d. Dynamic high off East London
- e. Turning offshore at East London to join the Agulhas return current
- f. Dynamic high over Davie Seamount
- g. Circulation within retroflexion
- h. Circulation within eddy west of South Africa
- i. Circulation in northern end of planetary wave

In Chapter F3 volume flux calculations for the 1969 cruise will be discussed. Very good agreement with the acceleration potential diagrams is evident. It illustrates the small contribution (5 sverdrups) of the Indian ocean water to the waters west of South Africa. Before the volume flux calculations are discussed it is necessary to present and discuss the  $\sigma_t$  sections on which the volume flux calculations are based. Several of the features discussed in Chapter F1 show very clearly in the  $\sigma_t$  sections. The sections and their discussion can be found in the next Chapter (F2).

CHAPTER F2.DISCUSSION OF SIGMA-T SECTIONS OF THE 1969  
AGULHAS CURRENT PROJECT

The sections are shown in figure 16. Some marked features need special attention and will therefore be commented upon. For all station lines the sigma-t sections are drawn. Their position and lettering is found in figure 8.

The Agulhas current starts properly only at section D (south of Durban) where it shows steep (400m. in 30nm. at the deeper levels) sloping levels close against the continental slope. The feature is maintained up to section E (Cape Hermes). After section E the current still follows the continental shelf slope. It is therefore found offshore as the Agulhas bank is situated between the coast and the shelf break.

The Agulhas current as a western boundary current extends only from approximately Durban to East London, a distance of about 300 nautical miles.

At the point where the upper boundary (coast) is lost between Port Elizabeth and East London (sections G and H) upwelling must occur as the density levels break and surface (down to the 26.00 level). This feature is also very marked in the property distribution as will be seen later.

In the following sections (I - N) the sigma-t levels do not cut the surface but are lifted over the Agulhas bank and very steep slopes occur (800m. in 40 nautical miles 27.20 level section J).

After section N the density levels suddenly tilt back to a relatively horizontal position indicating the loss of the current between sections N and O. It is between these sections that the retroflexion of the current must occur.

Throughout sections C - N a deepening of the density levels can be noticed. This is especially clear when the maximum depth of the 27.00 sigma-t level is followed (950m. at section C, 1300m. at section M). This deepening might be due to a stretching of the water column necessary to satisfy the potential vorticity equation as the current moves south.

In sections I - M the eastward current shows, at a distance of 200 nautical miles offshore at section I to 300 nautical miles offshore at section J. Around station 197 in section I a very marked cyclonic eddy is present. From this section it is not clear whether this feature is an eddy or a cross-section through the outer end of a sharply curving Rossby wave which is a feature of the eastward current. Some of the density level shapes, that indicate eddies, are thought to be induced by seamounts. A good example of this is seen in section Q where an eddy seems to be present above Mount Erica (250 nautical miles offshore).

Another feature worthwhile mentioning is the curious shape of some levels in sections D and E. The shape is best seen at the 26.60 level in section D. After sloping down steeply to a depth of 420 m. it suddenly slopes up (about 50m.) after which it continues its slope down. This steplike shape in some of the density levels might be due to the meeting of two different water masses (convergence of the two inflows) having the same density level at different depths. Continuity created in such a density level might set up a counter current or might cause accelerations in the main current direction.

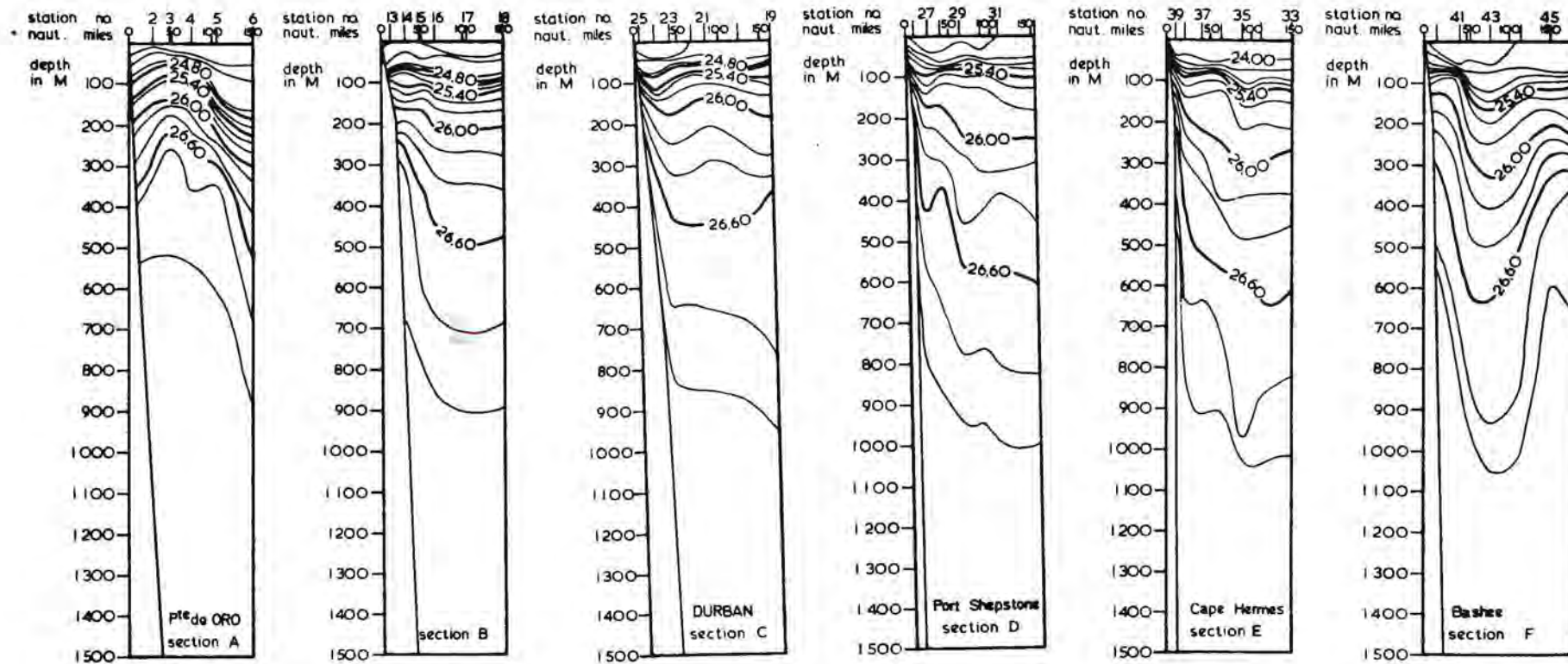
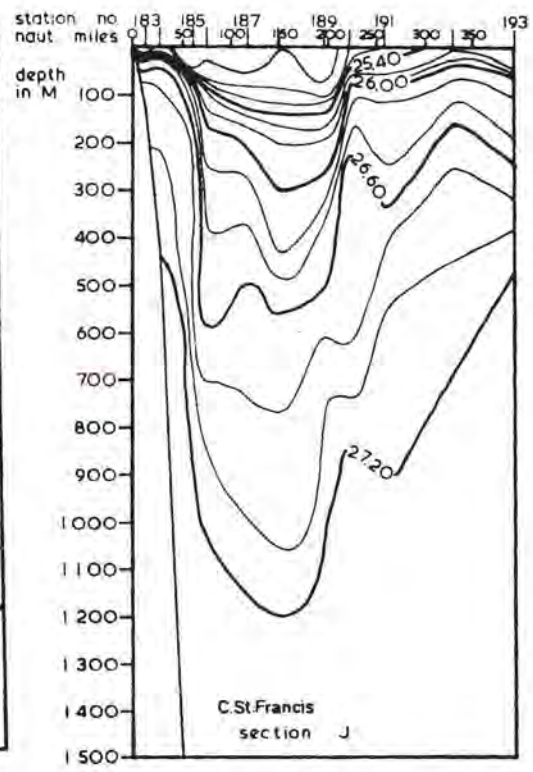
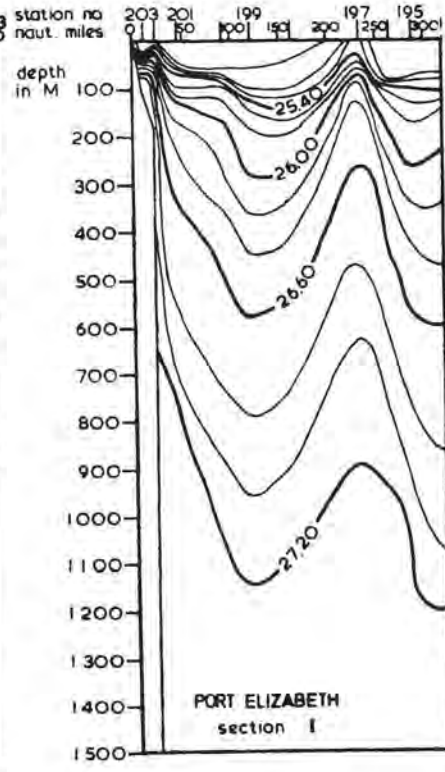
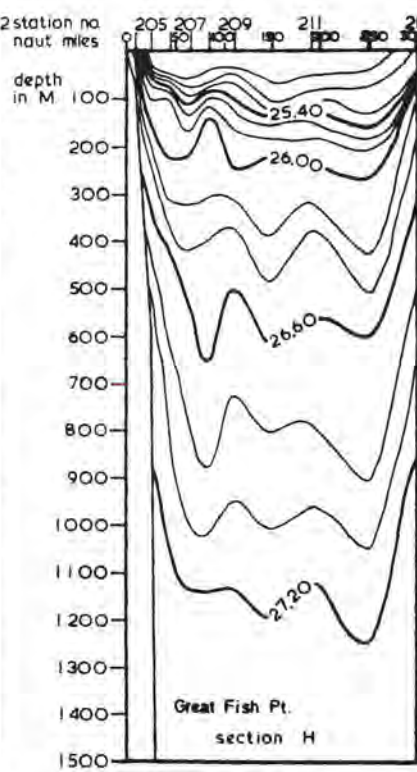
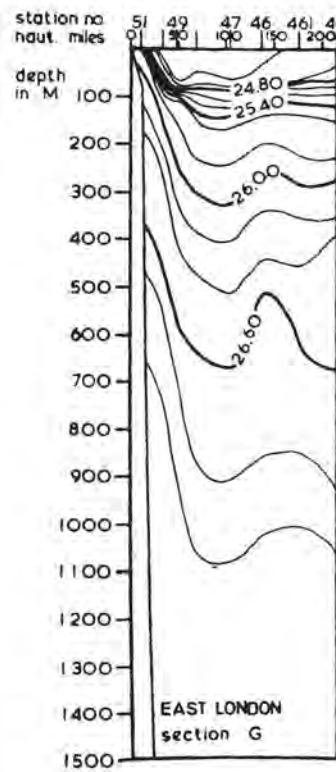
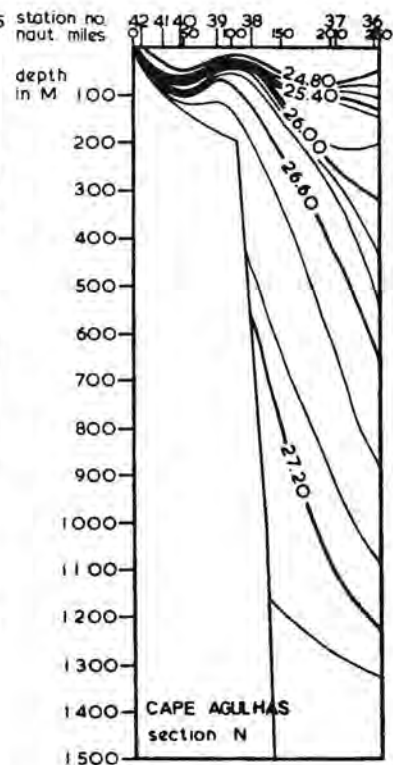
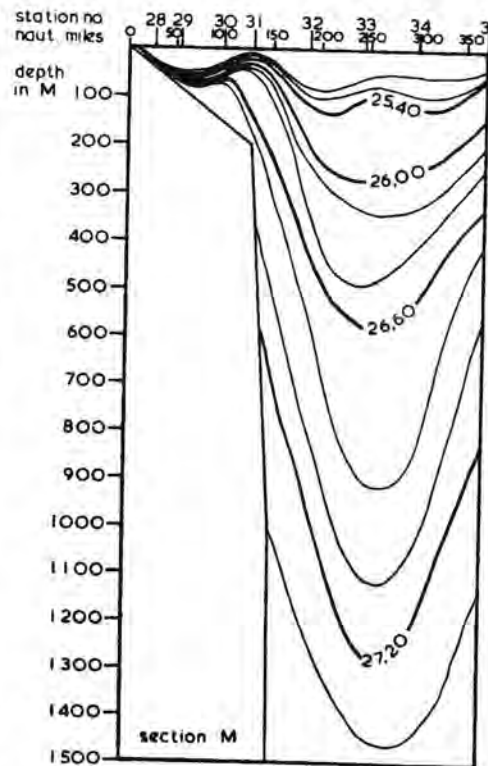
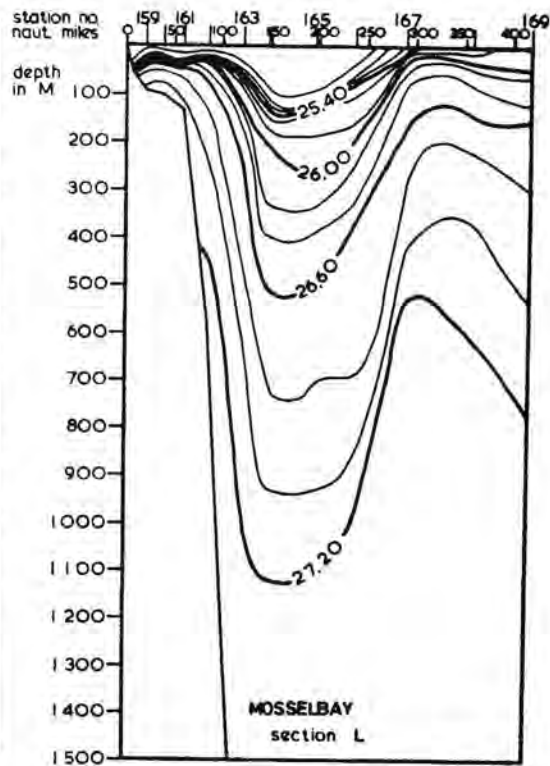
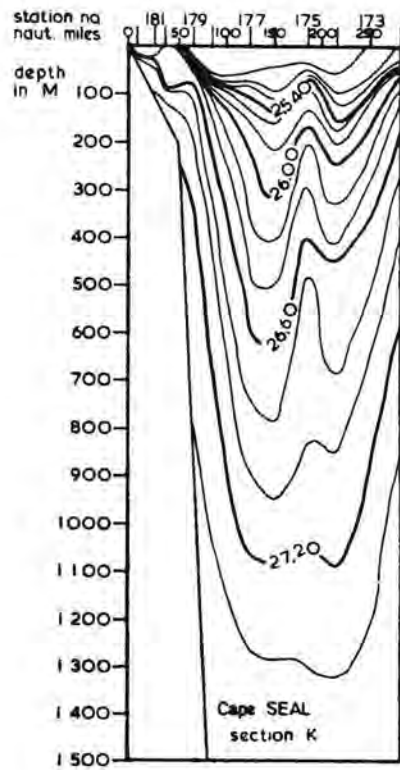


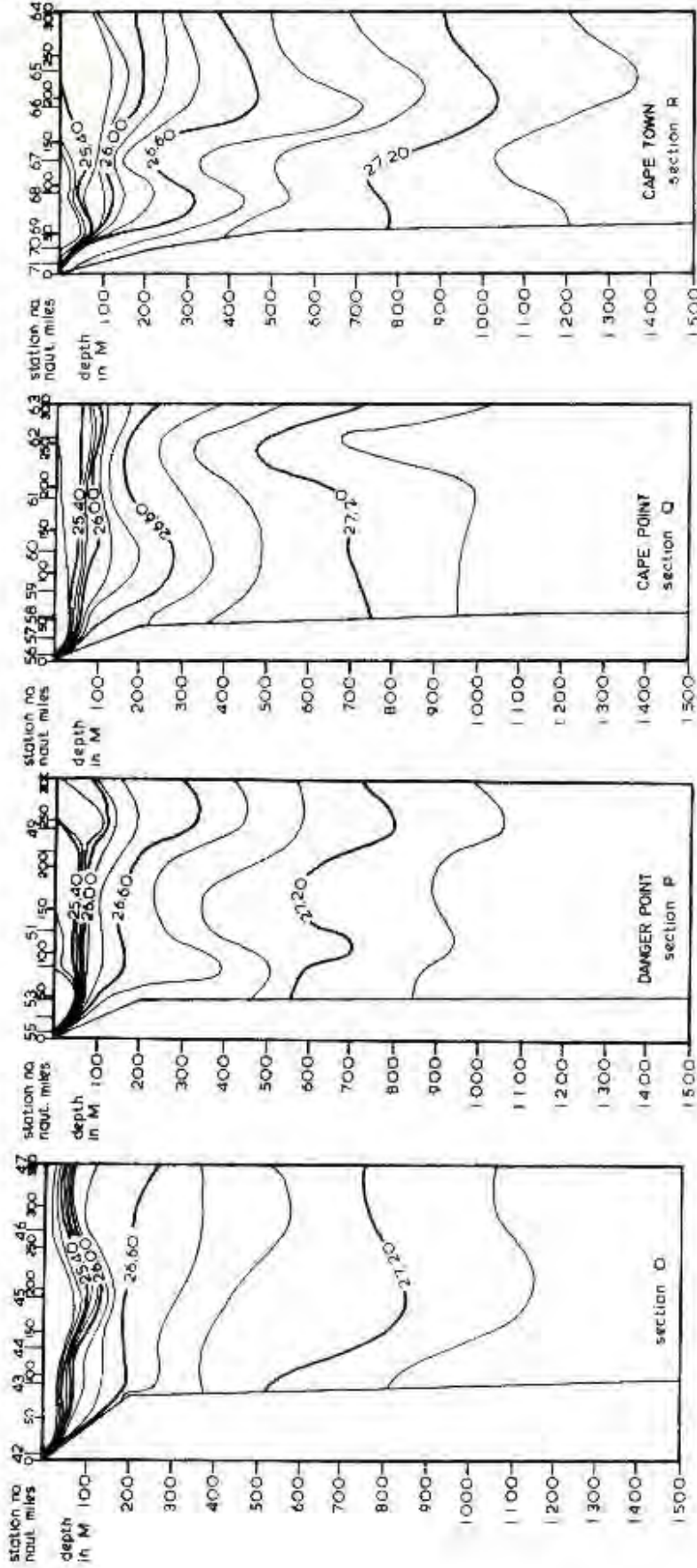
Fig. 16.

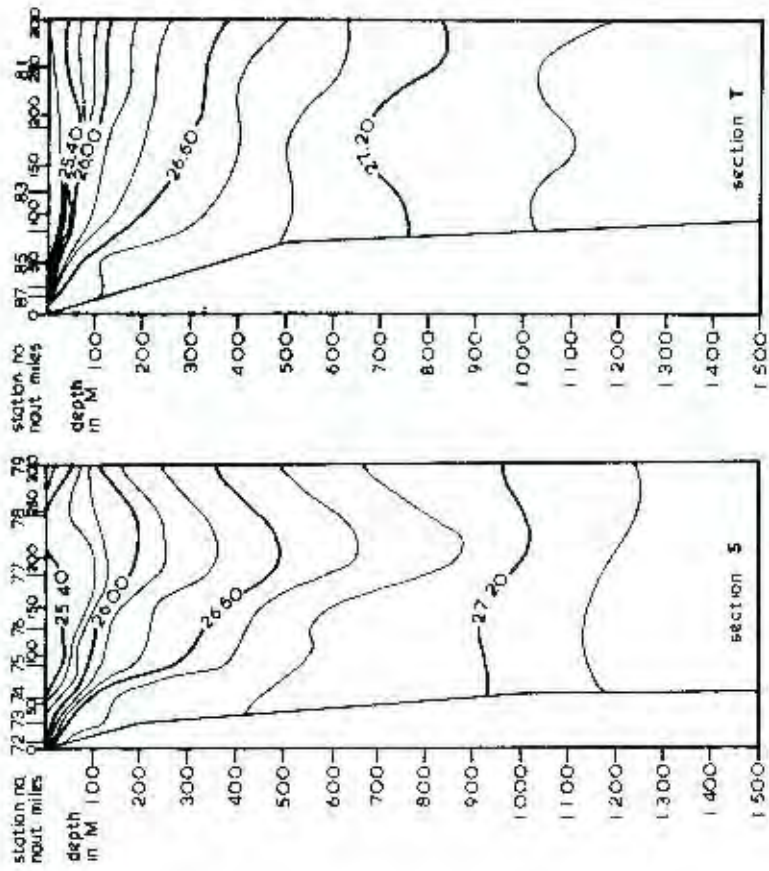
Agulhas current project March 1969.

Sigma-t sections. For section positions see Fig. 8.









CHAPTER F3.

DISCUSSION OF VOLUME FLUXES OF THE 1969 AGULHAS  
CURRENT PROJECT.

Two volume flux calculations were done. The first covers the whole 1969 cruise using a reference level of 1100 m. (fig. 17). The second only covers the AFRICANA II data of the 1969 cruise. The AFRICANA II data were studied for an Honours project and volume flux calculations were made using a reference level of 1500 m. (fig. 18). A more detailed diagram was thus obtained. The two volume flux calculations will be discussed separately.

Note: 1 sverdrup =  $10^6 \text{ m}^3/\text{s}$ . For the various section positions one is referred to fig. 8. In fig. 17, 18 the volume flux calculations have been presented in a line diagram. Each line represents 5 sverdrups, so the accuracy of the diagrams is of that order.

Complete 1969 Cruise using 1100m. as reference level (fig. 17).

From the initial 25 sverdrups flowing south through section A, only 15 sverdrups join the Agulhas current through section C. The remaining 10 sverdrups probably form the counter current at Durban (see Chapter G3) and turn seaward to join the eddy off Durban (see Chapter G1).

Through the outside section, between sections B and E, 15 sverdrups join the system from the east. This westward flow is discussed in detail in Chapter G2.

At section H 10 sverdrups on the outside of the current, which transports 35 sverdrups through section H, left the current to turn south. Five sverdrups thereof joined the eastward current while the remaining 5 sverdrups formed a circulation on its own, partly joining the westward flow (Chapter G2). Inshore of section U, at boxes G and H, 2 lines originated and joined the current on the inside. An

explanation for the origin of those lines is given in Chapter H. The inner 5 sverdrups line of the current found its way to the waters west of the Cape. The remaining 20 sverdrups retroflected east of section 0 forming the Agulhas return current. Within that anticyclonic retroflexion an anticyclonic eddy was present (A in fig. 17).

Of the 30 sverdrups passing through section K the outer 5 sverdrups turned back finally joining with the Agulhas return current. Within that retroflexion another anticyclonic eddy circulating 5 sverdrups was present (B), situated over the Davie Seamount. After being forced around the Agulhas plateau the Agulhas return current described a planetary wave (Chapter J).

In the southerly loop anticyclonic eddy C circulated 5 sverdrups. In the northern loop ( $35^{\circ}$  S.) a cyclonic vortex was present (D). As vortex D was at the edge of the data it could not be said how much water actually was circulating. In the western area an inflow of 10 sverdrups, between sections R and Q, and an anticyclonic circulation centred at  $15^{\circ}$  E,  $34^{\circ}$  S. were the dominant features.

AFRICANA II data, 1969 cruise, using 1500 m. as reference level (fig. 18).

The extra 400 m. depth and the two sigma-t levels (27.4 and 27.6) that could be included doubled the transports obtained with the 1100 m. reference level.

Fig. 18 shows that the main return flow of the Agulhas current takes place between sections M and O, where the westerly flow decreases from about 60 sverdrups at section M to 16 sverdrups at section O. Due to the retroflexion of the Agulhas current about 45 - 50 sverdrups were returned in to the South West Indian ocean.

No water was lost through the outside section between sections P and S (computer calculations showed an inflow at all levels). Presuming the outflow of approximately 5 sverdrups through the outside section between sections O and P was all Agulhas current water there was 10 sverdrups left to flow on north west through section P. The way in which that water presumably joined the waters west of South Africa is shown in the diagram (fig. 18). The net flow of 13 sverdrups through section O, running south from Cape Agulhas was of the order of magnitude Kort (1959) calculated to be necessary to compensate for the loss of Atlantic water entering the Indian ocean.

The area around  $30^{\circ}\text{S}$ . -  $14^{\circ}30'\text{E}$ . was marked by large inflows. About 15 sverdrups entered from outside the outer section, in between sections Q and R. That flow was increased to 50 sverdrups in between stations 62 - 65 due to a large (180 nm. diameter) anticyclonic eddy, E, centred round  $15^{\circ}\text{E}$ ,  $34^{\circ}\text{S}$ . and a small (60 nm. diameter) cyclonic eddy, F, round station 62. About 10 sverdrups were lost through section U into coastal waters, about 15 sverdrups were lost through section T, while of the remaining 25 sverdrups, 15 were recycled in vortex E and 10 recycled in vortex F.

The volume flux discrepancies, listed in Table II, in the inshore boxes could not be fully explained. A number of reasons that might be the cause of these discrepancies were found however and are summed up below. No discussion of the application of these probable reasons is given.

#### West coast of South Africa

a. During the sampling of some of the station lines strong south easterly winds were present. These winds cause upwelling. From a wind stress profile constructed by Bang (1973) a shear gradient for the south easterly winds is present to about 100 nm. from the coast. This shear could give rise to a slope current. Both these effects, slope current and upwelling, would result in a larger slope on the isopycnals. The variability of the winds during the sampling of the station

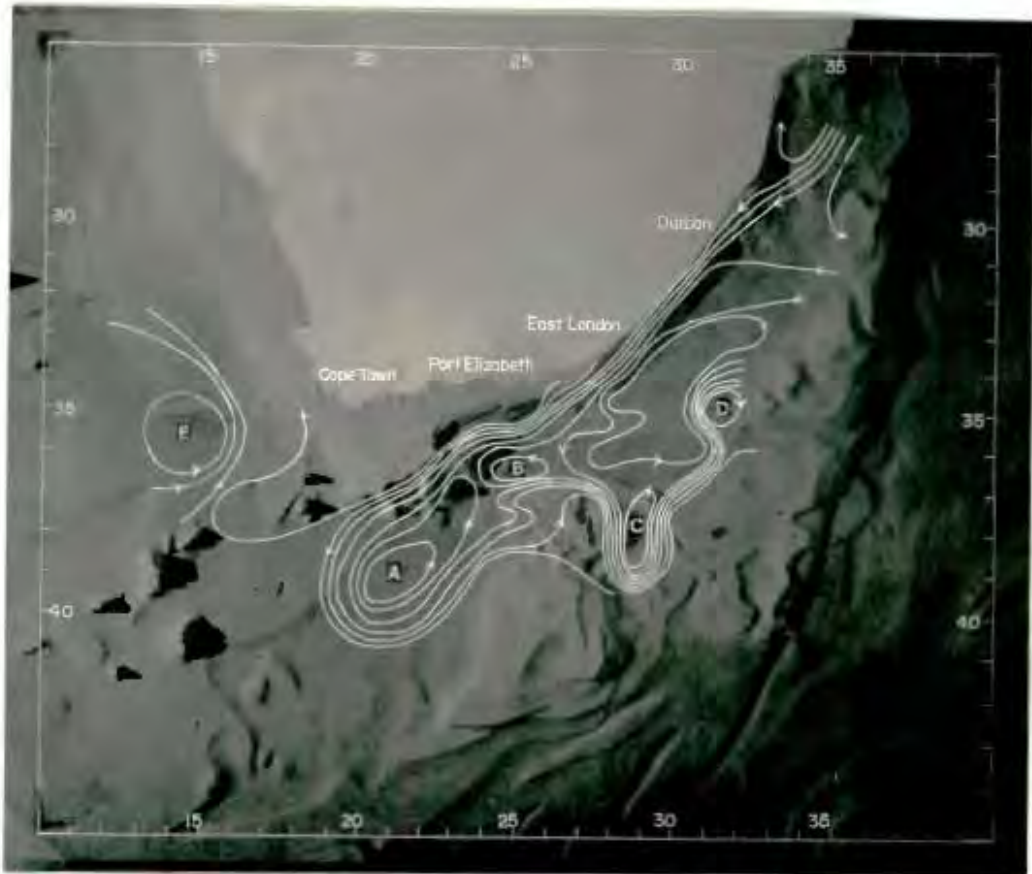


Fig. 17.

March 1969 Agulhas current project. Volume flux diagram (reference level 1100 m.). Each line represents 5 SVERDRUPS (1 SVERDRUP =  $10^6$  m<sup>3</sup>/s).

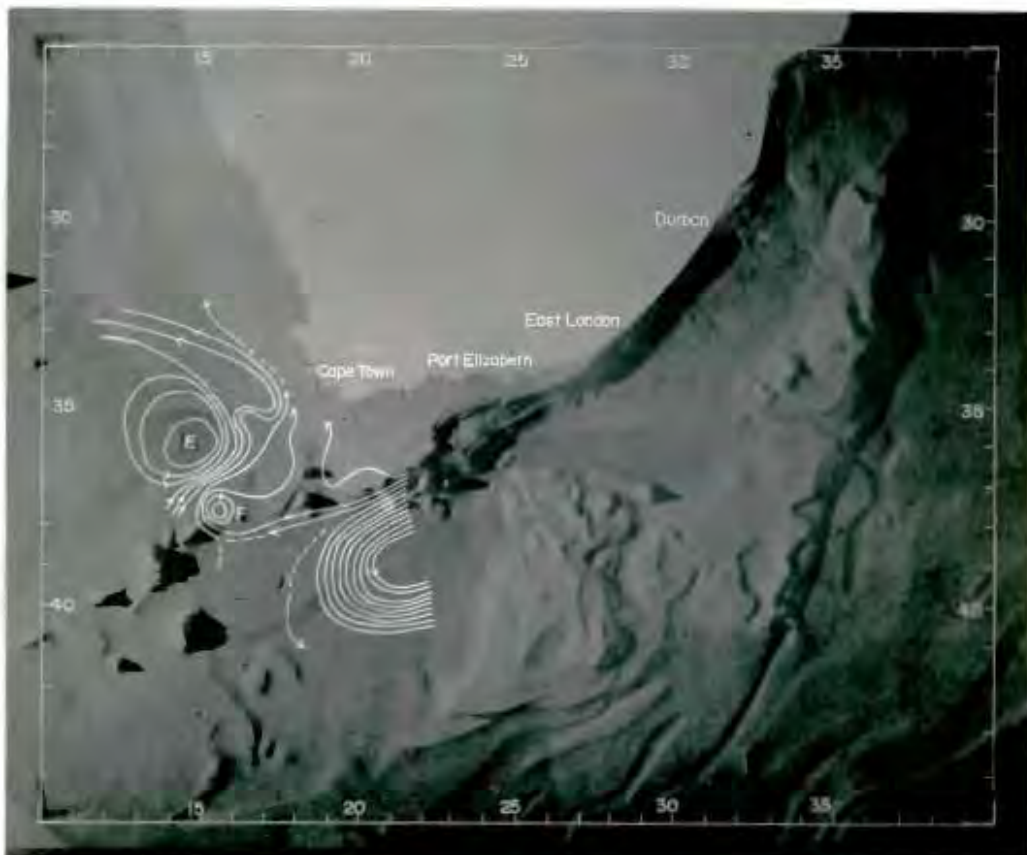


Fig. 18.

March 1969 Agulhas current project. Volume flux diagram for AFRICANA II data (reference level 1500m.). Each line represents 5 SVERDRUPS (1 SVERDRUP =  $10^6$  m<sup>3</sup>/s).

lines was such that the effects could have been present at the one station line but not at the next station line. This would give rise to discrepancies.

b. ERTS satellite photographs (Apel et al 1975) have shown that a considerable internal wave action can exist on the west coast of South Africa. (A rough calculation showed that the influence of internal waves on the slope of  $\sigma_t$  levels could be responsible for an error of  $\pm 2.10^6 \text{ m}^3/\text{s}$  in the volume flux discharges. The calculation was done for offshore box S using an internal wave height of 20 m.).

#### Agulhas bank region

a. A detailed picture (not shown) of buoy track 1116 over the Agulhas bank showed that current reversals of  $180^\circ$  took place in one day. As there was often a day or more in between the sampling of station lines over the Agulhas bank a discrepancy in the volume fluxes is bound to arise.

b. The discrepancies are further assigned to the complex situation on the continental shelf (Shannon 1966, Bang 1973).

#### East coast of South Africa

a. In the region of Durban (convergence of the two supplies to the Agulhas current) instabilities were encountered at several stations. The density depth curves were smoothed for the volume flux calculations. This might have caused errors in the determination of the  $\sigma_t$  depths.

b. The steep slopes of the isopycnals made it especially difficult to determine the intersection point of the isopycnals with the continent (see also Chapter E).

c. A slight change in the current path between the sampling of two station lines could cause discrepancies.

An inshore box can only balance (using Witte-Margules equation and assuming a constant coriolis parameter) if the intersection line of a  $\sigma_t$  surface with the continental slope is a level line (i.e. it is impossible to supply water from the continent). This was almost never the case.

The causes summed up above can be condensed into three:

- a. Problems in extrapolating the  $\sigma_t$  levels to the continent.
- b. Lack of sufficient synopticity.
- c. The geostrophic assumptions are invalid, so that the use of Witte-Margules equation was not justified.

The very large discrepancy in box G will be discussed in Chapter H.

TABLE II.DISCREPANCIES INSHORE OF SECTION U (see fig. 8).

(- sign indicates a shortage,  
+ sign indicates an excess).

Box	Discrepancy (rounded) sverdrups	
	1100 m. ref.	1500 m. ref.
A	+3	
B	-3	
C	0	
D	-3	
E	+6	
F	-2	
G	-12	
H	-5	
I	+5	
J	-3	
K	+2	
L	+5	
M	+1	+3
N	-1	-5
O	0	+2
P	+1	+6
Q	0	+5
R	-2	-1
S	+1	-2

CHAPTER G1.SOURCE AREA.

The situation in the source area was difficult to study due to the sparceness of data, especially in the eastern part. Satellite tracked buoys, satellite infrared images and the development of an inertial jet model (Warren 1963) had made it possible to look at the available data under a new light.

Discussion of new evidence

(1) Buoy track 1116 (fig. 19) deployed at  $28^{\circ}\text{S}$ ,  $40^{\circ}\text{E}$ . had penetrated northwards along  $40^{\circ}\text{E}$ . into the Mozambique Channel up to latitude  $23^{\circ}\text{S}$ . (Gründlingh 1976). It then described an anticyclonic motion which brought it 35 nautical miles off the African coast at latitude  $25^{\circ}\text{S}$ , after which it moved southward roughly along  $35^{\circ}\text{E}$ . The buoy entered the Agulhas current just south of Durban by flowing westward roughly along  $32^{\circ}\text{S}$ . Three interesting features occurred in the track.

- (a) After deployment it described cycloidal motion which gives the impression that it was caught in a cyclonic eddy from which it was quickly expelled ( $\pm$  2 weeks).
- (b) A small cyclonic rotation (diameter 15 nm. duration 5 days) was described close to the African continent ( $25^{\circ}30'\text{S}$ ,  $35^{\circ}0'\text{E}$ ).
- (c) An anticyclonic gyre was described centred round  $27^{\circ}0'\text{S}$ ,  $35^{\circ}30'\text{E}$ .

(2) Satellite infrared images (not reproduced) have shown warm water close to the South African continent and a trace of warm water rounding the souther tip of Madagascar. An inflow of warm water from the east just south of Durban, is evident but does not seem to be connected with the northern part of the source region.



Fig. 19.

Satellite buoy tracks in the Agulhas current system. (Dashed line, 1116; dotted line, 1120; crosses, EOLE; solid line, 1210; dash-dot, 776).

The following features are noteworthy.

The initially northerly movement of buoy 1116 (into the Mozambique Channel).

The westward flow described by buoys 1116, 1120 just south of Durban.

The different areas of retroflexion indicated by buoy EOLE and 1210.

The large planetary waves over and east of the Agulhas plateau, 1210.

The northerly penetration of buoy 776 roughly along  $21^{\circ}$  E.

(3) An estimate of the amount of east Madagascar current water rounding the southern tip of Madagascar has recently been made by Bang, Duncan, Lutjeharms (1976). Twenty sverdrups seemed to round the southern tip of Madagascar mainly in the subsurface layer. Unfortunately this was the only section available in that area so nothing can be said about the variability.

(4) The inertial jet model was started off at the position where buoy 1116 nearly reached the African continent just north of Lourenco Marques ( $25^{\circ}30'S$ ) to see whether a path similar to that of the buoy could be reproduced.

Surface velocities were varied between .5 m/s and 1.0 m/s while bottom velocities ranged from 10 cm/s to 20 cm/s. The buoy track could not be reproduced as depth change appeared inadequate to stabilise the unstable westward motion, nearly directly along  $32^{\circ}S$ , described by the buoy.

An interesting feature emerged however. All jets were started at  $23^{\circ}S$ . Jets started in water shallower than 650 m. tended to meander along the 1000 m. isobath. They therefore came very close inshore and reached the steep continental shelf starting just south of Durban. Three tracks with their starting values can be found in fig. 20 A. Jets started in water depths larger than 700 m. described a completely different pattern. Starting off flowing in a southerly direction, their behaviour south of  $27^{\circ}0'S$ . is quite different depending upon the initial conditions. Tracks with a list of their initial conditions can be seen in fig. 20 B.

B1, started in 700 m. depth, gained enough cyclonic vorticity, by going in to deeper water, to enable it to turn cyclonically towards the African continent at  $28^{\circ}30'S$ . The westward movement thus described did not become unstable. The jet did not turn back on itself but flowed northwards into shallower water gaining enough anticyclonic vorticity to turn towards the coast again. As it reached the coast it meandered along the shelf southwards towards Durban.

Fig. 20.

INERTIAL JET TRACKS (linear velocity profiles used for all tracks).



A. Starting depth less than 650 metres.



B. Starting depth more than 700 metres.



C. Examples of unstable tracks (indicating the possibility of cyclonic eddy formation).

	Surface velocity cm/s	Bottom velocity cm/s	Starting depth m	Current width km	Flux sverdrups	Starting direction degrees true
A1	100	10	500	40	11	182
A2	75	15	500	70	10	182
A3	100	20	500	40	20	182
B1	100	15	700	60	24	182
B2	100	15	1000	50	28	182
B3	100	10	700	60	30	225
B4	100	15	1800	40	41	182
C1	100	15	750	60	26	182
C2	100	15	800	70	32	182

B2, started in 1000 m. depth, crossed over the steep slope on the eastern side of the Mozambique Ridge entering deeper water and therefore gaining so much cyclonic vorticity, that it shot west reaching the African continent at  $28^{\circ}$  S.

B3, started in 700 m. depth, is essentially the same as B1 but only turned towards the west at latitude  $32^{\circ}$  S.

B4, started in 1800 m. depth, followed the eastern side of the Mozambique Ridge. The grid did not extend far enough south to determine whether it would flow round the southern end of the ridge ( $34^{\circ}$  S.) and join the Agulhas current or flow straight on south. Most jets started in water deeper than 700 m. became unstable as they turned westward. A few examples can be seen in fig. 20 C.

(5) Ten day mean sea surface temperature charts (Maritime Weather Office, Youngs Field, Cape Town) regularly show a tongue of warm water bifurcating close inshore in the neighbourhood of Lourenco Marques. One branch continues along the coast while the other seems to turn offshore and flow south roughly along  $35^{\circ}$  E. or east of  $35^{\circ}$  E. The charts did not show any connection of this latter branch with the Agulhas current. The charts are constructed using data received from merchant ships.

#### Discussion of hydrographic data

Surface dynamic height (0-1000 db.) had been contoured for the ALMIRANTE LACERDA 1964, COMMANDANT ROBERT GIRAUD 1960 and COMMANDANT ROBERT GIRAUD 1957 cruises in the Mozambique Channel (Harris, unpublished) and can be found in figures 21, 22, 23.

The main part of the Mozambique current flowing south along the western side of the Mozambique Channel returns north in an anticyclonic loop north of  $24^{\circ}$  S. The remaining part does not complete this return motion but flows on south, in a variable way, but always seems to be forced close to the

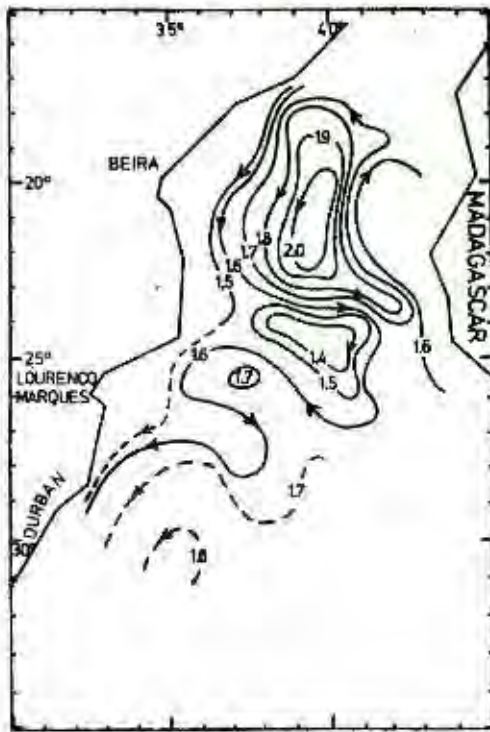


Fig. 21.

COMMANDANT ROBERT GIRAUD  
Oct-Nov 1957.  
Surface dynamic height. (dyn.m.)  
(reference 1000 db).

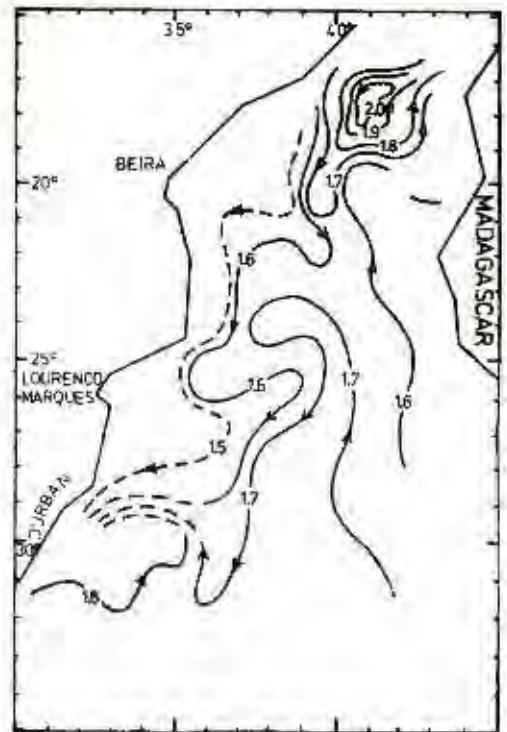


Fig. 22.

COMMANDANT ROBERT GIRAUD  
July-Sept 1960.  
Surface dynamic height. (dyn.m.)  
(reference 1000 db).

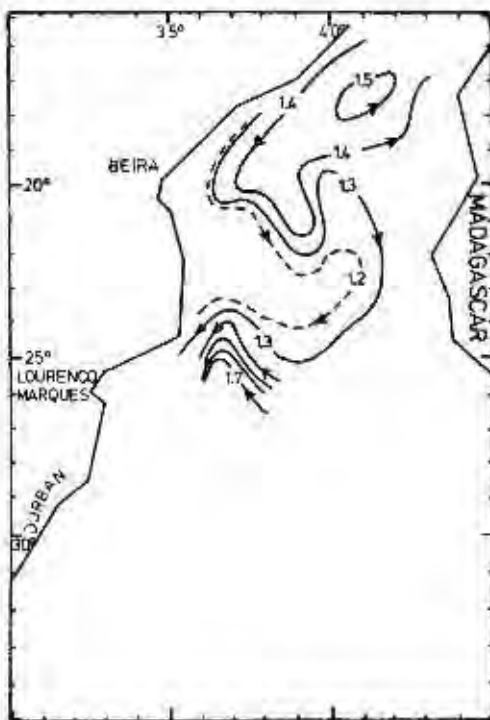


Fig. 23.

ALMIRANTE LACERDA  
Sept-Oct 1964.  
Surface dynamic height. (dyn.m.)  
(reference 1000 db).

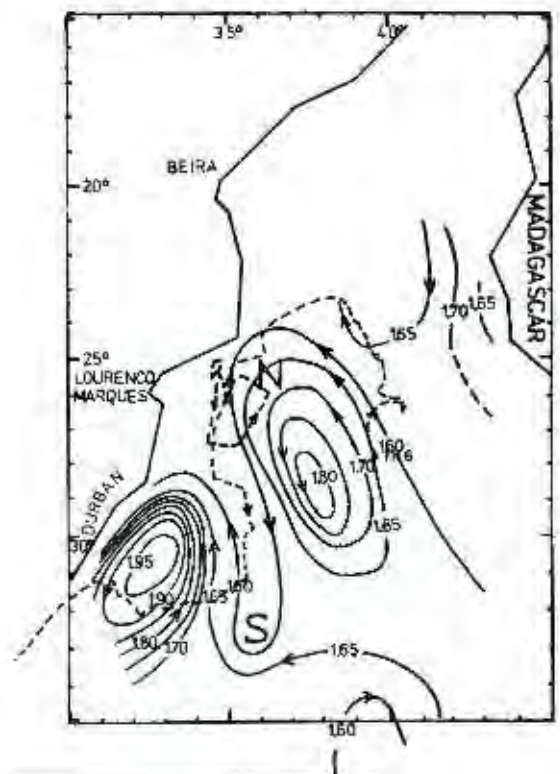


Fig. 24.

ANTON BRUUN July-Sept 1964.  
Surface dynamic height. (dyn.m.)  
(reference 1000 db).  
Superimposed is buoy  
track 1116.

African continent at latitude  $25^{\circ}$  S. (just north of Lourenco Marques).

Water penetrated the south eastern end of the Mozambique Channel from the south and possibly from the east (round the southern tip of Madagascar). For the COMMANDANT ROBERT GIRAUD 1960 cruise water looped up from the south to latitude  $23^{\circ}$  S. The loop was narrow at the northern end and curved towards the African continent attempting to cut off the Mozambique Channel water. Just south of the northern end of this loop Mozambique Channel water turned offshore giving the impression of an anticlockwise eddy in formation (fig. 22). For the ANTON BRUUN and ALMIRANTE LACERDA 1964 cruises (fig. 24), a similar loop was drawn but seems to cut off the Mozambique Channel water nearly completely just north of Lourenco Marques ( $25^{\circ}$  S.). Within the northern end of this loop some anti-cyclonic circulation seemed to take place. The anticyclonic gyre described by buoy 1116 might have been caused by a similar circulation. That the buoy was expelled out of this circulation after one revolution and resumed its way south might indicate the variability of the system (1 revolution in 8 days). In the case of ANTON BRUUN and ALMIRANTE LACERDA 1964, and COMMANDANT ROBERT GIRAUD 1960, the dynamic height diagram (fig. 24) could be contoured in a way similar to the buoy track (alternative contouring would have been possible). How the southward flow of the loop in the data of ANTON BRUUN and ALMIRANTE LACERDA 1964 and COMMANDANT ROBERT GIRAUD 1960 connects with the Agulhas current is not clear but the jet model and contours of  $H \cos \theta$  (fig. 25), (Gill and Parker (1970) although not detailed), were of considerable help. The 6 line in fig. 25 comes in close to the African continent roughly along  $32^{\circ}$  S. similar to the buoy track. The constant dynamic height lines (fig. 24), were therefore drawn flowing south along the eastern part of the Mozambique ridge looping back up through the gap in the ridge and joining the Agulhas current at Durban. Another possibility was to treat the eddy off Durban (discussed later in this Chapter), in the data of ANTON BRUUN 1964 as a separate

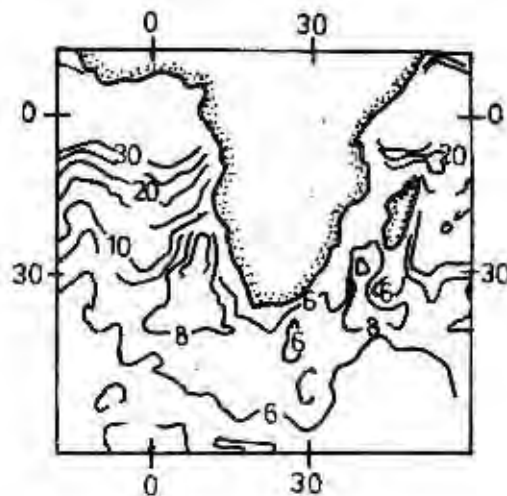


Fig. 25.

Contours of  $D = H \operatorname{cosec} \theta$  around Southern Africa, drawn on a mercator projection. Values are given in kilometres. The corresponding value of  $f/H$  on each contour is given by  $f/H = 2\Omega/D$ , where  $2\Omega = 1.47 \times 10^{-4} \text{ s}^{-1}$  is twice the rate of rotation of the Earth. Contours are not drawn where the actual depth  $H$  is less than 3 km. From Gill and Parker (1970).

feature. This makes it necessary to draw the lines 1.6 and 1.65 dyn.m. south of the eddy similar to the buoy track. In all three cruises, stations do not extend far enough south (or station coverage is too sparse) to establish the westerly inflow discussed in Chapter G2 with certainty. In the case of COMMANDANT ROBERT GIRAUD 1957 the flow pattern over the Mozambique ridge did not seem to be present (fig. 21).

In all three occasions the south eastern corner of the Mozambique Channel seemed to have a separate circulation penetrating from the south. Due to a lack of data south and south west of the southern tip of Madagascar it could not be established whether this water flowed round the southern tip or flowed up directly from the south.

A dynamic high area was present east of Durban indicated by 1.80 dynamic metre lines in the data of COMMANDANT ROBERT GIRAUD 1960, 1957. This dynamic high was very well developed (or intercepted at the centre) in the case of ANTON BRUUN



Fig. 26.

ANTON BRUUN, 1964.

Surface salinity 35.xx‰ (35 is omitted).

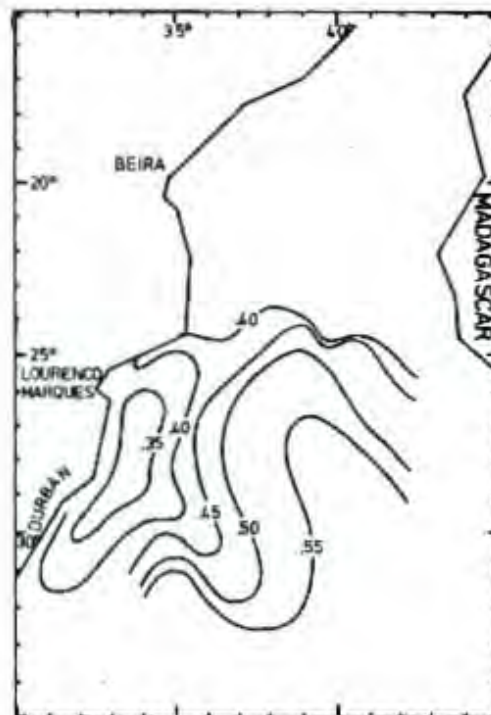


Fig. 27.

COMMANDANT ROBERT GIRAUD, 1957.

Surface salinity 35.xx‰ (35 is omitted).

1964 and it had been contoured as an eddy (Harris 1972). The dynamical reason for the existence of such an eddy is not clear but a factor which might influence the formation is suggested in Chapter G3. The contrasting water masses of the Mozambique current (low salinity, low oxygen) and the water from the south (high salinity, high oxygen) form a front on the western side of the Mozambique Channel extending down south of Durban. The mixing in eddies along this front in the channel was discussed by Harris (1972). The surface salinity of the COMMANDANT ROBERT GIRAUD 1957 cruise gave a nice example of such an eddy in formation (fig. 27). In the ALMIRANTE LACERDA 1964 cruise salinity distribution (fig. 26) a tongue of high salinity (35.40) water reached the African continent in the region of Lourenco Marques, leaving a patch of lower salinity water separated from the Mozambique current. In the COMMANDANT ROBERT GIRAUD 1957 cruise surface salinity distribution (fig. 27), a high salinity value (35.33‰) was found at a station close to Lourenco Marques but was separated from the southerly water by a flow of Mozambique current water (salinity  $< 35.25‰$ ). The higher salinity (and oxygen) values found in the region of Lourenco Marques close to the continent indicated that water from the south gets very close to the shore at times (in agreement with dynamic topography).

The variability of the source area is illustrated by 5 sigma-t sections off Durban (fig. 28). No satisfactory explanation for these sections have been found. The variability can be explained if one assumes that loop S (fig. 24) or the eddy off Durban change position or disappear at times. An explanation need not be a seasonal one as suggested by earlier workers (Darbyshire 1964, Duncan 1970). The eddy-like feature in the October section (fig. 28) could either be a strong current loop or an eddy. The possibility of an eddy will be discussed in Chapter J.

Thus one can conclude that the supply of the Agulhas current broadly takes place in the following ways:

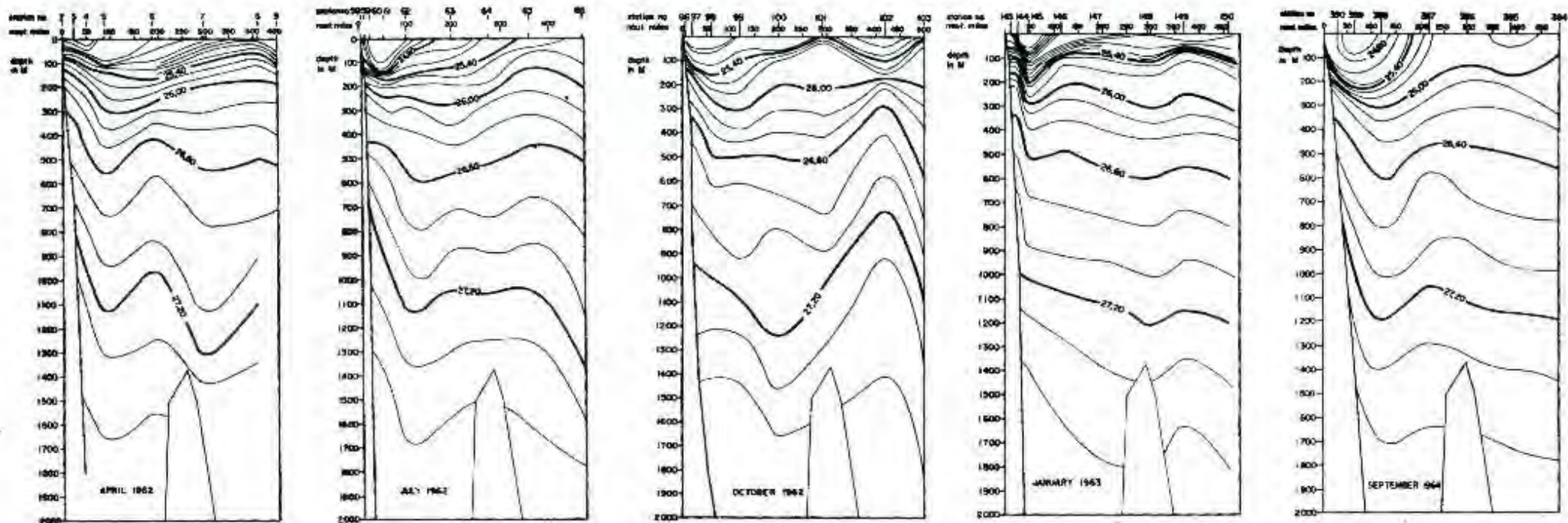


Fig. 28.

5 sigma-t sections out of Durban, indicating the variable situation. The feature on the right in the October section could be an eddy (see Chapter J).

A. If the loop formed by the water coming up from the south (loop N in fig. 24) is not dominant, i.e. leaving a gap just north of Lourenco Marques through which the Mozambique current can freely flow, it seems possible that the supply of the Agulhas current will take place along the inshore pathway as indicated by the jet model (fig. 20 A). The supply to the Agulhas current will then mainly exist of Mozambique current water, i.e. low salinity, low oxygen, and high temperature, flowing down from the north.

B. When the southern loop is dominant, nearly or completely cutting off the Mozambique current in the neighbourhood of Lourenco Marques, another pathway seemed to get preference. The buoy track 1116 (fig. 19) as well as the jet model (fig. 20 B) have shown that this path initially runs along the Mozambique ridge. Its fate then was not quite clear. The buoy track suggests that it would flow west entering the Agulhas current south of Durban while the jet model suggested a looping back north after which the Agulhas current was joined north or south of Durban.

It was strongly felt that the offshore path suggested by the buoy track and the jet model was the main source for supply from the east (Chapter G2). The Agulhas current would then be fed by water from the south (high salinity, higher oxygen) although some mixing with Mozambique current water might have taken place.

Some supporting evidence for the existence of these two pathways could be obtained from the 1969 cruise (see also Chapter F1). The acceleration potential diagrams (fig. 12, 13, 14) showed the two major inflow areas. The first entering through section A in between stations 4 and 6 and flowing south west more or less parallel to the coast could correspond with A. The second entering from the east, in between sections C and D, just south of Durban might be pathway B. Data coverage does not extend far enough north east to establish this. Evidence for the existence of this inflow from the east was discussed in Chapter G2.

At this stage it is interesting to see whether the property distributions (1969 cruise) are in agreement with the two different pathways, A and B, postulated on page 62. Pathways A and B can be seen in fig. 20 A, B. Although in the discussion salinity is more used than temperature the diagrams are generally temperature distributions as these were often more clear. The water of equatorial current origin is characterised by salinities lower than the salinities found in the high salinity band of the South Indian ocean (Wyrski 1971) (from surface down to the lower central water). If one looks at the distribution on a  $\sigma_t$  level the temperature of the water of equatorial origin will have to be colder than the temperature found in the high salinity water. Above the 26.40  $\sigma_t$  level pathway A contributes lower salinity and lower temperature water compared with pathway B. A considerable amount of the water flowing along A was probably recycled above the 25.60  $\sigma_t$  level, in the eddy off Durban (see Table I). The low salinities in the water brought down from the north indicate that it might originate from the Mozambique Channel. Uninterrupted flow down the current of this water seemed to take place especially at the 26.00  $\sigma_t$  level (fig. 30) while at the other levels the inflow along pathway B seemed to cut or nearly cut off the supply from A in the neighbourhood of East London. The flow via pathway B above the 26.40  $\sigma_t$  level was always higher in salinity and temperature compared with A. This side inflow seemed to supply a variety of water masses to the current. It appears that the high salinity water (from the high salinity band in the South West Indian ocean) was replaced by lower salinity water but sometimes a residual of the high salinity water remained (see 25.60  $\sigma_t$  level  $> 35.50\%$  salinity band). The northern part of the side inflow seemed to supply a transition water mass (between the water of equatorial current origin and the high salinity water from the band of the South West Indian ocean).

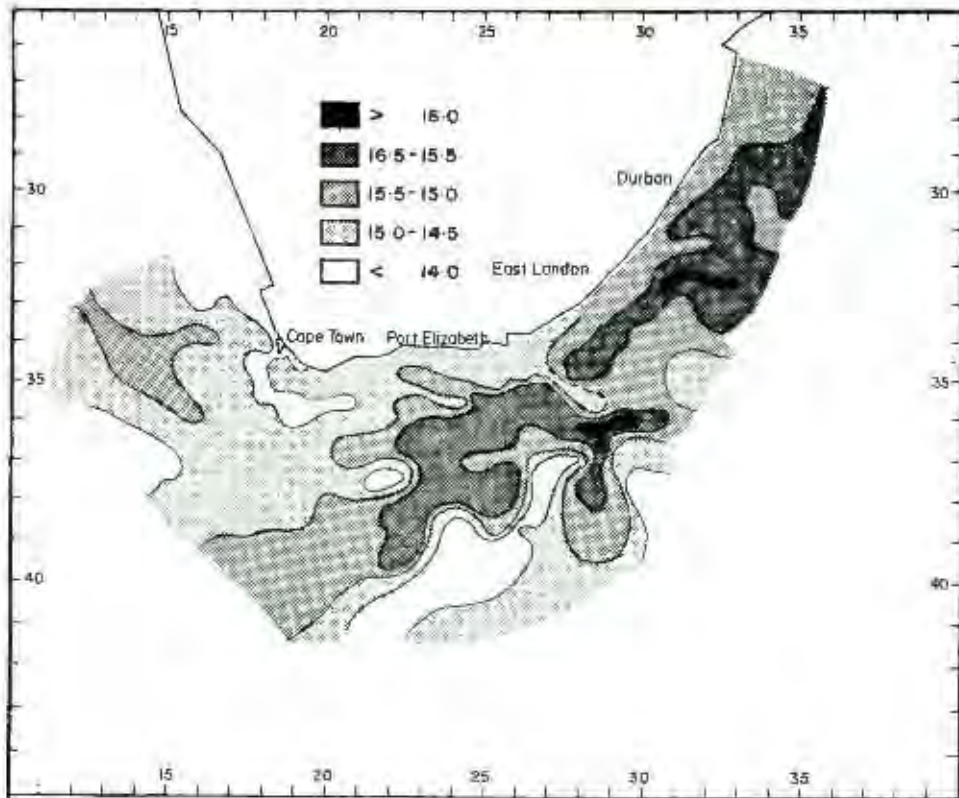


Fig. 31.

March 1969 Agulhas current project. Temperature distribution  
26.2 sigma-t level.

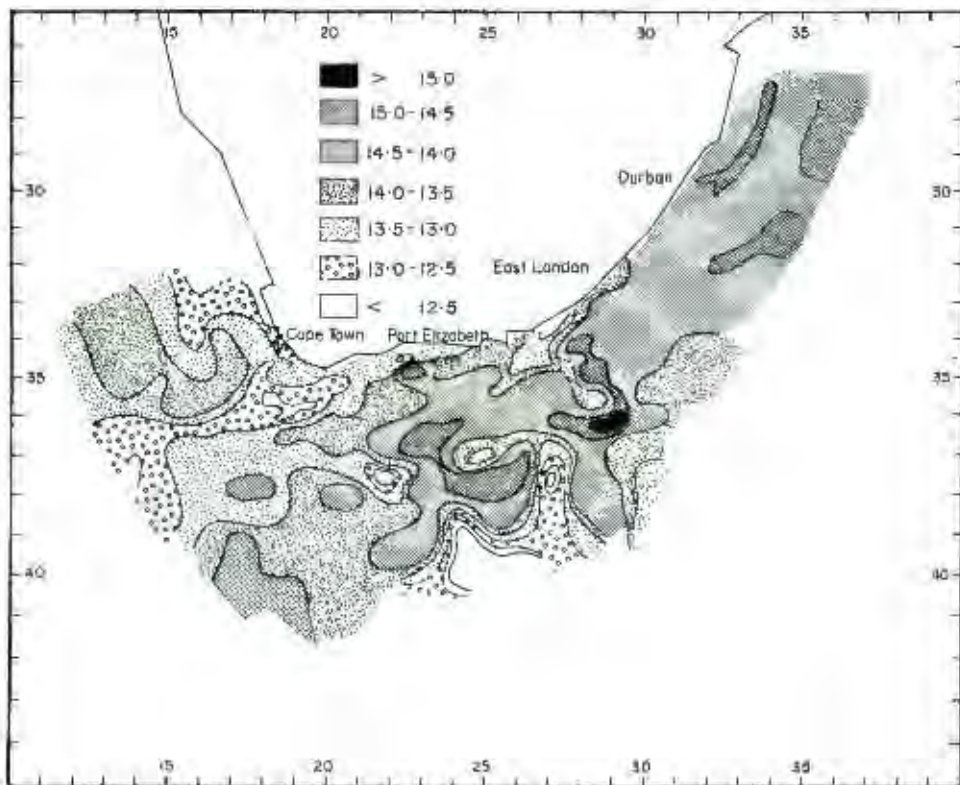


Fig. 32.

March 1969 Agulhas current project. Temperature distribution  
26.40 sigma-t level.

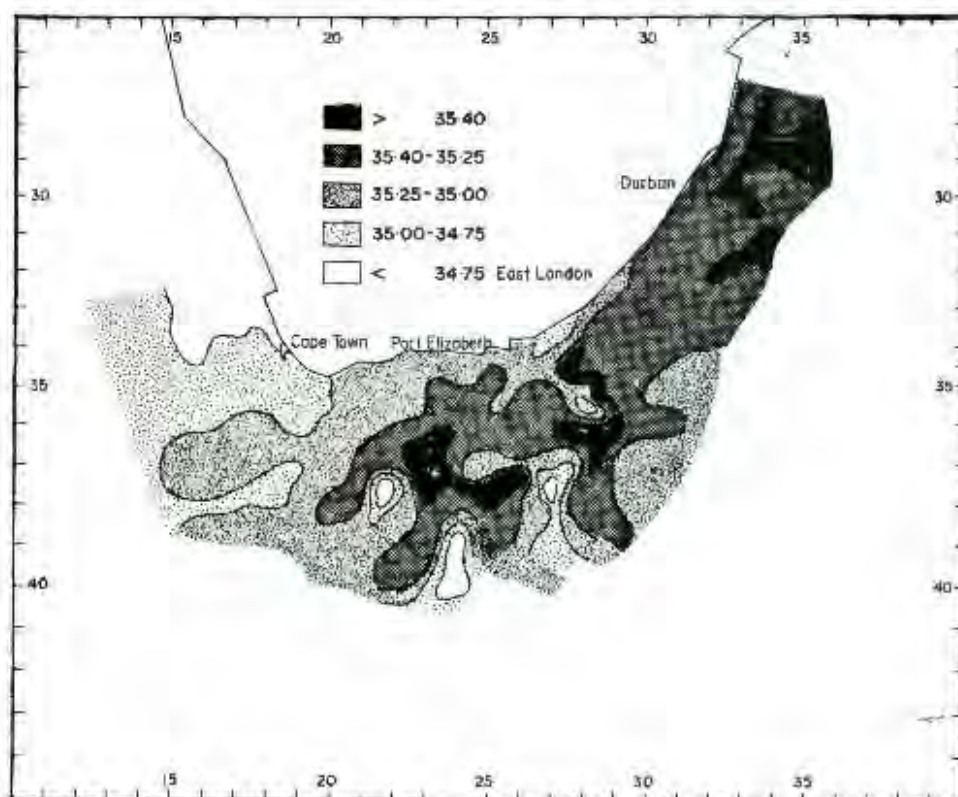


Fig. 33.

March 1969 Agulhas current project. Salinity distribution  
26.40 sigma-t level.

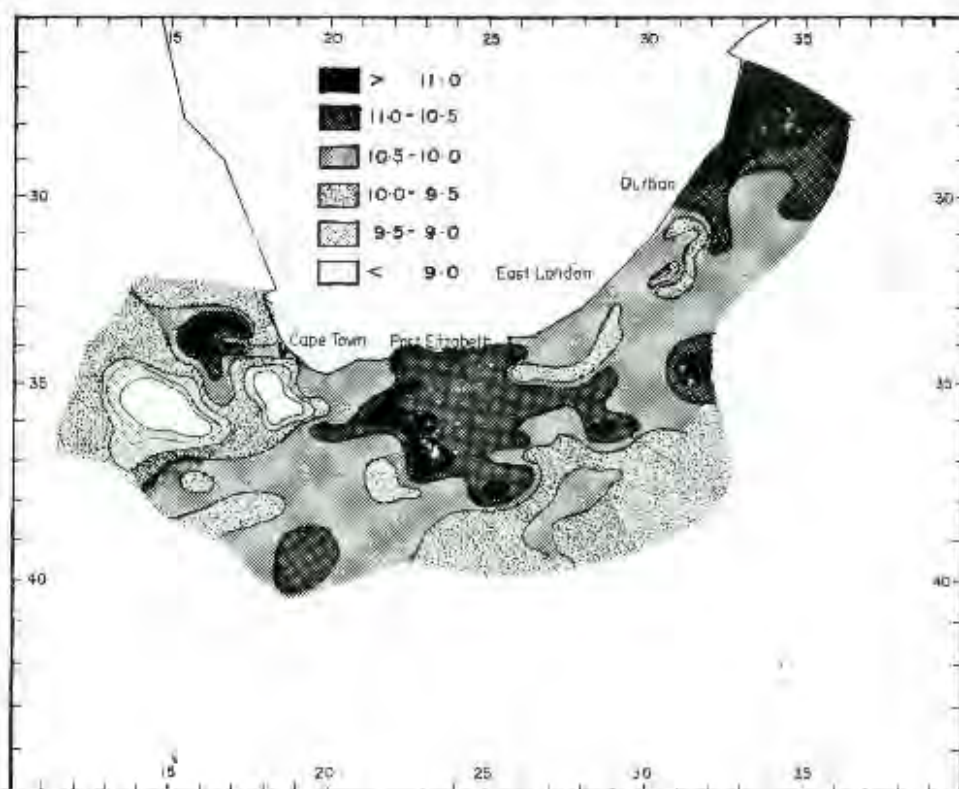


Fig. 34.

March 1969 Agulhas current project. Temperature distribution  
26.80 sigma-t level.

On the 26.40 sigma-t level property distributions, it was difficult to distinguish between the two inflows as can be seen from figures 32 and 33. Below the 26.40 sigma-t levels a very marked change took place. The supply via pathway A now brought in the high temperature, high salinity water while the inflow from the east B supplied lower salinity and lower temperature water (see 26.80 levels (fig. 34) pathway A,  $10.5^{\circ}\text{C}$ , pathway B  $10.5^{\circ} - 10.0^{\circ}\text{C}$ ). That this must have been a pulsating supply can clearly be seen from figure 34. As south of the inflow from the east, cutting off the supply from the north completely, a patch of water with temperatures  $> 10.5^{\circ}\text{C}$  was still present south of Port Elizabeth. Assuming a current speed of 0.5 knots on the 26.80 level, in the main current, the separation between the two patches (360 nm.) gave an approximate time lapse of a month. The patches of cold water ( $10^{\circ} - 9.5^{\circ}\text{C}$ ) on the 26.80 level in between Durban and Port Elizabeth suggested that at one stage water from the subtropical convergence could have entered along pathway B, possibly cycled round eddy D (fig. 17). The oceanographic atlas of the International Indian Ocean Expedition (Wyrtki 1971) shows that on the 26.60 level the high salinity level of the Indian ocean has a salinity of approximately  $35.25\text{‰}$ . From the salinity distribution on the 26.60 level (not reproduced) it could then be argued that this water was at the time supplied along A and only partly along B but that the lower salinity water entered via B. This lower salinity water could have been supplied from the south (possibly cycled round eddy D) but the possibility that it originated from the equatorial current could not be excluded (salinity fits the salinity in the Mozambique Channel), as this could have been transported south along the Mozambique ridge. (See buoy track 1116, fig. 12).

CHAPTER G2.

INFLOW AREA SOUTH OF DURBAN.

A westward flow feeding the Agulhas current has especially become evident from satellite tracked buoys 1116 and 1120 (fig. 19). The buoy tracks have made a considerable contribution to the interpretation of other data.

The westward flow has been observed in:

1. The 1969 Cruise

The acceleration potential diagrams (fig. 12, 13, 14) show a westward flow around  $32^{\circ}$  S. (between station lines C and D, fig. 8). Volume fluxes calculated for this cruise using a reference level of 1100 m. have shown that this flow could be estimated at about 10-15 sverdrups (fig. 17).

Direct current measurements were made during this cruise at stations 21 to 25. The deepest current profiles have been reproduced in fig. 35. The measurements are very unusual as no shear takes place down to 1000 m. (except for fluctuations in the upper 100 m.) at station 22. Unfortunately no deeper measurements are available. Directions of the currents measured varied between  $230^{\circ}$ - $280^{\circ}$  true. If one assumes these direct measurements are correct the reference level of 1100 m. used for the various calculations must be considered as not too reliable. The unusual measurements could be due to the fact that the measurements were obtained using the free drift method. During these measurements the hydrographic wire often cut the surface under a considerable angle so that the current meter (savonius rotor) was probably not in a vertical position. This might have influenced the measurements. A check on the validity of the direct measurements was made by the construction of the velocity profile between stations 32 - 19. Velocities were calculated with the use of Witte-Margules equation. The stations in the section where the direct measurements had been made have not been used for the calculation because they had shown the current to be nearly parallel

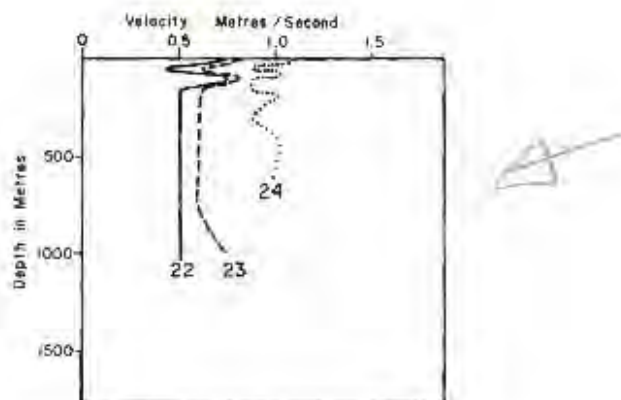


Fig. 35.

Agulhas current project March 1969. Direct current measurements MEIRING NAUDE stations 22, 23, 24.

STATION 22			STATION 23		
Depth (m)	Speed (m/s)	Direction (degrees true)	Depth (m)	Speed (m/s)	Direction (degrees true)
16	.7	239	17	.8	225
32	.6	260	37	.6	231
51	.7	259	53	.6	238
78	.8	228	82	.7	230
104	.7	230	106	.7	228
152	.5	229	157	.6	226
205	.5	232	210	.6	232
305	.5	231	307	.6	227
406	.5	231	411	.6	227
609	.5	221	605	.6	232
805	.5	232	804	.6	232
1000	.5	230	1000	.7	228

STATION 24		
Depth (m)	Speed (m/s)	Direction (degrees true)
11	1.4	249
37	1.3	245
52	1.1	247
78	1.3	243
104	1.1	249
154	1.1	248
203	1.2	239
305	1.1	247
404	1.1	249
601	1.2	251

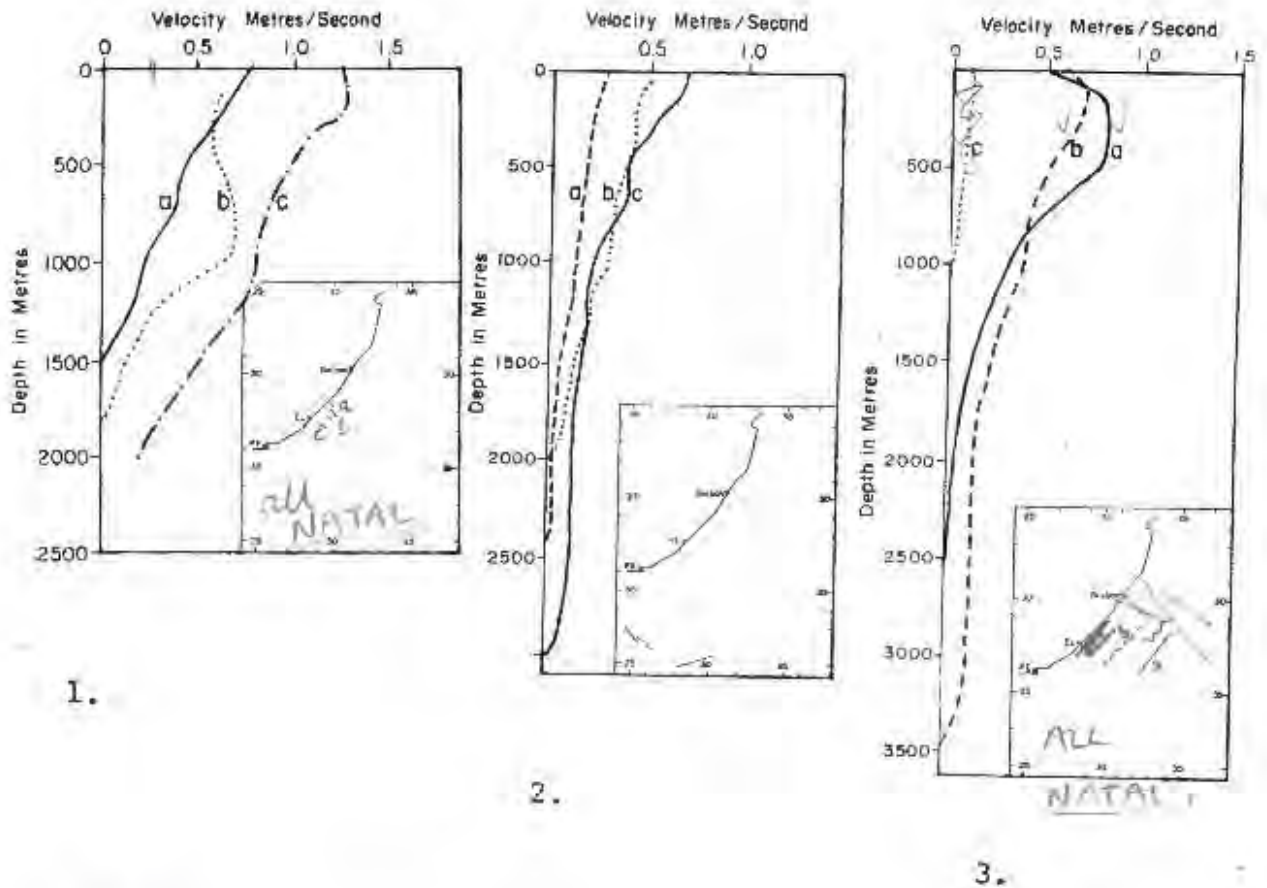


Fig. 36.

Calculated Velocity Profiles (Witte-Margules equation)  
(for positions see insets).

1. Agulhas current
  - (a) NATAL April 1962 (stations 16-15)  
Reference level 1500 m.
  - (b) NATAL July 1962 (stations 73-72)  
Reference level 1800 m.
  - (c) NATAL January 1963 (stations 157-156)  
Reference level 2000 m.
2. Agulhas return current
  - (a) NATAL July 1962 (stations 87-82)  
Reference level 2400 m.
  - (b) NATAL January 1963 (stations 173-72)  
Reference level 2000 m.
  - (c) NATAL April 1962 (stations 33-32)  
Reference level 3000 m.
3. Inflow south of Durban
  - (a) NATAL April 1962 (stations 13-6)  
Reference level 2350 m.
  - (b) NATAL January 1963 (stations 146-155)  
Reference level 3500 m.
  - (c) Agulhas current project March 1969 (stations 32-19)  
Reference level 1100 m.

to that section where they were taken. The velocity profile obtained has been plotted in fig. 36.3 (dotted line). The surface velocity of the calculated profile was only about 15% of the smoothed measured surface velocity (first 100 m.) which indicated that the reference level was not suitable. The calculated current profile shows little shear (0.1 m/s in 1000 m.).

Notable are the curious ("hooked" shape at the top) T-S diagrams in and around the inflow area. (Stations 20, 21, 22, 29, 30, 31, 32, 33, 34, 35, 36, 42, 44, 45, 45/1). The T-S diagrams can be found in the appendix. The low saline water mass found in the top part of the T-S diagrams was probably Mozambique current water. The T-S diagrams illustrate the complexity of water masses meeting around the inflow area, giving rise to the instabilities found at several stations in that area.

## 2. NATAL Cruises (Darbyshire 1964)

The NATAL cruises have been difficult to interpret due to the very large station spacing. The detailed 1969 cruise and the satellite buoy tracks however, have made it possible to study the NATAL cruises with more confidence. A substantial westward flow south of Durban seemed to be present in most NATAL cruises. It was felt that a better estimate (compared with 1969 cruise) of the westward flow could be established as the sampling depth was much deeper (up to 3500 m. in most cases) so that a deeper reference level could be used.

The following results were obtained:

TABLE III.

Cruise	Flux (sverdrups)	Between stations	Reference level (m)
NATAL - January	29	146-155	4000
NATAL - July	11	71-62 (same position as for January).	2500
NATAL - April	22	13-6	2500
NATAL - October	16	99-108	2000

The positions of the sections for which these calculations were done are shown in fig. 36.3. Velocity profiles were also constructed for these sections and are shown in fig. 36.3. Table III suggests that the westward inflow might form up to 35% of the total current transport while at times this may decrease to about 20%. Although in none of the velocity profiles (fig. 36) calculated a no-shear condition down to 1000 m. was formed, the subsurface velocity magnitudes (up to .8 m/s below 180 m.) were in reasonable agreement with the measured subsurface velocities (between .5 - .1 m/s) of 1969. In the case of the NATAL April cruise a no-shear condition between 180 and 500 m. was encountered.

### 3. CSIR Direct Current Measurements (Anderson 1965)

A large number of direct current measurements have been made on a line extending 80 nautical miles out of Durban. The lines do not extend far enough offshore to get into the region where the westward flow dominates. Therefore only a limited number of measurements have been studied. They did contribute to the fact that the westward flow was present. Current profiles along the axis of the Agulhas current were constructed from these measurements (fig. 37). Figures 36.1 and 37 show a reasonable agreement between the measured and calculated current profiles in the Agulhas current.

### 4. R.K. FRAAY Direct Current Measurements (1966)

No westward flow in particular was encountered during this one cruise but the current profiles are remarkable as again little decrease in speed with depth was found at several stations. Some selected profiles are shown in fig. 38. For all direct measurements (points 1, 3, 4) the same method was used (drift technique).

### 5. Satellite Tracked Buoys

Buoys 1120 and 1116 showed the westward and the flow perpendicular to the coast. These tracks are shown in fig. 19. The buoy deployed in 1973 (EOLE) showed a very marked similarity with the acceleration potential diagram of the 1969 cruise

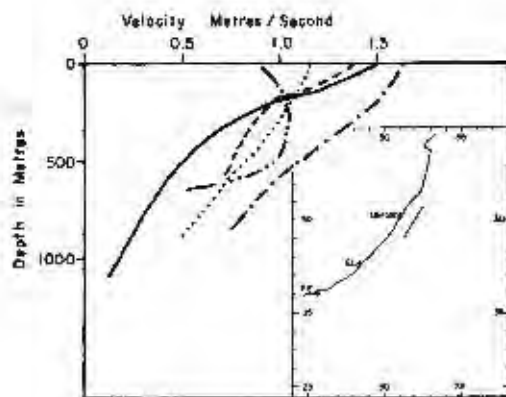


Fig. 37.

Taken from current profiles constructed by the C.S.I.R. with direct measurements (June 1965). Profiles represented are along the main current axis (usually not vertical).

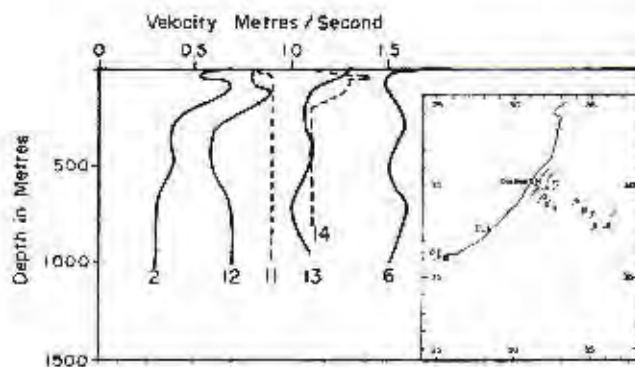


Fig. 38.

R.K. FRAAY (June 1966) direct current measurements (see inset).

(fig. 12, 15). Initially this buoy exhibited (diameter 25 nm.) cyclonic motion which was in agreement with the shear that must exist between the westward inflow and the eastward flow caused by the eddy north of Durban. Buoys 1116 and 1120 described a slight cyclonic movement before they got caught in the main current. The same curvature was evident in fig. 12 (acceleration potential 25.60 .70 dynmeter line).

For the westward flow to exist, a cross-stream pressure gradient must be present with the high pressure to the south. This might have had important implications to part of the Agulhas current (between Durban and East London). This will be discussed in Chapter H.

#### 6. Satellite Infrared Images

These show the inflow of warm water from the east south of Durban. No connection of this water mass seemed to exist with the area north of it, which could indicate that supply took place intermittently. The evidence will not be discussed in detail.

CHAPTER G3.

COUNTER CURRENT AT DURBAN.

A marked feature off Durban is a current, inshore of the Agulhas current, reversing from south west to north east with a period of roughly 7 days. The north east current flows opposite to the Agulhas current and is therefore generally referred to as the counter current off Durban.

This counter current does not extend beyond 40 nm. offshore at Durban and current speeds seldom exceed 1 knot. The temperature and salinity within the reversing current were usually less than in the core of the Agulhas current. Attempts in relating the counter current with atmospheric pressure systems have been (Pearce, 1976) satisfactory in explaining the feature (low pressure regions travel north east along South Africa's east coast causing north east winds). In some cases however, this explanation did not seem to be sufficient.

The counter current was not studied in detail as this has been done by Pearce (1976) (off Durban), but some new suggestions towards an explanation of the anomalies will be given. Sigma-t sections A and B (fig. 16) (1969 cruise) show that a counter current was present north of Durban. Unfortunately no salinities were measured at line A/1 and temperatures only down to 500 m. (XBT). From the temperature section (fig. 39) it is evident that a north east current was present extending 75 nm. offshore. Although close inshore (within 25 nm.) a southward flowing current might have been present (section A/1 was not deep enough to establish this with certainty). Volume flux calculations (fig. 17) showed the transport of the counter current through section A to be approximately 4 sverdrups ( $\pm 1$ ). Acceleration potential diagrams could not be drawn with much confidence to show the counter current as the stations inshore were too shallow ( $< 400$  m. in most cases) to take a reference level deep enough to make comparison with

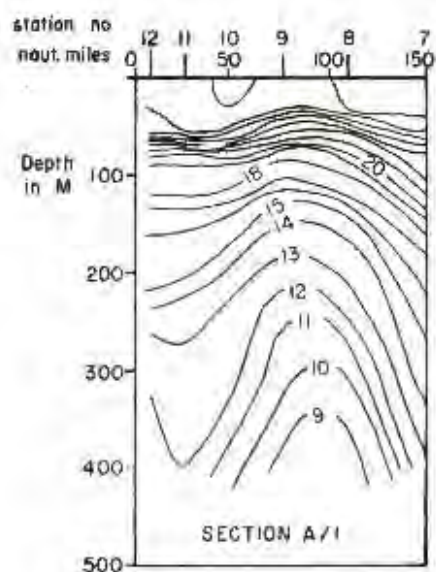


Fig. 39.

Temperature section of station line A/1 (Agulhas current project March 1969). For position of line A/1 see fig. 8.

offshore stations meaningful. Calculations with a reference level of 400 m. have however been made but are not represented. Figure 12 is an acceleration potential diagram on the 25.6 sigma-t level (50 - 200 m. depth), using a reference level of 1000 m. From these and the 400 m. calculations there was thought to be sufficient evidence to curve the lines of 1.35 - 1.45 dynamic metres, inshore of the Agulhas current northwards to represent the counter current. If the switching system suggested by the inertial jet (see source area) exists, the Agulhas current will be fed intermittently from the north and from the east while at times both sources will exist (1969 cruise). It is suggested that when the westerly flow converges with the flow from the north, part of the flow from the north may be blocked off. This could lead to the following effects:

1. Inshore of the flow from the north (pathway A fig. 20 A), just north of the region of convergence, water will be forced round in a cyclonic manner resulting in a counter current. The cyclonic action will lead to upwelling which might cause the lower salinities and temperatures often found within the counter current.

2. On the seaward side of the flow from the north, north of the region of convergence, water will be forced round in an anticyclonic way. This might form the start of the eddy off Durban as discussed in the source region.

3. At the region of convergence the pressure exerted on the Agulhas current by the westerly flow will force the Agulhas current closer inshore.

Depending upon the mode of the whole Agulhas current system, especially the amplitude of the planetary waves east of the Agulhas plateau (Chapter J), the westerly flow may set in more to the north or to the south. Displacement of the westerly inflow will displace the southern end of the counter current so that the intensity of the counter current at Durban will vary.

A theoretical illustration of points 1, 2 and 3 is suggested in fig. 40 (Robertson: Hydrodynamics in theory and application p. 451).

Here two jets bounded by free streamlines are considered in plane steady motion. Jet D will be related to the flow from the north while jet B represents the westerly flow. Although no boundary is present and the angles of the two converging jets are not in agreement with the situation off Durban the resulting flow pattern of the two impinging jets is interesting.

The formation of jet A is similar to the anticyclonic movement seaward of the flow from the north, while jet C suggests the forcing inshore and the increased flow of the Agulhas current. If a boundary was present part of jet C might flow in an opposite direction to jet D thus forming the counter current. More detailed modelling will show whether the idea suggested here is relevant.

The switching system of the inertial jet also suggests that water will follow the inshore path (flow from north). If one assumes that some flow along this path is always present one can imagine a pulsating jet along the coast. Along the front of these pulses some "backwash" will take place, as shown in fig. 41 (Robertson) giving rise to a counter current as the front passes.

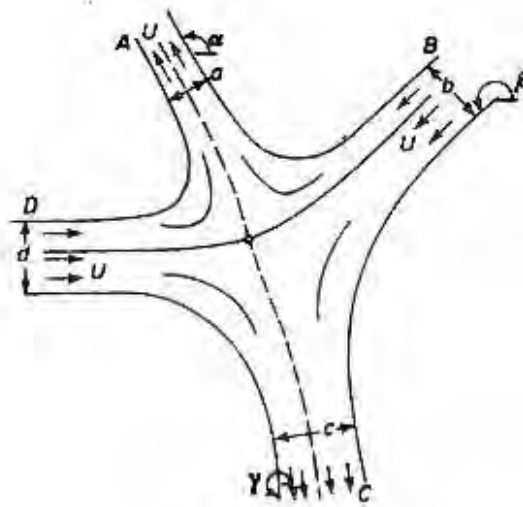


Fig. 40.

Intersection of two fluid jets (see text page 77). (according to Robertson 1965).

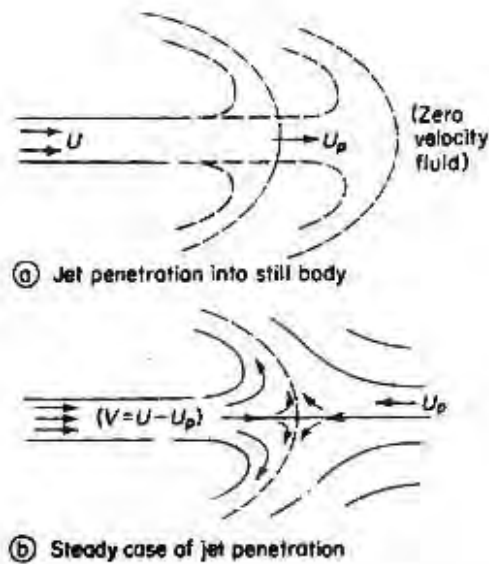


Fig. 41.

Some cases of jet penetration (see text page 78). (according to Robertson 1965).

CHAPTER H.

AREA BETWEEN EAST LONDON AND PORT ELIZABETH.

The region is characterised by cold water, caused by severe upwelling, inshore of the Agulhas current. The most marked features obtained from hydrographic data are as follows:

1. The sigma-t sections (fig. 16) drawn for the 1969 cruise showed that the isopycnals (down to 26.4) suddenly cut the surface at sections G and H, which would indicate that upwelling was taking place. Wind induced upwelling is not likely as the winds in the area from 17th to 25th of March 1969 (stations in the area were occupied from 19th to 24th March) were variable. Upwelling conditions were favourable however on the 18th, 22nd and 23rd but wind speeds were too low ( $< 10$  knots except on the 22nd when 20 knots were recorded) to cause the severe upwelling encountered. As a result of the upwelling cold surface water was encountered close inshore. Ten day mean sea surface temperature charts, derived from ship sea temperature recordings, showed the marked drop in temperature as did all the oceanographic cruises studied in the area (NATAL 1958, NATAL 1962-1963) (Darbyshire 1964). The cold temperatures were always recorded in the same region. If the cold temperatures were caused by wind induced upwelling there would be no reason that they would not occur north of the Bashee River (60 nm. north of East London), as the low pressure systems (causing upwelling conditions) move north along the South African east coast. It is therefore highly likely that the upwelling was dynamical and is fairly common.

The surface temperature difference between the upwelled water inshore and the water in the core of the Agulhas current was generally  $6^{\circ}\text{C}$  (typically  $18^{\circ} - 20^{\circ}\text{C}$  inshore compared with  $23^{\circ} - 26^{\circ}\text{C}$  in the core of the Agulhas current). An extreme low surface temperature of  $14.8^{\circ}\text{C}$  has been recorded (see fig. 42, 1969).

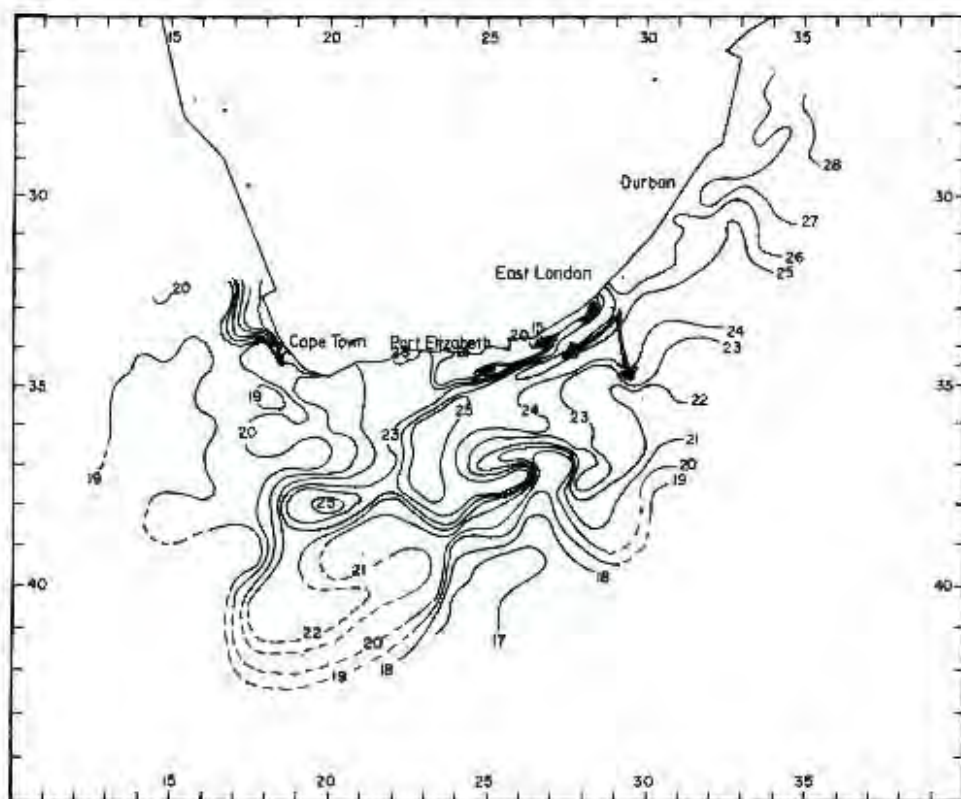


Fig. 42.

Surface temperature. Agulhas current project March, 1969.  
 Arrows indicate the two possible current directions  
 (see text page 83).

The acceleration potential diagrams (fig. 12, 13, 14) for the 1969 cruise showed that the outer part of the current (see also fig. 42) tended to leave the coast and joined with the eastward current thus retroflecting east of the Agulhas plateau.

Volume flux calculations done for the 1969 cruise showed a discrepancy of 12 sverdrups within inshore box G (see Table II, page 50).

Property distributions on various  $\sigma_t$  levels show above the 26.8 level, cold, low salinity water inshore of the current (fig. 29, 30, 31, 32, 33, 34). This water mass was very different from the water masses in the main current but similar to water masses at the subtropical convergence.

No supply mechanism from the convergence to the upwelling region could be established. The steepness of the isopycnals in the upwelling region might make it possible that mixing across different  $\sigma_t$  levels took place. This would be an explanation for the water masses found on  $\sigma_t$  levels in the upwelling region.

2. Satellite tracked buoys and infrared images have shown the following:

Buoys 1116 and 1120 (fig. 19) showed that the maximum current speeds in the Agulhas current occurred between East London and Port Elizabeth (approximately 5 knots). This was not in agreement with results obtained from the merchant ship drift data (Tripp 1967), as the maximum current speeds were reported in between Port St. Johns and Cape Hermes. Disagreement could be due to the fact that the current is closest inshore between Port St. Johns and Cape Hermes. Merchant ships usually keeping close inshore would then feel the current most strongly in that particular area as they are in or close to the current core.

The buoy deployed in 1973 (Eole), showed a remarkable identity with the flow pattern obtained from the 1969 cruise. This buoy's most westerly position was  $25^{\circ}\text{E}$ , where it turned back on itself probably due to the dynamic high above the DAVIE Seamount (fig. 19, 15).

A series of infrared images (3rd and 4th August, 1976) showed very clearly the inshore cold water starting just north of East London, and the cold water over the Agulhas bank (fig. 43). A marked loop of cold water was present (extending 160 nm. offshore) and seemed to progress in a south westerly direction at a speed of 7 nm. per day (see fig. 43).

In the Agulhas current cruise it was unfortunate that lines G (24/3/69) and H (19/3/69) lacked synopticity as there is a 5 day difference between them (measured by different ships). The lack of synopticity between station lines G and H together with the satellite images (fig. 43) have contributed towards an explanation of the discrepancy (12 sverdrups in box G, see Table II) in the following way:

when line G (24/2/69) was occupied the current probably turned offshore which is indicated by the bending southward of the surface isotherms (fig. 42). Five days earlier (19/3/69), however, when line H was occupied, the current probably flowed parallel to the coast indicated by the warm tongue ( $27^{\circ}\text{C}$ ) crossing lines G, H and I. The southward movement of water was even more clearly illustrated by the various property distributions on the  $\sigma_{-t}$  levels (fig. 30 - 34). The same feature was noticed in several other cruises studied (see also Darbyshire 1964). For the  $\sigma_{-t}$  sections, (i.e. also for the volume flux through these sections) one can conclude the following:

in section G the  $\sigma_{-t}$  slopes will be relatively small as at the time the current component perpendicular to this section was relatively small (relatively small volume flux). When section H was occupied the current flowed straight through giving relatively large slopes on the  $\sigma_{-t}$  levels (i.e. large volume flux). Inshore box G will not be in



Fig. 43.

Satellite infrared images. Offshore deflection of the Agulhas current between East London and Port Elizabeth. Between 27th July and 4th August 1976, the feature had moved towards Port Elizabeth over a distance of 60 nm. (7-8 nm. per day).

geostrophic balance (cannot supply water out of the continent) giving rise to the discrepancy of 12 sverdrups. The reason the current should turn offshore in the first place was not clear but a suggestion towards an explanation will nevertheless be given. It was strongly felt that it links up with the westward flow south of Durban (see Chapter G2). Such a westward flow can only exist when a high pressure region is present to the south of it. This high pressure region can be seen in the acceleration potential diagrams (fig. 22, 23, 24) although it was probably compressed due to the influence of eddy D.

In the NATAL cruises (1962-1963) station spacing and especially spacing between station lines is too large to establish the high pressure region accurately. There is evidence however that it is present (from dynamic height distributions on the Port Elizabeth and Port St. Johns line). In fig. 44 the surface dynamic heights (0-1500db.) are plotted for the Port Elizabeth line (NATAL cruises). From fig. 44 it is obvious that the positions of the pressure regions are variable as are their magnitudes. The general trend for the pressure distribution in fig. 44 is low, high, low, high, low. The first high is associated with the edge of the high pressure region under discussion while the second high might be caused by the anticyclonic circulation, C in fig. 17. (Unfortunately in the October line a station had to be abandoned due to bad weather). Around this first high anticyclonic circulation must take place dragging the current offshore. The inertial jet model has shown that an anticyclonic (offshore) motion can exist in between East London and Port Elizabeth (Darbyshire 1972). This motion must be associated with the dynamic high region to the north of it. If the turning offshore is vorticity controlled the current width might be an important factor. Inertial jet tracks (not reproduced) have shown that the tendency for the current to turn offshore is large when the starting depth (jets were started off just south of Durban) is of the order of 300 m. (or deeper). This could indicate that for a wide current the outer part might turn offshore.

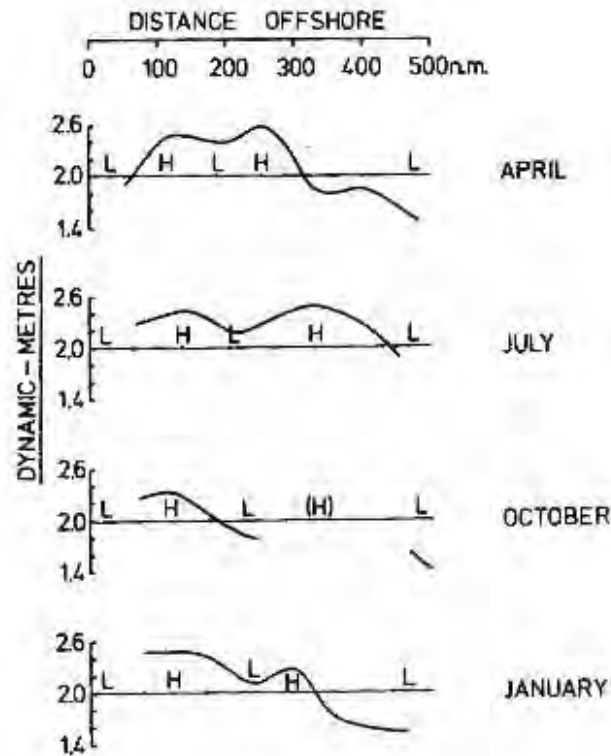


Fig. 44.

NATAL cruises 1962-1963. Surface dynamic height (reference level 1500 db.), on the Port Elizabeth line. The first high is associated with the dynamic high region south east of East London. The second dynamic high is associated with circulation C in fig. 17.

The turning offshore would cause a development or intensification of the dynamic high region to the south east of East London. Therefore there would be a stronger westerly flow to the south of Durban. The westerly flow might block off the supply from the north which could result in a smaller current transport. As a consequence the current might get narrower. A narrower current would be less subject to the offshore turning motion as shown by the jet model. Another cycle of events could then develop.

How the offshore motion is related to the upwelling is not clear. A possible reason for the upwelling can be given in the following way. Satellite buoys showed that maximum current speeds occur south of East London. These high speeds could be due to the fact that the current reaches its maximum transport there (due to the inflow from the east south of Durban (see fig. 12)), but does not increase in width very much as it is still trapped against the steep continental shelf break. Whatever the reason of the high speeds, the slope of the density levels in the narrow current will have to accommodate these high speeds. This apparently leads to slopes so big that the density levels have to cut the surface thus causing the upwelling.

It is interesting to refer to Bryan and Cox's (1968) model ocean and to quote Godfrey from his discussion of the model (the model was developed for the northern hemisphere). "There is a long shore pressure gradient throughout the upper layers of the western boundary region, which is not geostrophically balanced at the shore (water cannot flow out of the wall); several related phenomena occur as a result. First, the outflow needed to balance the gradient geostrophically offshore is largely provided by vigorous upwelling near the wall .... The longshore pressure gradient, and all the associated phenomena, intensify spontaneously at certain locations .... Much of the vorticity production in these places escapes the effect of friction, so the current spins seaward in an anti-cyclonic arc, to form the northern edge of an eddy ....".

## CHAPTER I.

### MIXING AREA.

The mixing area will be defined as the area west (west of  $24^{\circ}$  E.) of the Agulhas plateau (see fig. 11). It will be seen below, that it is in this area that the current can lose its coherent structure, thus making study very difficult.

There were only two synoptic cruises available that extend far enough west and south to make study of interaction with the South Atlantic useful. Those cruises were the Agulhas current project of March 1969 and the Schmidt-ott cruise of March 1964 (visser 1969). Satellite tracked buoys 776 and 1210 have contributed towards an understanding of the region (fig. 19).

#### 1. Westward penetration and eddy formation

Penetration of the Agulhas current as far west as  $13^{\circ}$  E was evident from buoy track 1210. The Schmidt-ott cruise showed the retroflexion of the Agulhas current east of  $21^{\circ}$  E. (Visser 1969) (fig. 45). According to the volume flux calculations (fig. 17) and the acceleration potential diagrams (fig. 12, 13, 14) the Agulhas current retroflected east of  $18^{\circ}$  E. during the 1969 cruise. Satellite infrared imagery has shown the warmest water to retroflect east of  $18^{\circ}$  -  $21^{\circ}$  E. while the less warmer water could penetrate as far west as  $14^{\circ}$  E. (Harris et al 1977).

The Schmidt-ott cruise of March 1964 has shown a marked eddy above the Richardson Seamount (Duncan 1968). The Agulhas current at the time retroflected well to the east of the Richardson Seamount ( $21^{\circ}$  E.). An acceleration potential diagram for this cruise has been drawn for the 26.60 sigma-t level and can be found in fig. 45. T-S curves for the Agulhas current and South Atlantic ocean are very similar (Shannon 1966). This similarity makes it impossible, using T-S data, to establish whether eddies or patches of water found in the

mixing area are of Agulhas current or of South Atlantic ocean origin. (Discussion of the water masses in the Schmidt-ott cruise was given by Visser 1969). It is however not possible for the eddy in the Schmidt-ott cruise to have been separated from the Agulhas current as penetration west as far as  $14^{\circ}\text{E}$ . is possible (buoy 1210) and as penetration of convergence water from the south probably exists (buoy 776). Buoy track 776 reached the area of interest in August 1976 roughly along  $40^{\circ}\text{S}$ . It was very fortunate that the buoy headed straight for the Richardson Seamount and therefore its track was especially interesting. It described half an anticyclonic circle exactly around the Richardson Seamount, ending up just north of  $40^{\circ}\text{S}$ . at longitude  $17^{\circ}\text{E}$ . It then moved slightly south while flowing eastward and looped up north between longitudes  $20^{\circ}\text{E}$ . and  $21^{\circ}\text{E}$ . Its most northerly position was approximately  $37^{\circ}20'\text{S}$ . After that the buoy apparently was caught in an anticyclonic eddy which drifted westward. It could have been an Agulhas eddy. The track is shown in fig. 19.

The movement of buoy 776 round Mount Richardson and surface dynamic heights of Durban made it very attractive to speculate on the possibility of the formation of a Taylor column above Mount Richardson (acceleration potential 26.60 (fig. 45) is basically the same as the surface dynamic height pattern). A streamline pattern of a Taylor column for the Southern Hemisphere is shown in fig. 46 (mirror image from McCartney 1974). The Taylor column developed would be anticyclonic (downwelling).

No clear evidence of eddies separated from the Agulhas current could be found in the 1969 cruise. The property distributions (fig. 29-31) showed that the water found in the northern and north-western part of the area were, generally speaking, colder and less saline than the core of the Agulhas current. On the 26.60 and 26.80 sigma-t levels (fig. 34, 26.80 sigma-t level temperature distribution), however a

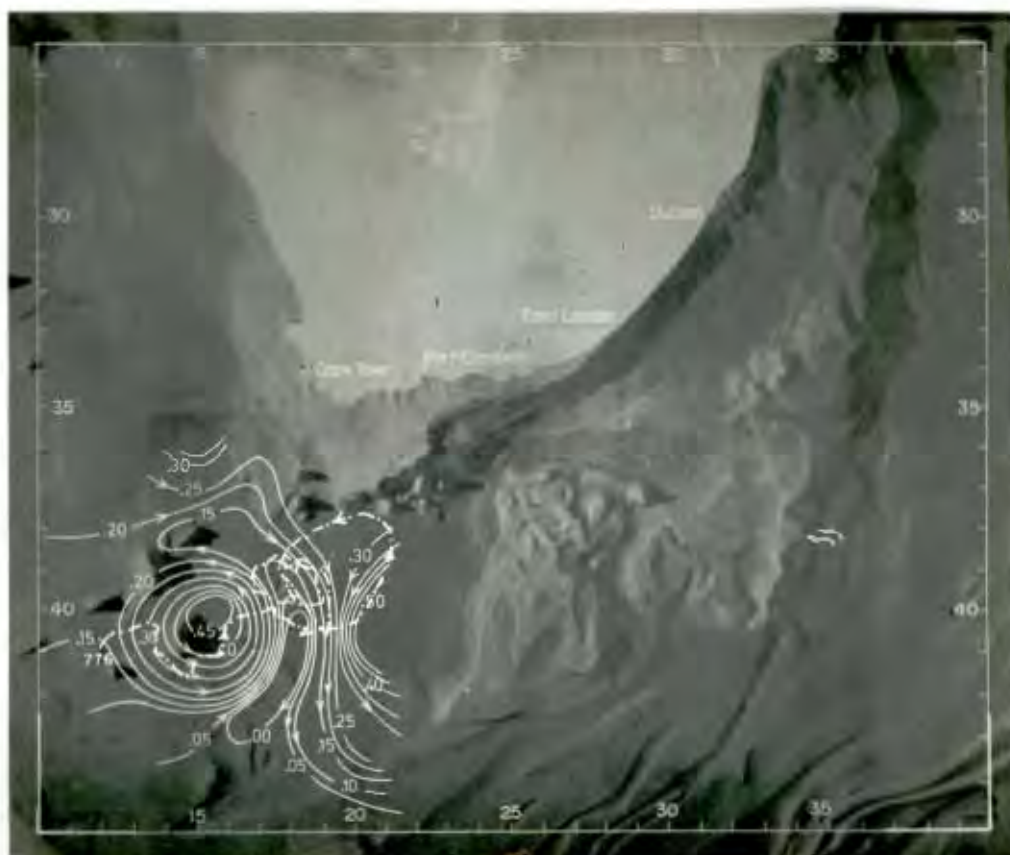


Fig. 45.

Schmidt-ott Cruise, March 1964. Acceleration potential on the 26.60  $\sigma_t$  level. (contour interval 0.05 dyn.m., 1. is omitted). Superimposed is buoy track 776.

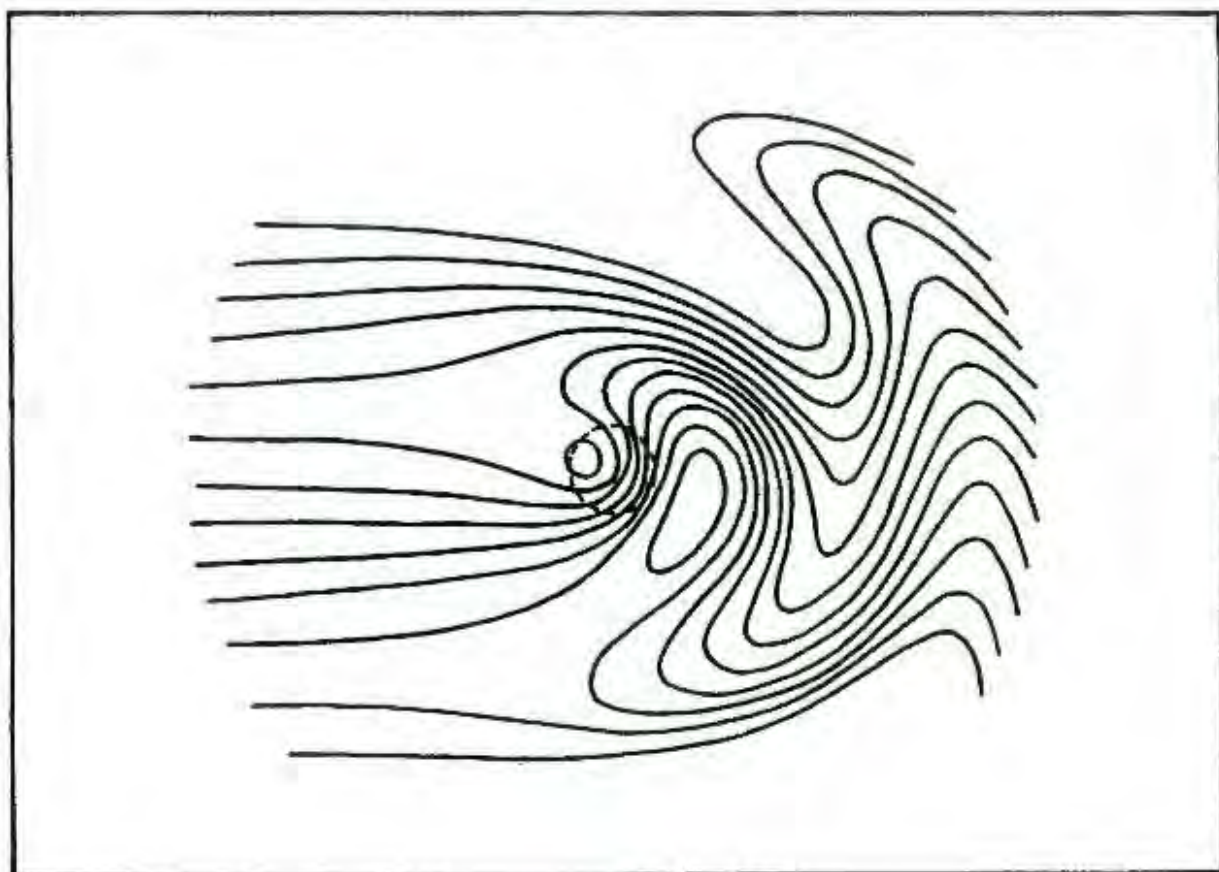


Fig. 46.

Inertial Taylor Column. Lower layer stream lines for eastward flow past a right circular cylindrical bump (dotted line). Mirror image of McCartney's fig. 4 (1974).

warm high saline patch was found over lines S. ( $11.17^{\circ}\text{C}$  on the 26.80 level). It was not possible to establish the origin of the warm saline water patch.

2. Supply to the upwelling region off the South West of South Africa and the Benguela Current; Agulhas Bank Region

Strong south-easterly winds cause upwelling off South West Africa (northwards from the Cape Peninsula) and are the driving force for the Benguela current. Due to the intensification of the South Atlantic high in southern summer the south-easterly winds are most marked in that season.

From the volume flux calculations for the 1969 cruise (reference level 1100 m.) it can be said that the boundary between the Agulhas current and the South Atlantic was formed by  $18^{\circ}\text{E}$ . except for the odd 5-10 sverdrups finding its way into the South Atlantic (fig. 17). The volume flux calculations (fig. 18) for the AFRICANA II data, reference level 1500 m. have shown that 10-15 sverdrups enter the coastal region around Cape Town through section U. Bang 1973, associates a meandering belt of thermal gradient off the edge of the continental shelf, (west coast of South Africa) that shows up in his surface temperature charts 65, 66, with a shelf edge jet. The temperature distribution on the 26.00 sigma-t level (fig. 30) shows a similar sort of thermal gradient belt ( $15.5^{\circ} - 15.0^{\circ}\text{C}$  band indicates the position). This belt can only be said to follow the continental shelf edge between  $35^{\circ} - 33^{\circ}\text{S}$ . Although the flux discrepancies (Table II) inshore of section U make it difficult to establish such a jet it seems possible that the 10-15 sverdrups entering the coastal region through section U feed this continental shelf edge jet. From the property distributions (fig. 29, 30, 31, 32, 33, 34) it can be seen that a boundary between the Agulhas current and the South Atlantic ocean was not so easy to define. The property distributions were thought to have indicated the

following. Cold water inshore of the Agulhas current seemed to form a boundary between the Agulhas current and South Atlantic on  $\sigma_t$  levels less than 25.80. (See 25.60  $\sigma_t$  level in fig. 29, 35.40 - 35.25 ‰ band). On the levels below 25.80  $\sigma_t$  the boundary seemed to be formed by an inflow entering from the west (and possibly from the south) between stations 63-64, (38°S, 14°E.) from outside the data limit. Temperature and salinity distributions within this inflow were similar to those found at the subtropical convergence. This feature is illustrated for the 26.40 and 26.80  $\sigma_t$  levels in fig. 32-34. The cold (less than 11.5°C) and low salinity (less than 34.80 ‰) patch on the 26.60 level within this inflow suggest that water from south of the convergence might enter in an intermittent way. The cold, low salinity patch, centred round 18°E, 36°S. (stations 52-59) at the edge of the continental shelf seemed to be present at most levels.

Just north of the inflow between stations 63-64 a dynamical high region was present in which part of the inflow water was recycled (see fig. 17 eddy E and acceleration potential diagrams fig. 12, 13, 14). The two different sources supplying the inflow region between stations 63-64, above 25.80  $\sigma_t$  possibly from inshore the Agulhas current and from the west and south below 25.80, gave rise to the curious shaped T-S diagrams at stations 63 and 64. The T-S diagrams are shown in fig. 47 and an explanation is given in the following way. Where the Agulhas current encountered the subtropical convergence the warm Agulhas current water flowed over the subtropical convergence water. Intense mixing between Agulhas current water and subtropical convergence water took place along the 26.00  $\sigma_t$  level which is clearly visible on the T-S characteristics of stations 63 and 64. Further mixing with subtropical convergence water had taken place on the 26.20 - 26.40 levels while the part between 26.40 - 26.60 nearly wholly consisted of subtropical convergence water. The part below 26.80 is found to lie within the limits of subantarctic water. The formation of the T-S characteristics of station 64 is illustrated in fig. 47, where

T-S diagrams from subantarctic and subtropical convergence water (Orren 1966) are drawn together with the T-S diagram of stations 63 and 64.

The acceleration potential diagram (fig. 45) of the Schmidt-ott cruise indicated a similar inflow at the northern edge of the data ( $36^{\circ}\text{S}$ ,  $15^{\circ}\text{E}$ .) (see Visser 1969).

The Agulhas bank region has not been studied in detail. The following, however, is notable. From  $\sigma_t$  sections (fig. 16, 1969) it is clear that dense water is lifted over the Agulhas bank ( $26.80 \sigma_t$  in water 100 m. deep). Above  $26.60 \sigma_t$  the characteristics of this water are similar to those found in the upwelled water where the current leaves the coast (Port Elizabeth, East London - see Chapter H). This cold water bulged out as far west as  $14^{\circ}\text{E}$ . ( $26.40 \sigma_t$ , see fig. 32) over the western side of the Agulhas bank. Below and on the  $26.60$  level the upwelled water at Port Elizabeth was confined to a patch and the Agulhas Bank was covered with warmer water (over the bank temperatures exceeded  $11^{\circ}\text{C}$  while in the upwelled patch temperatures were lower than  $10^{\circ}\text{C}$  on the  $26.80$  level, fig. 34).

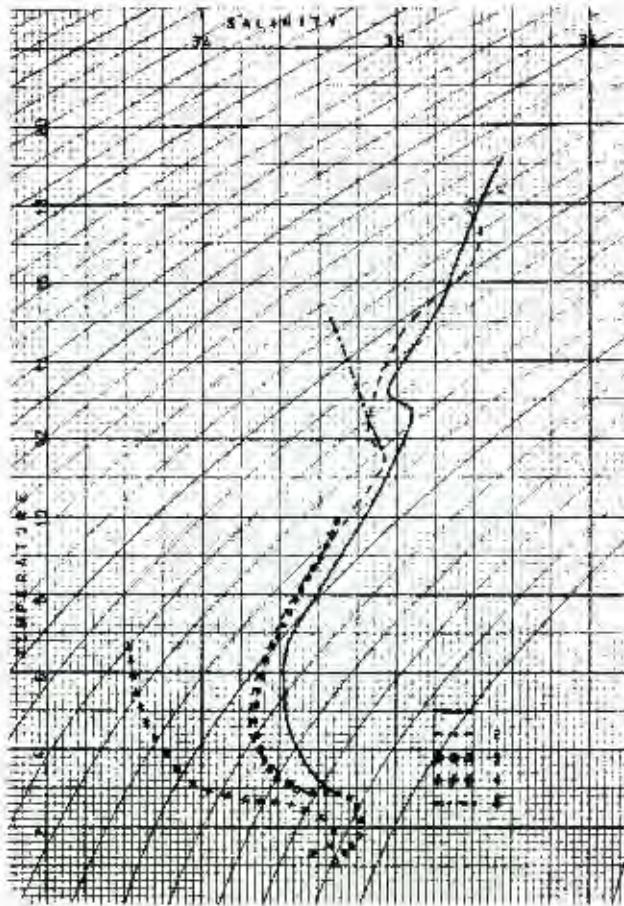


Fig. 47.

T-S characteristics of stations 63-64 (1969 Agulhas current project). see text page 93.

- 1 station 63
- 2 station 64
- 3-4 limits of subantarctic water (Orren 1966)
- 5 subtropical convergence water (Orren 1966)

CHAPTER J.

THE AGULHAS RETURN CURRENT.

A well established feature of the Southern ocean is the subtropical convergence. Along the subtropical convergence an eastward current must exist set up by the density differences across the convergence. South of the African continent the convergence is especially marked due to the fact that the Agulhas current, after retroflection, flows along the convergence. Temperature differences in the region between  $20^{\circ}$  and  $35^{\circ}$  E. can be as large as  $10^{\circ}\text{C}$  (in  $1^{\circ}$ - $2^{\circ}$  change in latitude) while the normal temperature discontinuity along the rest of the convergence is about  $5^{\circ}\text{C}$  (Deacon, 1945). The presence of the Agulhas current along the subtropical convergence will lead to a bigger contrast in properties. The strong current (upto 6.5 knots, Bang 1970), in the area where the Agulhas current flows along the convergence (especially between  $20^{\circ}$  -  $30^{\circ}$  E.) probably causes an intensified contribution of central water formation (Orren 1963, 1966) through turbulent mixing. As the Agulhas return current flows eastward it impinges upon a number of ridges (Agulhas plateau, Mozambique ridge, Madagascar ridge - see fig. 10). The importance of these ridges upon the formation of planetary waves has been investigated theoretically (Harris 1970B, Darbyshire 1972). The amplitude of these planetary waves only became clear studying the 1969 cruise.

From the acceleration potential diagrams (1969, fig. 12, 13, 14) it could clearly be seen that the Agulhas return current flows round the Agulhas plateau. As it reached its southern most position (approximately  $40^{\circ}\text{S}$ .) on the eastern side of the plateau the current curved sharply to the north reaching its most northerly position at nearly  $33^{\circ}\text{S}$ . (wave height of 360 nm.). Unfortunately the connection between the different parts of the described current path fell just outside the data limit. The path was drawn continuously because of the

evidence given by buoy 1210 (see fig. 12). Confirmation was also sought in the property distributions of the 1969 cruise. These did not always agree with the acceleration potential diagrams. Above the 25.80  $\sigma_t$  level the distributions were not very helpful as can be seen from the 25.60  $\sigma_t$  salinity and surface temperature distributions (fig. 29 and 42). The cold water above the 25.80 level does not seem to have reached as far north as the acceleration potential diagram would suggest (see 25.60 level). For the  $\sigma_t$  levels in between 25.80 and 26.60 the temperature (and salinity) distributions were in good agreement with the acceleration potential as far as the planetary wave was concerned. This was especially clear for the 26.00  $\sigma_t$  temperature distribution (see fig. 27). Below the 26.60  $\sigma_t$  level the situation was complicated. The acceleration potential diagrams are still basically the same as for the higher levels but property distributions are not in very good agreement with them. This is illustrated by the acceleration potential and temperature distribution on the 26.80 level (fig. 14, 34). The recycling of water around eddy D from the Agulhas return current could be supported with the evidence of some T-S diagrams (see Appendix). The T-S diagram of station 33 was similar to the T-S diagram of station 46/1, situated in the flow round eddy D below the 25.00  $\sigma_t$  level. This did not really prove the recycling but assuming it did exist it was at the time limited below the 25.00 level.

Formation of current rings, similar to the Gulf-stream, within the northern loop of the planetary waves may be possible.

If one assumes that this type of eddy formation exists, as seen in the figure by Parker (fig. 48) the following would represent equivalent water masses:

Slope water = convergence water; Gulf-stream water = Agulhas return current water; Sargasso water = Agulhas water. With this assumption an explanation is given below for the eddies found in the source region (mentioned in Chapter G1).

Sections across presumed eddies have been made on a number of

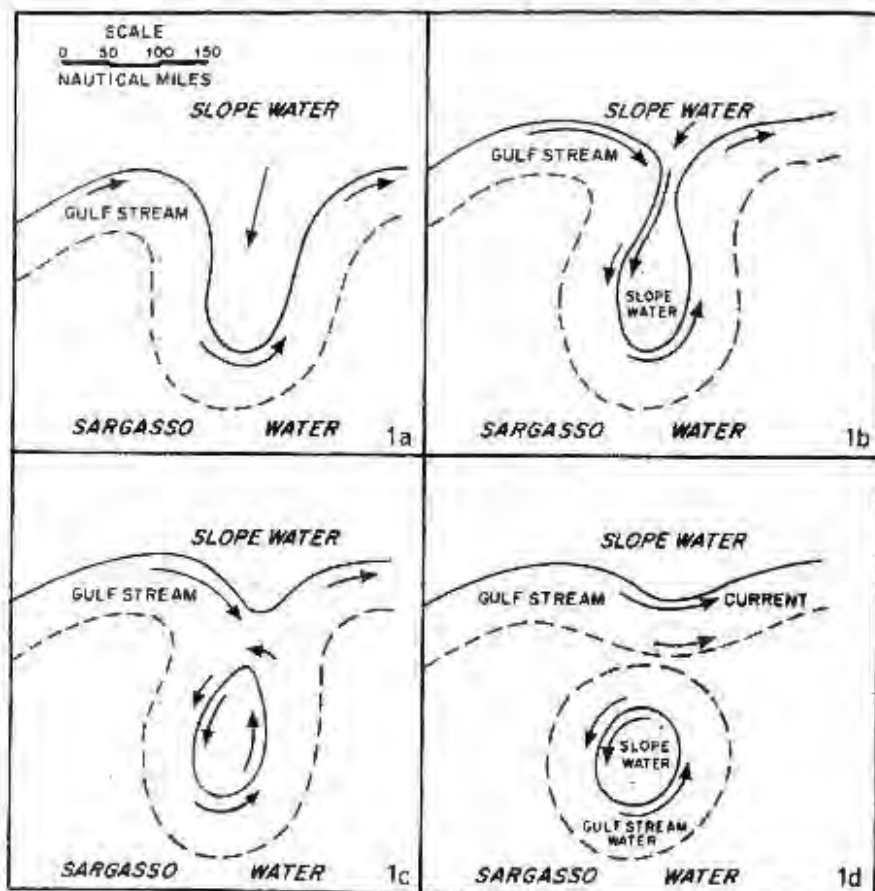


Fig. 48.

Diagram of ring formation from meander development (1a), to separation from the stream (1d). Solid lines represent the position of the  $15^{\circ}\text{C}$  isotherm at 200 m. Dashed lines represent the approximate limit of the Sargasso side of the Gulf-stream (after Parker 1971). For the Agulhas current the picture should be inverted.

occasions (January 1963 - NATAL cruise off East London; October 1962 - NATAL cruise off Durban, (fig. 28); August 1975 - (Gründlingh 1976)). A common feature in these sigma-t sections was that the isopycnals reversed their slope close to the surface ( $\pm 200$  m. depth) indicating that the maximum cyclonic circulation took place below the surface. This effect would be expected as the cold core eddies, formed at approximately  $35^{\circ}$ S, drifting north into warmer water would tend to sink. During their drift north a certain amount of mixing is likely to take place within these eddies giving rise to the formation of central water (the eddies would have to cross the high salinity band in the Indian ocean (Wyrski 1971) to drift to the source region).

The existence of the planetary waves over and east of the Agulhas plateau was confirmed by the track of buoy 1210 and the satellite infrared imagery. To illustrate the feature an infrared image of the feature over the Agulhas plateau is shown in fig. 49. After the two waves described by buoy 1210 no significant oscillations followed, indicating large damping, possibly due to the bottom topography. The 1969 cruise acceleration potential diagrams (fig. 12, 13, 14), the satellite buoy track (track 1210, fig. 19), and the infrared imagery have shown that the scale of the planetary waves is such that the station line spacing of the NATAL cruises (Darbyshire 1964), is so great that the planetary waves could fit in between them without necessarily affecting the hydrographic stations, making interpretation of the NATAL cruises very difficult. The existence of the wave over the Agulhas plateau can be satisfactorily explained with Warren's inertial jet model as shown by Gründlingh 1977, (see also Darbyshire 1972), but he could not reproduce the wave east of the Agulhas plateau completely.

A new feature of the Agulhas return current has become apparent in satellite infrared imagery. Nothing can be said with certainty yet, as the images are still in their distorted edition and no means of compensating for this was available

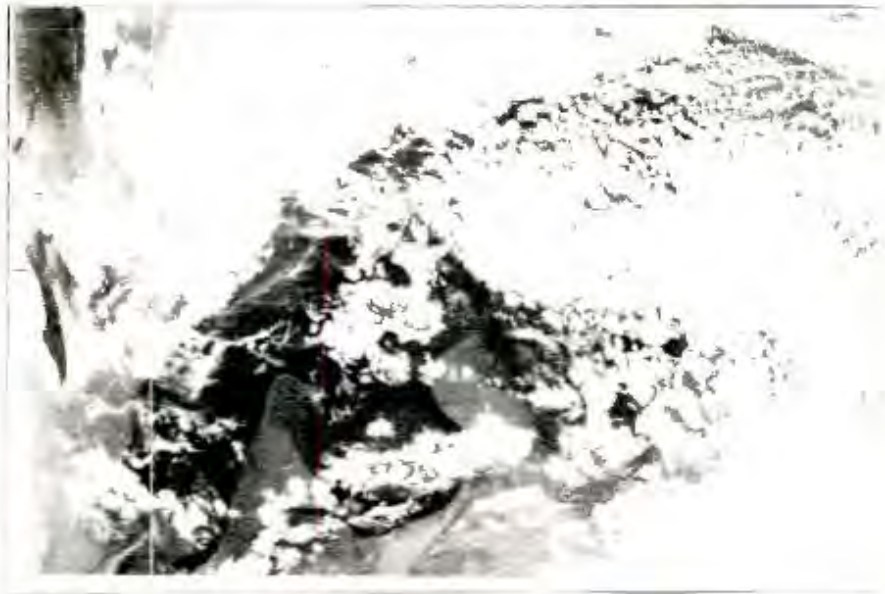


Fig. 49.

Infrared image showing the wave form over and east of the Agulhas plateau. The feature is probably a topographic Rossby wave.

at the University of Cape Town. However, it looked as though the penetration of the Agulhas current, while retroreflecting to form the Agulhas return current, can be much further south than was previously suspected. In fact it looked as though the current might at times have flowed south or over the southern end of the Agulhas plateau. The change in the path of the current might be as quick as several weeks as in some of the images presumed older tracks could be seen. The evidence of the passing south of the Agulhas plateau was supported by some of the property distributions of the 1969 cruise. The temperature distribution on the 26.00 and 26.80 sigma<sub>t</sub> levels (fig. 30, 34) showed a tongue of relatively warm water (16.5° - 17.0° C on the 26.00 and 10.0° - 10.5° C on the 26.80 level) coming up from the south at the edge of the data at approximately on 26°E. This could be part of a current flowing south of the Agulhas plateau. Southward penetration west of the Agulhas plateau to 43°S, was evident from the Schmidt-ott cruise (see fig. 45).

Evidence from satellite infrared images possibly support the northward branching currents between 44°E. and 60°E. as discussed by Harris (1970). Careful study is necessary before this can be concluded with certainty. Sea temperature charts derived by the South African weather bureau (10 day mean sea surface temperatures) showed tongues of colder water reaching north from the Agulhas return current up to 30°S. latitude.

A supply of low saline, oxygen rich water will be necessary to maintain the marked boundary of these properties across the south equatorial current and southern entrance of the Mozambique Channel (Duncan 1970). Calculations of diffusion and turbulent mixing across this boundary should give an estimate of the amount of low saline, oxygen rich water necessary to maintain this boundary.

CHAPTER K.CONCLUSIONS.

1. The source area is dominated by two large anticyclonic loops. The one is situated in the Mozambique channel and formed by the Mozambique current. The other situated south of the Mozambique channel is formed by water coming up from the south (buoy 1116). This loop probably consists of water recycled from the Agulhas return current and East Madagascar current water. Part of the Mozambique current continues down south and is confined to the south-western corner of the Mozambique channel due to the interaction of the two large current loops.
2. Inertial jet tracks have shown that two pathways possibly exist to connect the south-western corner of the Mozambique channel with the Agulhas current at Durban. The first, followed by jets starting in water shallower than 650 m., runs close inshore from just north of Lourenco Marques to Durban. The second, followed by jets started in water deeper than 700 m., runs initially down the Mozambique ridge and then meanders westward to join the Agulhas current in the neighbourhood of Durban.
3. Mainly from the 1969 cruise it could be argued that the inshore pathway supplies Mozambique current water above the 26.40  $\sigma_{\theta}$  level. The amount supplied along this path was estimated at 15 sverdrups for the 1969 cruise. The offshore path supplied higher salinity water above the 26.40  $\sigma_{\theta}$  level and entered the Agulhas current just south of Durban ( $32^{\circ}$  S). Below the 26.40  $\sigma_{\theta}$  level the supply was found to be more intermittent and the distributions of salinity are reversed. The lower salinity now entering from the east might indicate a bigger influence from the East Madagascar current. The inflow from the east was estimated at 15 sverdrups (1969 cruise).

4. More evidence for an inflow from the east, south of Durban, was obtained from other data (NATAL cruises). The volume flux of this inflow is shown to be variable (10 - 30 sverdrups), possibly supplying upto 35% of the total current transport. Within this inflow some remarkable direct current measurements have been made showing a no shear condition upto 1000 m. depth. The validity of these measurements remains to be verified. If they are considered to be valid the reference level of 1000 m. used in this thesis (and previous work) must be considered as unreliable. (Duncan (1970) suggested that 1000m. would be sufficient to show the correct current direction and relative magnitude).
  
5. The counter current off Durban is generally explained by the influence of atmospheric pressure systems. Anomalies do however occur. The convergence of two currents (these currents being the two supplies to the Agulhas current, see 2) might influence the formation of the counter current off Durban as well as the formation of the eddy off Durban. The eddy off Durban, found in several hydrographic cruises, is apparently situated in between the two supply paths over the northern end of the Natal Valley. The situation at Durban is shown to be extremely variable. Data to the north of Durban were found to be too sparse to explain the variability.
  
6. Between East London and Port Elizabeth severe upwelling is encountered. No clear cut explanation for this remarkable feature has been found. Attention is drawn to the following facts:  
Maximum current speeds are reached in this area; The continental shelf break starts to leave the coast; A dynamic high region is present south-east of East London; On the outside of the current some water turns offshore to join the eastward current (5 - 10 sverdrups for the 1969 cruise).

It is suggested that the inflow from the east and offshore turning between East London and Port Elizabeth must occur together as they are connected with a dynamic high region situated in between. Noteworthy is the spontaneous and intense upwelling occurring in Bryan and Cox's ocean model (1968).

7. As the current reaches the southern end of the Agulhas bank it turns anticyclonically towards the east. This motion can be explained with the potential vorticity equation:

As the current moves south it constantly gains planetary vorticity. Initially this can be compensated for by moving into deeper water along the continental shelf break. When the current reaches the end of the Agulhas bank it runs out of depth compensation so that the still increasing planetary vorticity can only be compensated by anticyclonic curvature.

The main retroflexion area was found to be variable (east of  $21^{\circ}$  E. for the 1969 cruise; east of  $18^{\circ}$  E. for the Schmidt-ott cruise 1964). Buoy track 1210 showed a westward penetration to  $13^{\circ}$  E. before retroflexion. A line running over the Cape rise (Cape Town to  $40^{\circ}$  S,  $10^{\circ}$  E.) is suggested as a maximum western limit for retroflexion. The limit of southward penetration during retroflexion was not clear from the available data. Recent satellite infrared images suggested that part of the current may pass to the south of the Agulhas plateau. Slight evidence of this was also obtained from the 1969 cruise. Penetration beyond  $43^{\circ}$  S. is thought to be unlikely.

8. During retroflexion, eddies may separate from the main current and drift westward. The way in which these eddies are formed was not clear. Buoy track 776 suggested that intrusions of water from the south might be the cause of separation. This could be supported by the 1964 cruise. A warm eddy was found, in the 1964 cruise, over the Richardson Seamount. This eddy was separated from the

Agulhas current by an intrusion of cold water from the south. The acceleration potential diagram of the 1964 cruise showed some resemblance with a Taylor Column streamline pattern. No certainty about the validity of the comparison has been obtained.

Approximately 10 sverdrups of the Agulhas current (with reference to 1500 m.) was found to contribute to waters west of South Africa.

9. The area to the north of the separation line (see 7) was dominated, in March 1969, by a large anticyclonic gyre (recycling 15 sverdrups with reference to 1500 m.). A supply of 15 sverdrups, entering from the west, between stations 63 - 64 could be feeding the Benguela current and the upwelling regime of the coast of Southern Africa. Two different water masses could be established within this inflow. The upper levels (above 25.80  $\sigma_t$ ) were thought to exist of mainly cold water lifted over the Agulhas bank by the Agulhas current. In levels below 25.80  $\sigma_t$  the influence of convergence water was clearly established.
  
10. Two planetary waves in the Agulhas return current, one over and one east of the Agulhas plateau, showed very clearly in the acceleration potential diagrams of the 1969 cruise. The largest wave, to the east of the Agulhas plateau, had an amplitude of 180 nm. Buoy 1210 also showed two planetary waves in the Agulhas return current. The amplitude of the eastern wave (90 nm.) was considerably smaller compared to the 1969 cruise.

Recycling of water (1969 cruise) from the northern crest of the eastern wave seemed to occur. This water entered the inflow south of Durban.

Eddy formation in the northern loop of this planetary wave occurred, recycling 5 - 10 sverdrups (1100 m. reference). It was suggested that these eddies might drift towards the north-east into the source area. This process could be similar to the Gulf-stream. The idea was supported by eddies found on several occasions within the source area. These eddies are found to have their maximum cyclonic circulation subsurface. This could be expected when eddies formed in the colder eastward current drift northward into warmer water.

Buoy 1210 did not support the idea (Harris 1970) that northward branching of the Agulhas return current can take place in the neighbourhood of the Madagascar ridge.

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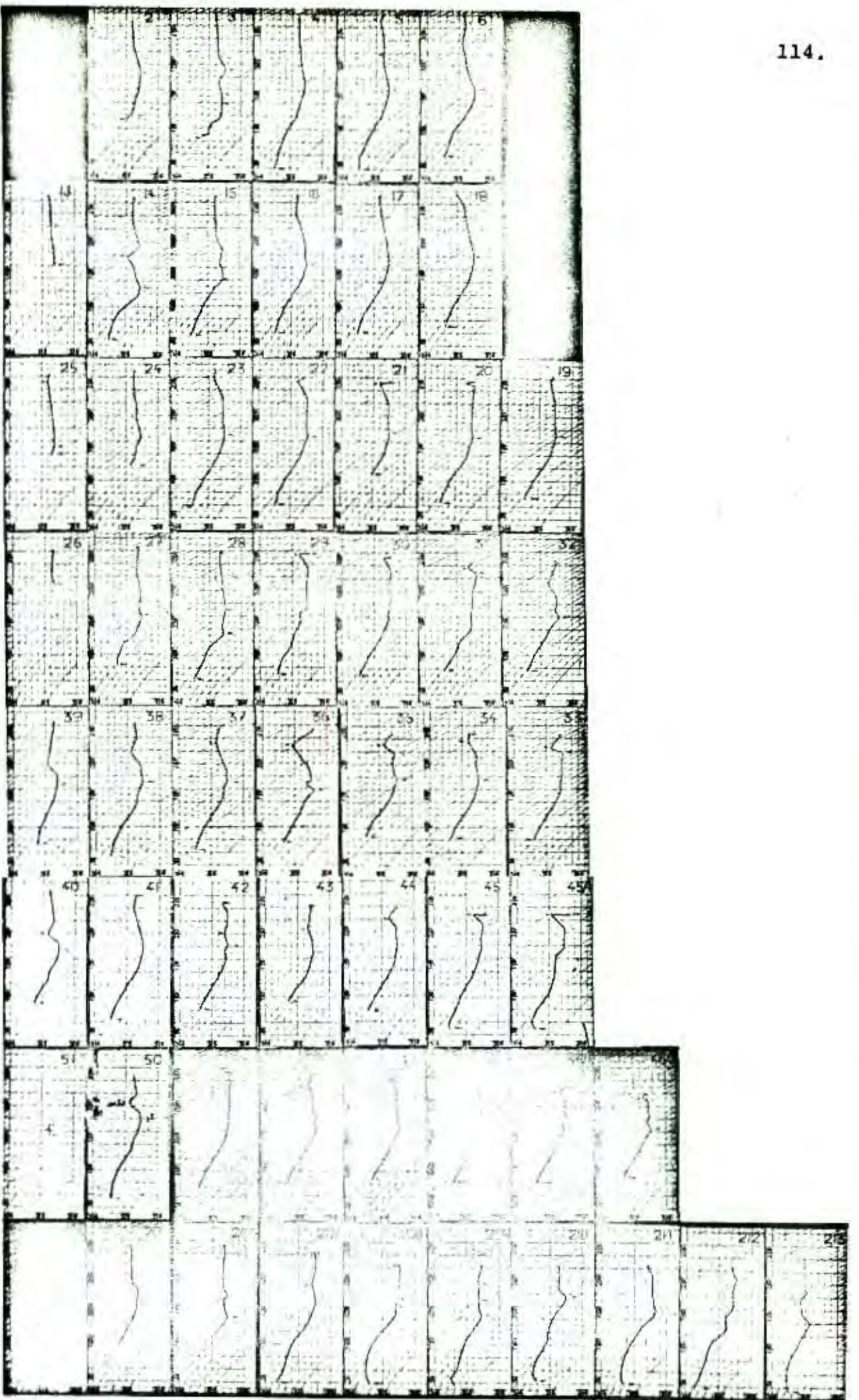
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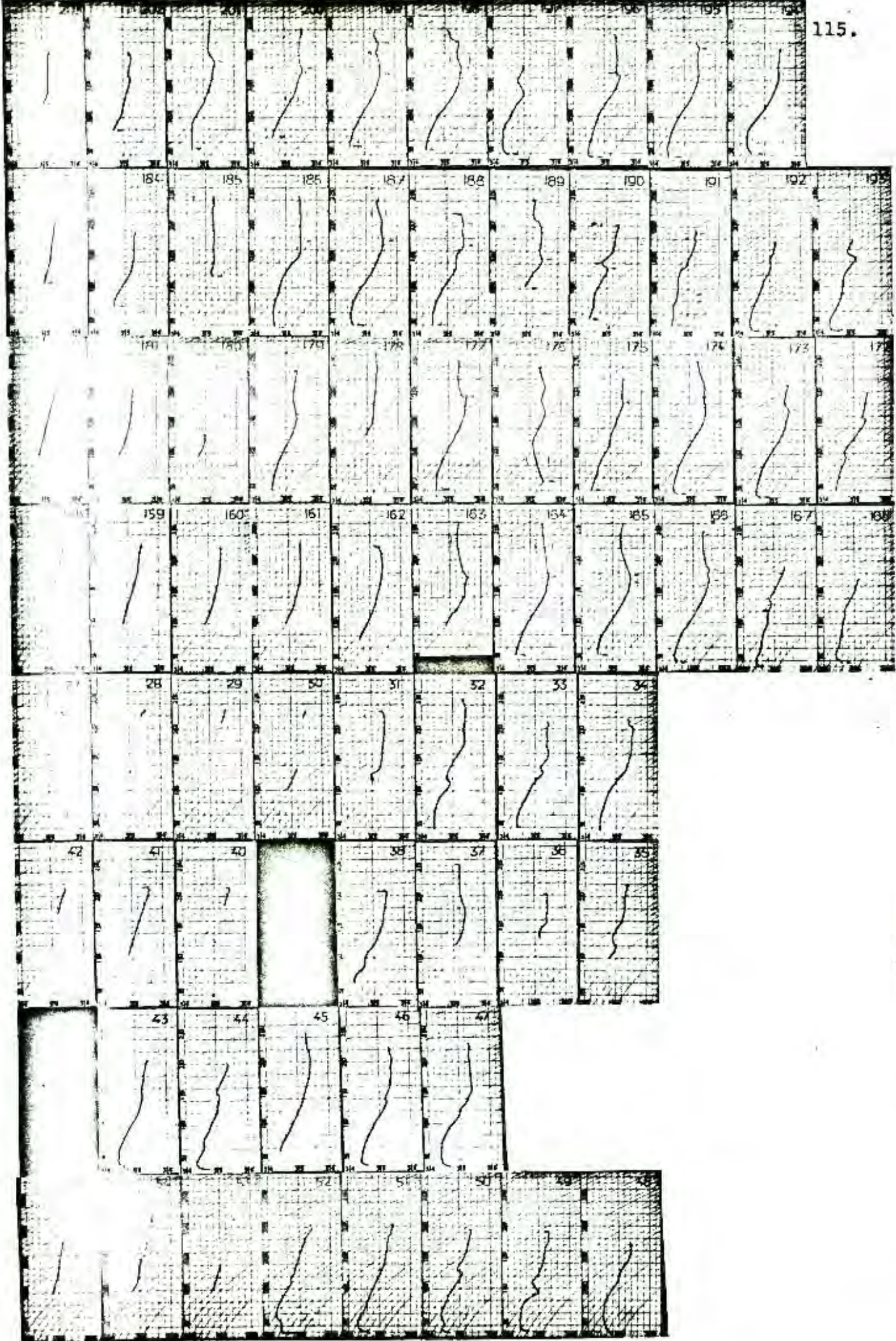
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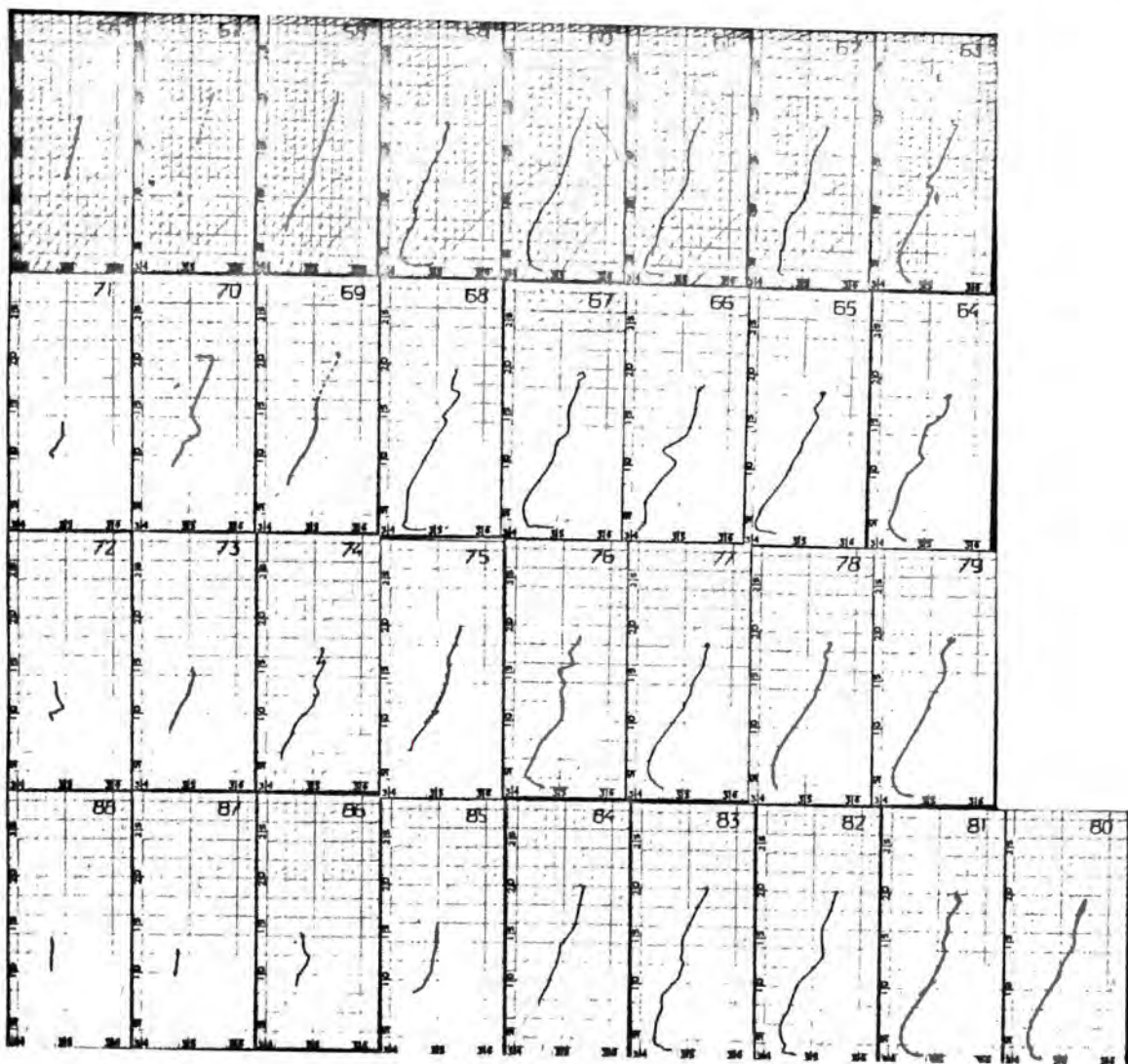
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APPENDIX

T-S diagrams of the 1969 Agulhas current project.







27 JUN 1977