Review of Coastal Currents in Southern African Waters

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A review prepared for the South African National Committee for Oceanographic Research (SANCOR) and for the Committee on Marine Pollution, National Programme for Environmental Sciences

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PREFACE

The Cooperative National Oceanographic Programme and the National Programme for Environmental Sciences are two of several cooperative national scientific programmes administered by the CSIR. The programmes are cooperative undertakings between scientists and scientific institutions in South Africa concerned with oceanographic and environmental research. They aim at identifying oceanographic and environmental problems which lend themselves to solution through cooperative research and at promoting and coordinating research which will contribute to the solution of such problems. The programmes include research designed to meet local needs as well as projects being undertaken in South Africa as contributions to various international programmes.

This review was undertaken under the aegis of these two programmes in an attempt to bring together all available knowledge about inshore circulation around the Southern African coast. Although it was recognized at the outset that, especially in certain areas, the information is still very limited, it was felt that the review would be a valuable working document for use by scientists and engineers who need information on coastal currents for marine biological, coastal engineering and marine pollution studies. It should also assist the Department of Transport in dealing with oil pollution incidents. The review does however also identify the most serious gaps in information and should therefore serve to direct future research.

Acknowledgements

In view of the fact that the material for these notes has been drawn from the work of many people it is important that, at the outset, grateful acknowledgement be made of their pioneer studies. Some of the sources of information are as yet unpublished. For permission to use these data I am indebted to the Durban City Engineer, the S A Industrial Cellulose Corporation, the Natal Town and Regional Planning Commission, the City and Water Engineer of Port Elizabeth, the National Research Institute for Oceanology, the Sea Fisheries Branch, the Marine Division of the Department of Transport, the Atomic Energy Board, the Fisheries Development Corporation and the Cape Town City Engineer. The results of unpublished research have also been generously made available by Mr E H Schumann, Mr E Beesley, Mr W Bricknell, Dr O G Malan, Dr D Baird and Mr B B S Tromp.

I am grateful to the following for discussion and useful comments: Mr W D Oliff, Mr D Mulligan, Dr L V Shannon, Mr C C Stavropoulos, Mr C A R Bain and Mr F P Anderson. The project was initiated by Mr O A van der Westhuysen and Dr C E Cloete who, together with their staff, edited and prepared the text for publication. The project was funded by the South African National Committee for Oceanographic Research.

Mr A Britten-Jones' help in preparing most of the drawings has been invaluable. A great many of the diagrams used have been copied from or based on the original sources. Acknowledgement in each case is indicated by placing the appropriate reference number at the end of the caption.

Finally I am indebted to the University of Cape Town for its hospitality.

ABSTRACT

A review has been made of existing knowledge of the coastal currents in Southern African waters betweeen Pta do Ouro on the northeast border, and the Orange River on the west coast. These waters have been divided into five sectors. For each, the larger scale forcing mechanisms are discussed and the results of localized studies summarized. The former involve consideration of, *inter alia*, the influence of the Agulhas Current on the east coast and the wind stress on the south and west coasts. The latter, the local studies, contain the results of investigations which have been carried out mainly for coastal engineering and effluent problems - and tend to be concentrated around built-up, or developing regions. They are consequently unevenly spaced. In regions where such studies were not available, recourse had to be made to ships' drift reports. Because of the nature of the data it was necessary to restrict the review, almost entirely, to surface currents. Where possible, wave driven currents - nearshore circulations - have been included.

In planning the review the needs of the user of coastal currents data were a primary consideration. Where important information has been found lacking recommendations for future research have been made.

An appendix contains brief descriptions of the more widely used methods for measuring coastal currents.

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INTRODUCTION

The purpose of this work is to outline our existing knowledge of coastal currents in Southern African waters between Pta do Ouro on the Mozambique border and the Orange River - a distance of some 2 600 km. Since only about 16% of the region has come under intensive study, the account is necessarily an interim one. Because it is directed towards the practical user, the policy has been to draw, wherever possible, positive conclusions, albeit with reservations, even when the balance of evidence does not amount to certitude. This is only justified by the fact that users sometimes have of necessity to make decisions which involve assumptions about coastal currents.

It is often difficult to set boundaries in the sea, and this is usually true of coastal waters. However, along the east and southeast coasts of Southern Africa the strong Agulhas Current is to be found flowing approximately parallel to the coast (poleward) and the current's inner boundary occupies a mean position over about the 200 m depth contour. This may be taken as a convenient offshore limit of the coastal waters. On the west coast the limit is less clearly defined because it merges with the Benguela Current whose driving mechanism is largely similar to that of the coastal currents.

It is arguable that water movements in the sea become increasingly complex as the water depth decreases. Certainly no simple statement can be made about the currents which are to be found in any particular region of the coast. The reason for this is that coastal waters are subject to a number of forcing mechanisms whose potency is variable and whose relative dominance is difficult to determine. The origin of the particular mechanism may be remote from the area of interest. Amongst the forcing mechanisms already identified on the Southern African coast are:

(a) the Agulhas Current - a quasi-permanent ocean current whose position and velocity nevertheless vary;

(b) the stress of the wind, the atmospheric pressure differences and their indirect effects (the Benguela Current will be dealt with later);

(c) the pressure gradients set up by density differences;

(d) the mass transport of surface gravity waves which influence a part of the sea within a distance of 2-4 surf-widths from the shoreline.

Although tidal currents are of central importance on some coasts of the world, they are insignificant in Southern African waters (except in certain bays) because the co-tidal lines tend to be parallel to the coast.

It is probably desirable to outline very briefly the general nature of the main forcing mechanisms which generate currents in our coastal regions.

FORCING MECHANISMS

The Agulhas Current

Figure 1 is a schematic representation of the mean current path. The current is a continuity current draining poleward the water accumulated from the Trade Wind current (South Equatorial Current) and other sources of more locally recycled water. Dynamically it must be associated with a land boundary on the western side (which may be a submerged ridge). It is a deep current - at least 2 000 m deep - and is usually to be found with its core (maximum velocity) just seaward of the shelf break (where the continental shelf gives way to the slope) in say 500-1 000 m of water. Meanders in the current causing deviations from the mean path are common.

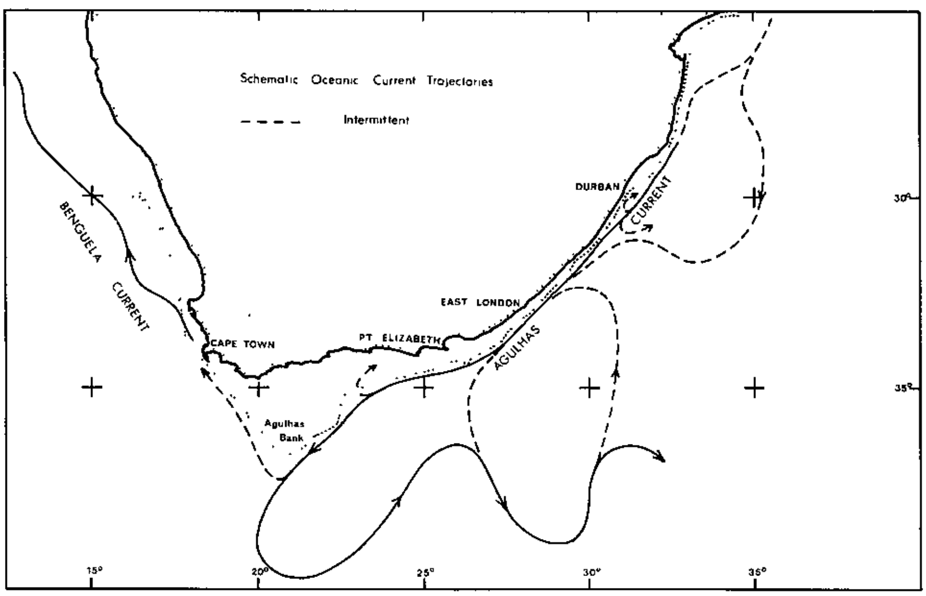


Figure 1. Schematic trajectories of the two major ocean current systems.

Existing evidence suggests that the Agulhas Current is initially formed by tributaries which converge near the western side of the southern end of the Mozambique Channel. The subsequent behaviour of the current may depend upon which tributary dominates - dominance almost certainly varies with time.

Near its source it may flow down the Tongoland coast past Cape St Lucia, or it may branch seaward and flow on an almost parallel course, adhering to the submerged Mozambique Ridge, finally converging with the St Lucia branch near Port St Johns. Thereafter the current flows close to the coast as far as East London, after which it diverges from the coast as it follows the depth contours.

The Current influences the coastal waters in at least four ways:

(a) Where the coastline and mean current path diverge (e.g. at bights and embayments) a cyclonic or clockwise vortex or eddy is induced because of entrainment of coastal waters at the divergence.

(b) Where the Current flows close to the coast the coastal waters will move in sympathy, but because of the meanders or horizontal waves in the Current the effect may be intermittent. There is mounting evidence of significant meandering motion. Off Richards Bay the mean offshore-onshore motion of the inner edge of the Current is 0,44 km h^{-1}, with periodicities of 5-10 days when meanders occur (Pearce 1977). Off Durban the offshore-onshore velocities have been shown to be about 0,8 km h^{-1} (Natal Town and Regional Planning Commission and CSIR 1969). Infrared imagery from satellites indicates meanders with wavelengths of 300-350 km and phase velocities of about 20 cm s^{-1} downstream of Port Elizabeth. Amplitude on one occasion was approximately 180 km (Harris, Legeckis and van Foreest in press).

(c) Between the Current and the coast there exists a zone of high current shear where cyclonic vortices can be induced, which may lead to contrary currents near the coast. These effects may be transient as the vortices advect downstream.

(d) The warmer, lighter water advected inshore by the Current, in association with colder heavier coastal waters, may set up pressure gradients.

Atmospheric Effects

It is convenient, though possibly an over-simplification, to consider the wind regime in the coastal waters as consisting of winds blowing anticlockwise round the coast, alternating with clockwise winds. This reversal of the wind direction is usually associated with the passage of 'fronts' or 'lows', and may take place in a matter of minutes off the Natal coast, or over a longer period, perhaps a day or so, in Cape waters.

The direct effect of the wind is its stress on the sea surface causing a transfer of momentum from air to sea such that the sea near the surface picks up a velocity of 2-3% of the wind speed. A value of 1,4% has also been used (Natal Town and Regional Planning Commission and CSIR 1969). Because of the earth's rotation, the induced wind drift is theoretically directed to the left of the wind direction, an effect which diminishes in shoaling water. Winds with the coast on their left (looking down wind) may therefore cause a convergence (piling up of water) at the shore, or conversely, with the coast on their right, a divergence (or upwelling). Both these effects alter the slope of the sea surface normal to the coast, and result in currents in sympathy with the wind throughout the whole of the water column.

There also appear to be effects due to the change in atmospheric pressure associated with the passage of fronts. The resulting changes in longshore gradients of pressure have been correlated with changes in the direction of flow of Natal coastal waters (Natal Town and Regional Planning Commision and CSIR 1969). The mechanism of this effect has not yet been elucidated.

Another possible atmospheric effect - suggested by Pople (personal communication 1978) - is evaporation by coastal winds leading to density currents. The validity of the idea in South African waters has yet to be established.

Density Currents

The juxtaposition of water masses of different density results in a pressure gradient directed from the lighter to the heavier water. Together with the effect of the earth's rotation this theoretically results in a current whose direction is at right angles to the left of the pressure gradient.

Wave-driven Currents

In deep water there is little mass transport associated with surface gravity waves. However, when the waves enter shoaling water - at a distance from the shore of several surf-widths - the mass transport becomes appreciable. Obliquely approaching waves can, in this nearshore region, generate currents in sympathy with the wave direction. These currents are strongest just inside the surf zone.

GENERAL

The problem of understanding and predicting the movement of coastal waters requires a knowledge of all the above factors, both in their separate influences and in their interactions. Especially lacking at present is an understanding of what controls the meanders in the Agulhas Current, what the nature and magnitude of the atmospheric pressure effects are, and what time elapses between the cessation of the forcing mechanism and the dissipation of its effects.

In the absence of good understanding, the best that can be done is to collect statistics about the frequency of occurrence of current vectors for different regions, and to make some tentative suggestions for the current regimes found.

Detailed studies of the coastal currents have been made at only a few places along the coast. There have been a number on the Natal coast notably at Richards Bay, Durban, Umkomaas and Port Edward; and a few on the Cape coast e.g. False Bay, Table Bay and the region just to the north of it. For the rest of the coast our knowledge of the currents has to rely primarily on ships' drifts.

Measurements made by ships are open to doubt on account of such unknown factors as windage on the superstructures and changing sea conditions.

Nevertheless, it is noteworthy that after a decade of studies on the Natal coast, summarized by Pearce (1977), the original concepts of the circulation derived from ships' drifts remain virtually unchanged. Furthermore the results of recent measurements by current meter made by Schumann (personal communication 1978) along the Natal coast indicate that the directional frequencies are in line with the ships' drift data. It should be noticed that ships' drifts represent the integrated effects of the current on the ship in its passage between two points along the coast.

Two kinds of ships' drift data have been used in this review. Those from the logs of Capt. Bray referred to below as 'ships' drift data' and those compiled by Commander Tripp referred to as 'Tripp's data', or 'ships' drift, wind subtracted,' because 3% of the wind vector had been subtracted. When Tripp's data are reported in tables or current roses the approximate directions have been described by symbols comprising points of the compass, sometimes followed by an 'I' (inshore) or an 'O' (offshore). NI for example, would refer to a current having north-going and shoreward components and SO would have south-going and offshore components.

The units used to describe distances and current velocities are commonly the kilometre and metres (or centimetres) per second, respectively. Mariners on the other hand make use of the system of nautical miles, knots and fathoms. Since much of the data used below is in the latter form both systems of units have been used. The equivalent values are as follows:

1 Nautical mile = 1,852 km
1 Knot = 0,515 m s^{-1}
1 Fathom = 1,828 m

ARRANGEMENT OF THE REPORT

It is proposed to divide up the coastal waters into five sectors.

(a) Pta de Ouro to North Sands Bluff - a sector including most of the Zululand and Natal coasts;

(b) North Sands Bluff to Cape Morgan - including the Transkei coast;

(c) Cape Morgan to Cape Agulhas - a sector in which the coastal shelf broadens into the Agulhas Bank;

(d) Cape Agulhas to Cape Columbine;

(e) Cape Columbine to the Orange River.

Each section will be divided into regions as considered suitable. The sectors are shown in Figure 2. An appendix discusses observational methods.

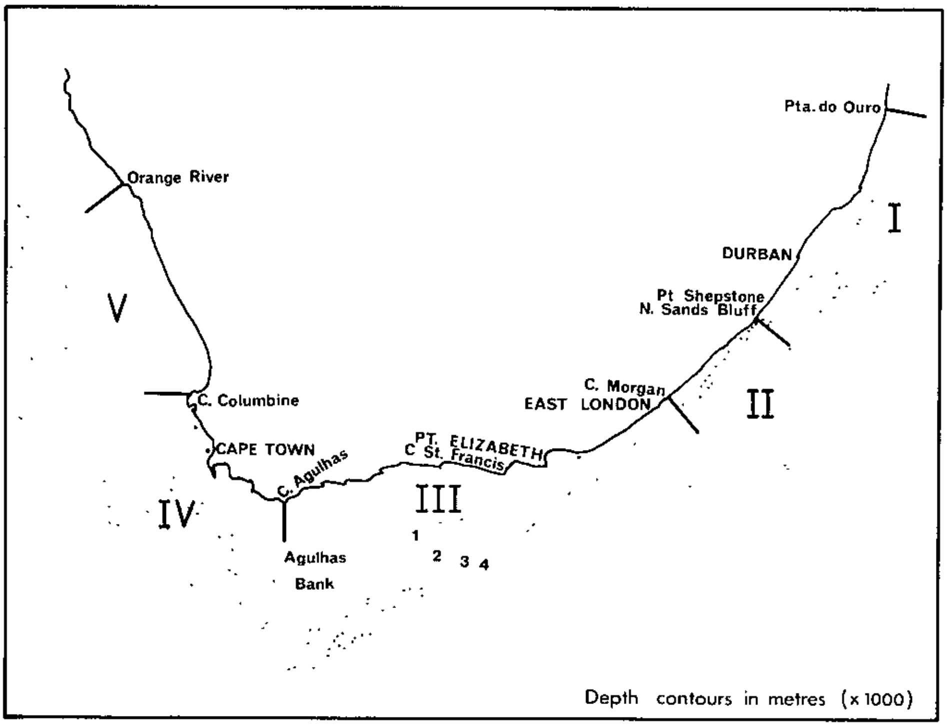
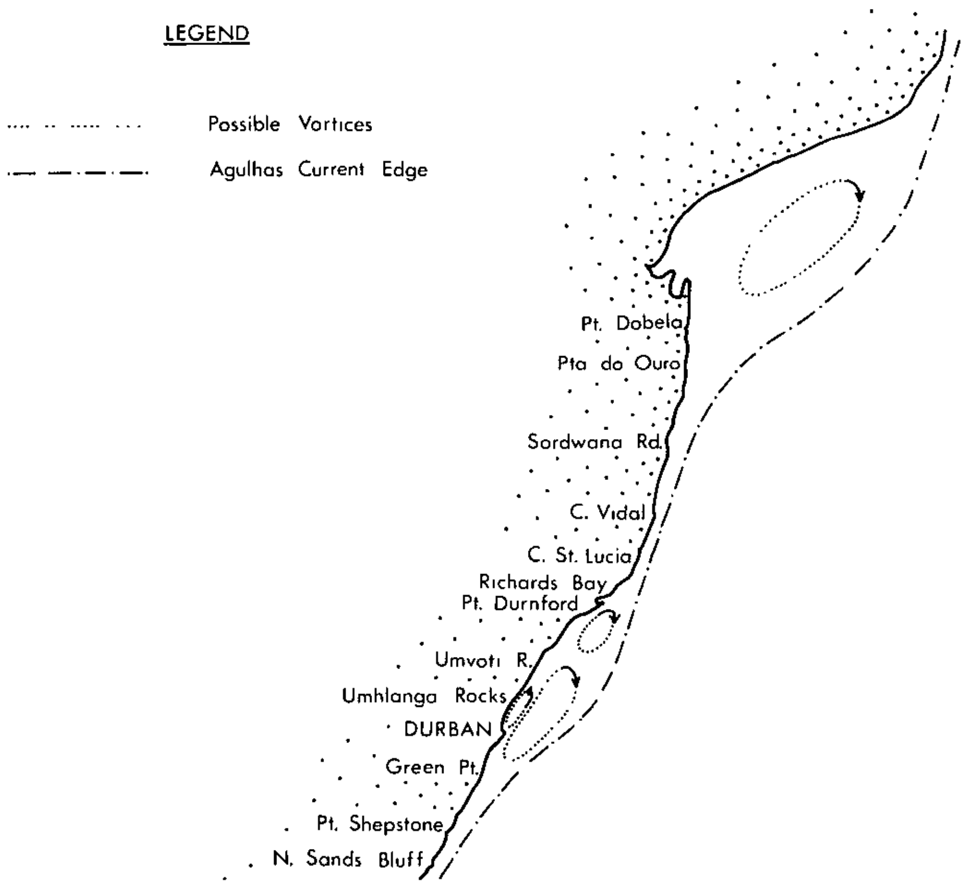


Figure 2. Location diagram of the five sectors and the bathymetry of coastal waters.

The presentation of data in a uniform format, which would facilitate intercomparisons, has not been possible. Raw data have not always been available, so diagrams from original publications have had to be used. This is particularly true for wind data and for the grouping of data into months or seasons.

SECTOR I PTA DO OURO TO NORTH SANDS BLUFF



The elements of the larger circulation in this sector are shown in Figure 3, which is based on a schematic diagram by Pearce (1977). Notable are:

(a) the close proximity of the Agulhas Current to the coast at Cape St Lucia;

(b) the possible induced eddy to the north of Cape St Lucia;

(c) the large Natal Gyre system induced by the separation of the Agulhas Current and the coast line just south of Cape St Lucia and/or large meanders in the Agulhas Current;

(d) the impingement of the main current on the coast near Port Shepstone;

(e) the subsidiary eddy in the bight just north of Durban induced by the Natal Gyre - a counter-counter current.

It should be stressed that, where the Agulhas Current system is shown in diagrams, the representation is schematic and greatly over-simplified.

The same applies to the gyres or vortices whose existences are not very well established.

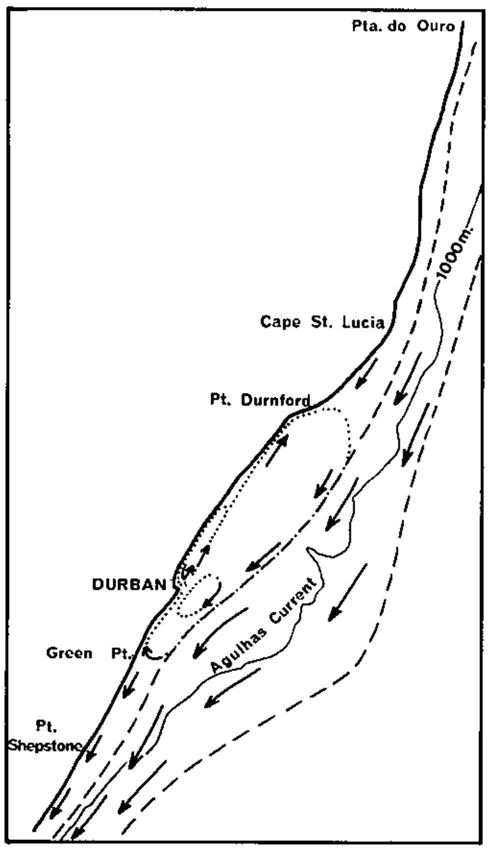
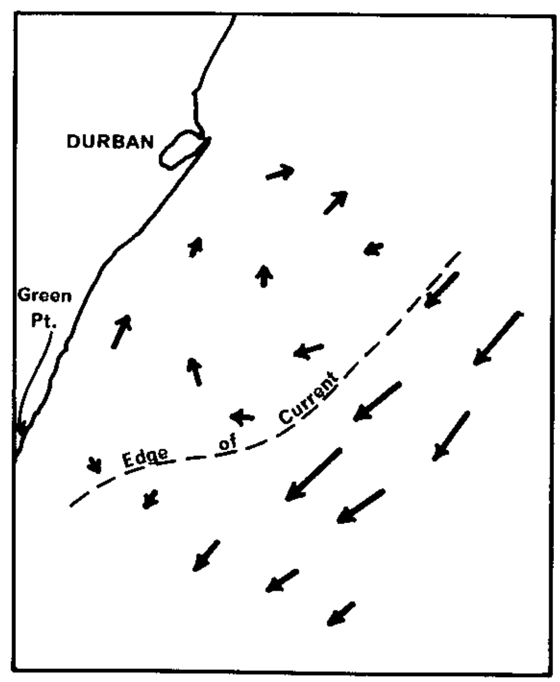


Figure 3 (left). Schematic conception of major circulation elements off the Natal coast. (After Pearce 1977 with permission).

Figure 4 (below). Measured surface currents off Durban, 29-30 June 1966. (Natal Town and Regional Planning Commission and CSIR 1969 with permission).



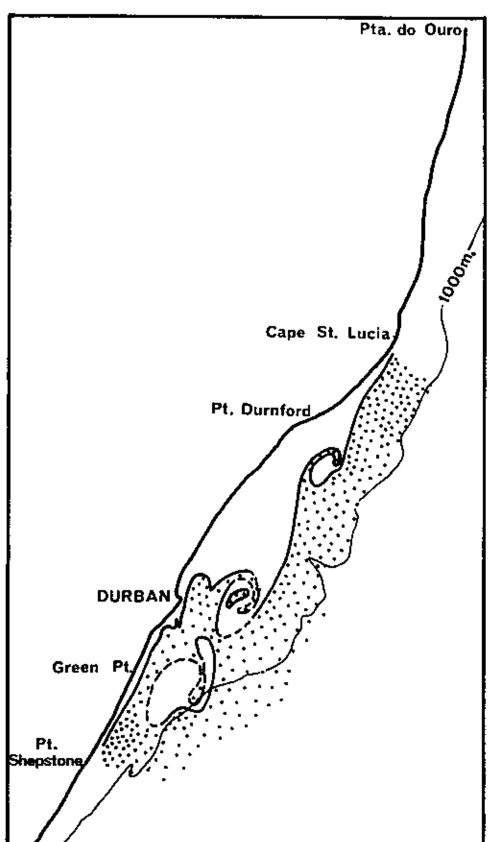


Figure 5 (left). Sketch made from Landsat image (band 4) of 73.01.29 indicating possible vortices. (Enhanced image by O G Malan).

Evidence confirming the reality of the Natal Gyre (or gyres) is however beginning to emerge. This includes

(a) direct current measurements made by the CSIR off Durban (Natal Town and Regional Planning Commission and CSIR 1969) (see Figure 4.);

(b) a satellite image (Malan personal communication 1978) obtained from Landsat in the visible spectrum, suggesting vortices between the Agulhas Current and the Natal coast. A rough sketch, Figure 5, indicates the kind of features it reveals;

(c) the oil spill from the World Glory, which originated some 60 n miles ENE of Durban, closed to within a few miles of Durban, and appears to have been advected in by a large vortex (CSIR 1968).

The schematic approach, although a little hypothetical, does help to indicate the possible coherence of the elements of the circulation.

This particular section of the coast has been closely studied by two institutions of the CSIR at Durban - the National Institute of Water Research and the National Research Institute for Oceanology (the Durban branch of which was formerly a division of the National Physical Research Laboratory). The work of these two institutions has, in part, been sponsored by the Town and Regional Planning Commission of the Natal Provincial Administration which has taken a lively interest in coastal investigations. The Commission's permission to use the results of its sponsored work is greatly appreciated. Many of the results of the coastal research appear in reports to the Commission's Steering Committee on the Marine Disposal of Effluents. Oliff and Addison (1970) and Pearce (1973, 1977) have summarized a good deal of the work, while a publication 'The Disposal of Effluents into the Sea off the Natal Coast' has been produced jointly by the Commission and the CSIR (1969). Impetus has also been given to the work through the sponsorship of research by the Durban Corporation and the S A Industrial Cellulose Corp (at Umkomaas), and by the SAR & H, which enabled CSIR institutes to make studies off Richards Bay in preparation for the construction of the new harbour (Zwamborn 1969).

Another source of information has been the records from the logs of coastal shipping. One in particular, by Captain Bray (1959-1964), covering the coast from Durban to Cape Town, has been particularly useful and has been analysed by Harris (1964). Tripp (1967) has also used this kind of data.

A useful compendium of literature on the Natal coast has been prepared by Pearce (1974). Darracott and Cloete (1976) have listed publications relating to effluent disposal. Lundie (undated) has analysed winds.

The main conclusions from these studies are that two of the main generators of coastal currents have been found to operate in this sector of the coast: towards either end (Cape St Lucia and South Sands Bluff) the Agulhas Current is close to the coast, and the currents near the shore are in sympathy 80% of the time. In between, the mean position of the core of the Agulhas Current is to be found of the order of 50 km off Durban, but it meanders off- and onshore such that its inner boundary (defined as where the velocity is 0,5 m s^{-1}) oscillates between 15 km and 40 km offshore. The wind of course always has a direct effect, due to the stress on the sea surface, but workers at the CSIR laboratories in Durban are convinced that there is also an indirect effect (Natal Town and Regional Planning Commission and CSIR 1969). This is such that when the atmospheric pressure is higher at Durban than St Lucia there are northerly currents, and vice versa.

Figure 6 gives a schematic representation of how the net direction of coastal currents within a few kilometres of the shore (Bray 1959-1964) varies within this sector. The arrows show net current direction, which is the difference between the percentage frequencies of the occurrence of north- (up coast) and south- (down coast) going currents. The arrow lengths are proportional to this difference. The diagram also contains an indication of the possible mean path of the Agulhas Current and the induced gyres. There are obvious dangers in such simplification of a variable system.

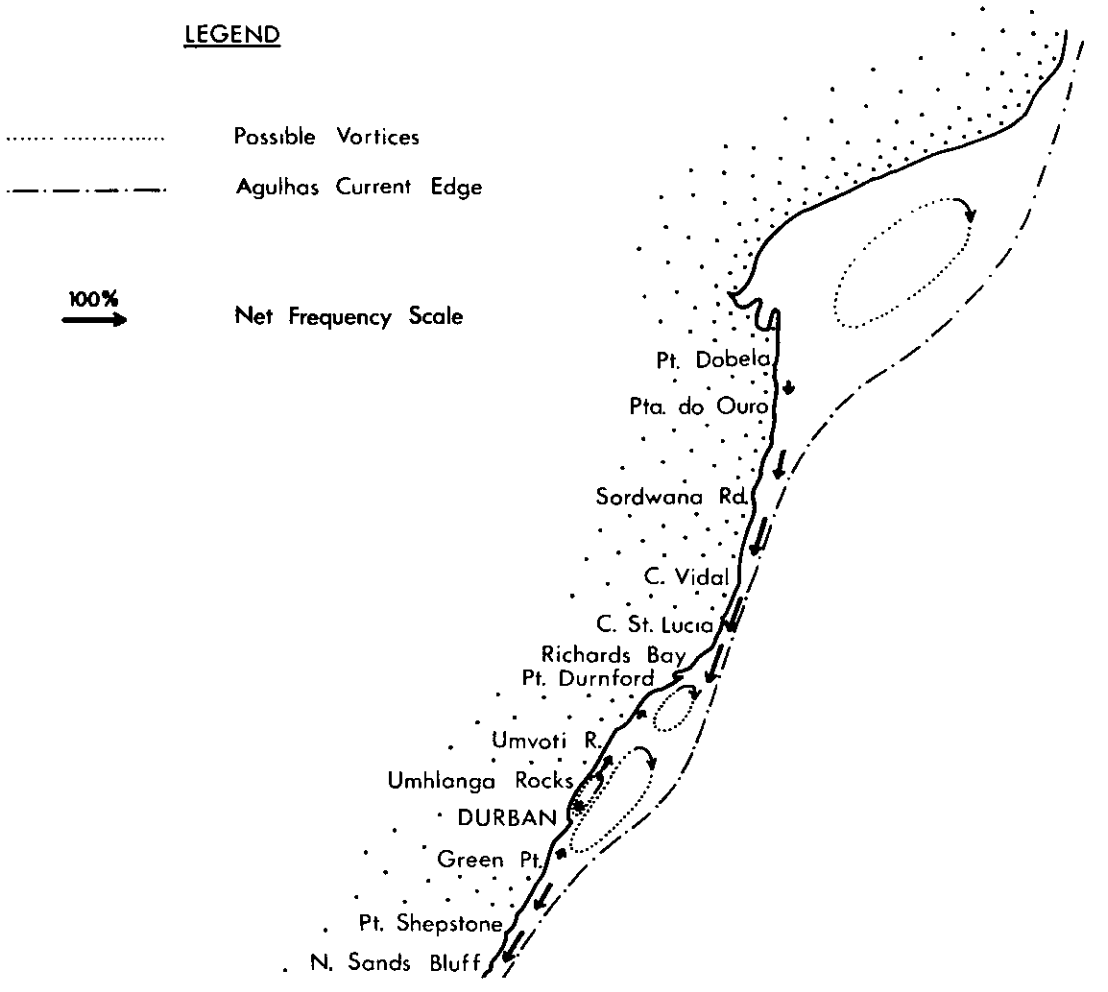
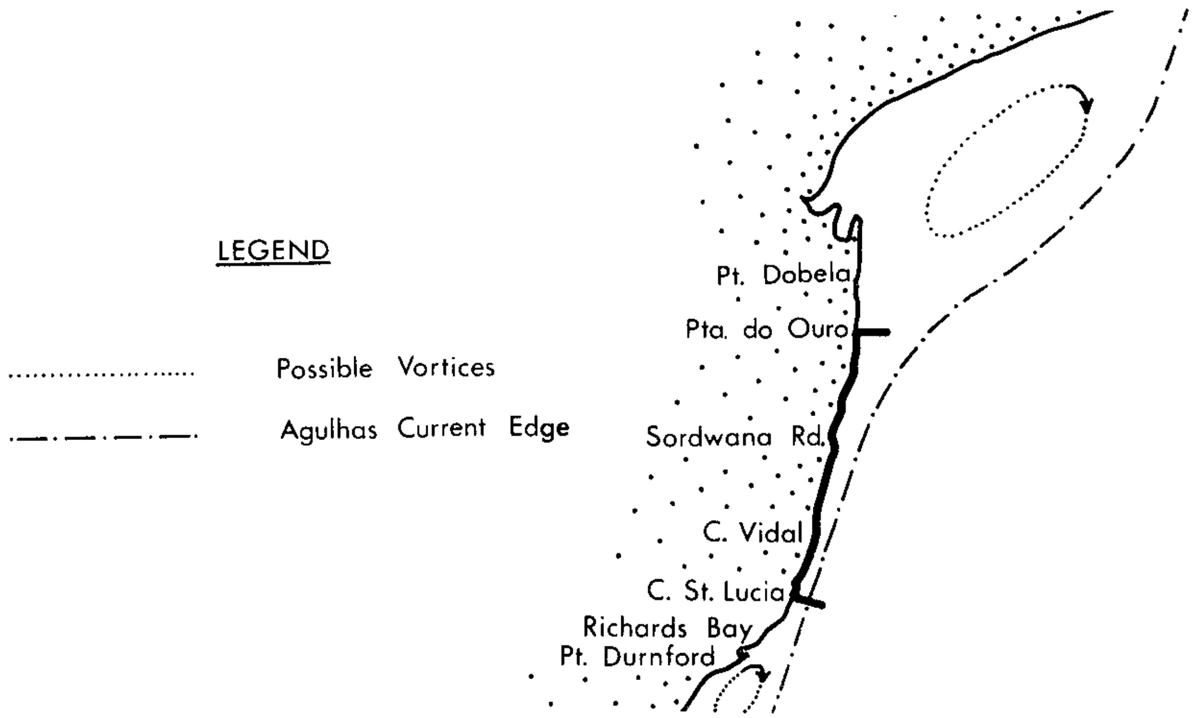


Figure 6. Net frequency of current direction from ships' drifts (data from Bray 1959-1964). (Arrow length proportional to net frequency).

1.1 PTA DO OURO TO CAPE ST LUCIA



The limited data for this region are from ships' drifts as reported by coasters. The percentage frequency of current directions as they affect a ship travelling about 2 km offshore parallel to the coast (approx. north and south) are as follows (Harris 1964):

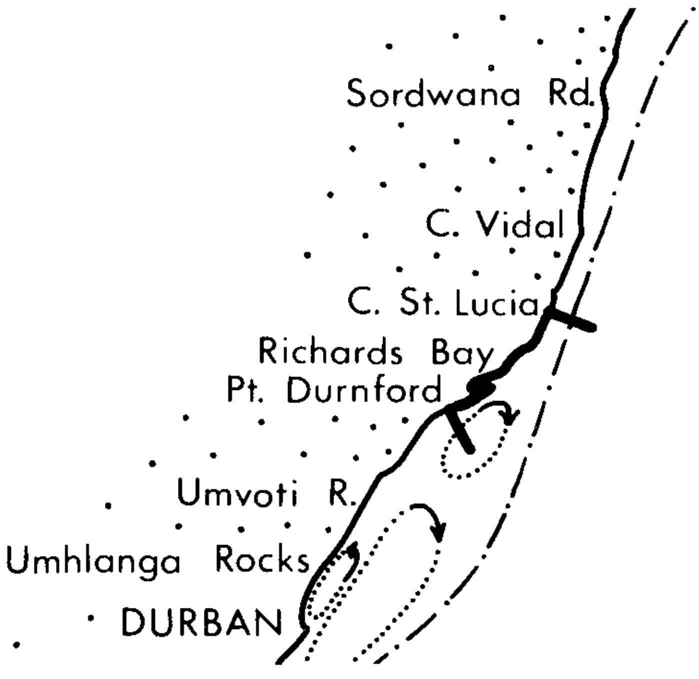
Table 1. Current directions (ships' drifts), Pta do Ouro to Cape St Lucia.

	No. of observ= ations	% north going	% south going	% slack water
Pta do Ouro to Sordwana Road	32	22	69	9
Sordwana Road to Cape Vidal	24	17	79	4
Cape Vidal to Cape St Lucia	33	12	76	12

The currents are predominantly to the south and are the consequence of the Agulhas Current flowing close to the coast. Although the sample is uncomfortably small, there is a suggestion that the frequency of north-going currents is higher to the north. It is probably reasonable to envisage a cyclonic gyre filling the shelf region off Maputo, and generated by entrainment in the Mozambique/Agulhas Current as it passes Cape Corrientes, when emerging from the Mozambique Channel.

From the ships' drift data it appears that in the Cape Vidal to St Lucia region the velocities associated with the south-going current exceed one knot (about 0,5 m s^{-1}) for 60% of the observations. The north-going currents were always less than 0,5 knots (about 0,25 m s^{-1}).

1.2 CAPE ST LUCIA TO PORT DURNFORD



Because of intensive studies in the Richards Bay area the coastal currents in this region are relatively well known. Data about them have been collected from ships' drifts (Harris 1964), moored current buoys close to the coast (Zwamborn 1969), moored current meters (Zwamborn 1969, Pearce 1973), ship-borne current meters, and airborne radiation thermometry (Pearce 1973). Summaries of the data have been made by Pearce (1973, 1977).

Generally speaking, this is a region where the coastline and the mean axis of the Agulhas Current separate. It is to be expected that, because of entrainment of coastal waters in the main current, a cyclonic circulation will be formed, though its existence and intensity will depend on the actual direction and distance offshore of the main current axis. The latter will depend upon the stability of the current and whether meanders are present. Upon this variable regime the local wind stress or atmospheric pressure effects must be superimposed.

Over the region as a whole the drift data from ships on course between 2 km off Cape St Lucia and 13 km off Port Durnford show the following percentage frequencies of current direction (Harris 1964).

Table 2. Current directions (ships' drifts), Cape St Lucia to Port Durnford.

No. of observations	% north going	% south going	% slack
33	15	82	3

The evidence from the current measurements made by moored current buoys at Richards Bay and ship-borne current meters in this region have been summarized in Figure 5.5 of Pearce's thesis (Pearce 1977). This diagram is reproduced in Figure 7, which shows the percentage frequency of north- and south-going currents (apparently neglecting nil current conditions) with distance from the shore.

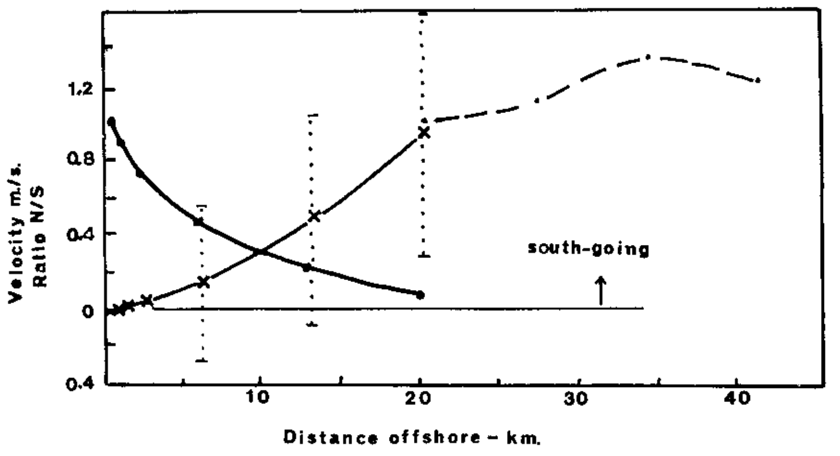


Figure 7. 'Cross-shelf profiles of mean alongshore current components (crosses) from moored buoys and 'Meiring Naude' measurements, and the ratio of the frequencies of northerly to southerly flow N/S (circles). The bars denote the standard deviations about the mean speeds. The dashed curve is the mean velocity profile from 6 long lines. The velocity component is positive to 208°T.' (After Pearce 1977 with permission).

Selected values are as follows -

Table 3. Current directions off Richards Bay.

Approx. distance from the shore km	north-going %	south-going %
0,6	50	50
5	35	65
10	23	77
15	12	88
20	3	97

The tendency for south-going currents to gain increasing dominance with distance offshore is apparent. Pearce (1977) also reports that north-going currents near the shore are more frequent when the axis of the main current is further offshsore. Furthermore, he finds (from the moored buoy data) that the north-going currents near the shore are in sympathy with the wind approximately 80-90% of the time.

The above discussion has only treated those current directions which are broadly north- or south-going i.e. approximately parallel to the shore. There are, however, occasions when the current directions are directed shorewards or offshore. The percentage of these is shown in Figure 8.

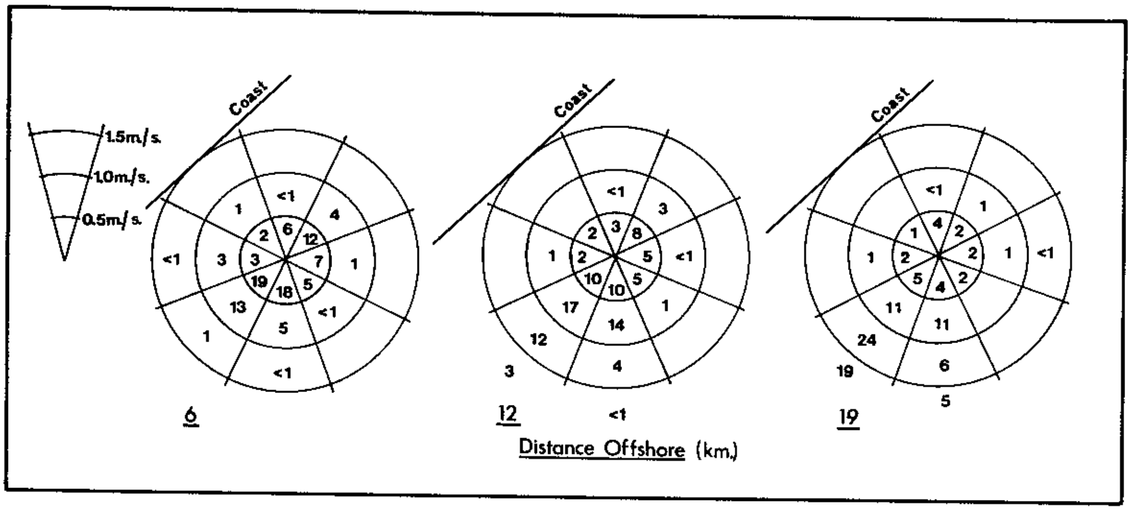


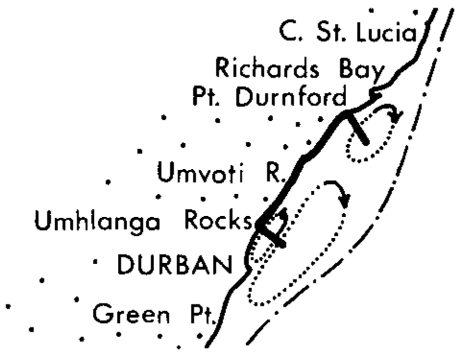
Figure 8. Current roses for indicated distances offshore off Richards Bay. (Data from Pearce 1973 with permission).

The tendency for the offshore motions to be greater nearer the shore is interesting, and would be consistent with the concept of entrainment in the main current.

Figure 8 also shows the distribution of current velocities. Confining attention to the data in the current rose nearest the shore, it appears that current velocities are generally less than 0,5 m s^{-1}, except for those south-going, a substantial number of which may be up to 1 m s^{-1}.

A feature of the inshore currents which is widespread on the Natal coast is the frequent reversing of current directions - the current direction reverses (south-going to north-going) and then returns (north-going to south-going). The former is almost invariably accompanied by the passage of an atmospheric low up the coast (falling pressure and south-westerly winds). With the re-establishment of high pressure (and northeasterly winds) the current direction reverts to south-going (Pearce 1973). Grundlingh (Pearce 1973) reports that low pressures move up the Natal coast at an approximate rate of 2-3 per week. Complete understanding of the way in which wind/pressure influences current regimes has not yet been established. North-going currents persist for a day or so (not more than 3) but south-going currents are more persistent (up to 7 days).

1.3 PORT DURNFORD TO UMHLANGA ROCKS



This region lies within the shallow bight between Durban and St Lucia. The shelf is wide and the mean axis of the Agulhas Current is some 50 km or more offshore. It is to be expected that the waters near the shore will not show much direct influence of the main current. Ships' drift data for currents within a few kilometres of the shore are as follows (Harris 1964):

Table 4. Current directions (ships' drifts), Port Durnford to Umhlanga Rocks.

	No. of observ= ations	% north going	% south going	% slack water
Port Durnford to Umvoti River	32	53	44	3
Umvoti River to Umhlanga Rocks	21	52	34	14

The sample is rather small, but there is a suggestion that the north-going currents may be slightly more frequent.

Measurements made closer inshore (about 800 m from the shore) by moored current buoys at Port Durnford and Umhlanga Rocks show the following current directions:

Table 5. Current directions, close inshore at Port Durnford and Umhlanga Rocks.

	% north going	% south going	% slack
Port Durnford*	42	43	15
Umhlanga Rocks**	37	63	not reported

* For December, January, July and August 1965/66. A wind vector equal to 1,4% of the wind speed has been subtracted (Natal Town and Regional Planning Commission and CSIR 1969).

** For March to May 1965 (CSIR 1965b).

At Port Durnford the current velocities indicated by the moored current buoys were low, seldom exceeding 0,3 m s^{-1}. The persistence of north-going and south-going currents was about 1-2 days and very rarely 4 (north-going currents being slightly more persistent than south-going).

At Umhlanga Rocks currents of more than one knot (about 0,5 m s^{-1}) were measured on six occasions out of 40 days. Offshore-onshore motions occurred on 2,5% of the observations. Persistence of both north- and south-going currents was seldom more than two days.

The tentative conclusions from these data are:

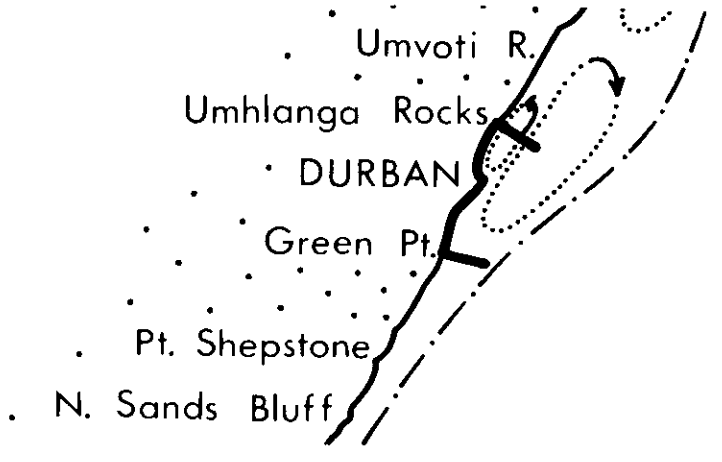
(a) close inshore at Port Durnford the currents are weak, without any preferred direction. No doubt this is associated with the shallow water and the prevalence of shoals in the vicinity;

(b) between Port Durnford and Umvoti River the percentage frequency of current directions is fairly evenly balanced. Possibly the Natal Gyre system is in two parts, and this region lies in a rather neutral zone. Winds may therefore be a determining factor; though wind resultants are not markedly longshore (Lundie undated).

(c) the section from the Umvoti River to Umhlanga Rocks is probably under the influence of the southern part of the Natal Gyre system, but currents are rather weak;

(d) at Umhlanga Rocks there is already an indication of the influence of the counter-current formed within the Durban Bight. South-going currrents are slightly predominant.

1.4 UMHLANGA ROCKS TO GREEN POINT



This is a region in which the coastal currents are very complicated - due in part to the large coastal discontinuity at Durban. South of Durban the currents within a few kilometres of the coast, are preponderantly north-going. As these flow past the Durban Bluff they induce a separation vortex between them and the shore - in the Durban Bight (see Figure 3). As a consequence of the anticyclonic circulation formed, the currents along the shore of the Bight are more frequently south-going - but there are many variations on this theme.

The Agulhas Current itself, off Durban, still has the mean position of its shoreward edge (the 1 m s^{-1} contour) at a considerable distance from the coast - of the order of 30-40 km (Pearce 1977). South of Durban the distance decreases.

Currents just north of Durban, as measured by moored current buoys (0,8 km offshore) are reported to be as follows (CSIR 1965b):

Table 6. Current directions, close inshore just north of Durban.

	No. of observ= ations	% north-going	% south-going
Umhlanga Rocks (20 km north of Bluff)	34*	37(1,5)	63(1)
Virginia Beach (15 km north of Bluff)	51*	41	59
Bel-Aire (10 km north of Bluff)	95**	28(1)	72(1-2)

* March to May
** January to June

The figures in brackets are rough estimates of the more frequent persistences of the current directions in days. The directions are clearly very changeable.

Further information about the circulation in the Bight has been reported by Anderson (1965), who used tracked floats to obtain his data. He notes at least five patterns. Four are depicted in Figure 9.

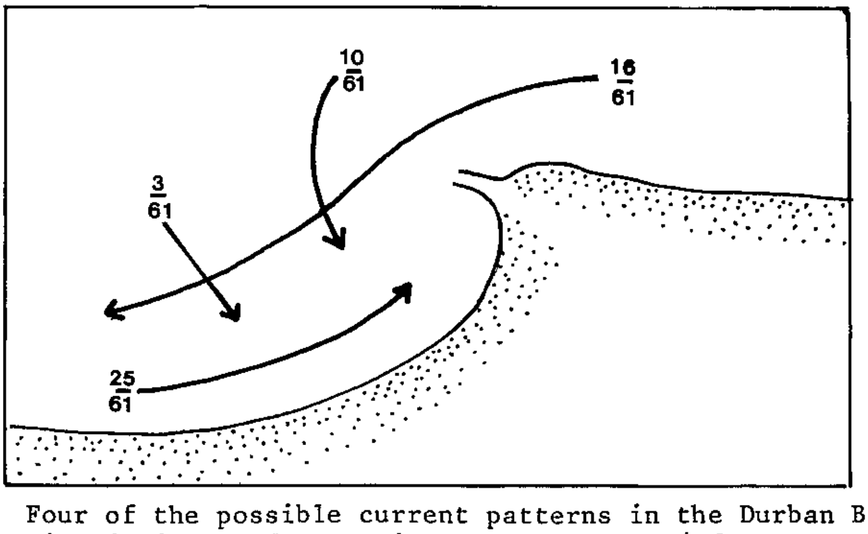


Figure 9. Four of the possible current patterns in the Durban Bight with indicated frequencies of occurrence (after Anderson 1965 with permission).

Between Durban and Green Point the distance offshore of the mean axis of the Agulhas Current, where the current's direction is virtually always south-going, remains considerable (30-40 km).

Figure 10 shows silt-laden water streaming round the Durban Bluff under conditions of a northeasterly wind. Figure 11 is referred to later.

Figure 10 Silt indicating current flow around Durban Bluff (photograph from CSIR Laboratories Durban)

Figure 11 Silt marking northward flow of nearshore currents under wave action and contrary flow of coastal currents. (Photograph from CSIR Laboratories Durban).

Inshore at Durban and southwards there have been intensive studies from which the main conclusions about current directions are as follows:

Table 7. Current directions, inshore at Durban.

	No. of observ= ations	% north-going	% south-going	% no current
(a) from ships' drift data collected within about 2 km of coast, 1959-1964 (Harris 1964):				
Cooper Light (Durban) to Green Point	97	38	34	28
(b) from moored current buoys, January-March 1963, about 1 km offshore (CSIR 1963):				
Durban (SAS Bluff)	146	48	52	
Amanzimtoti (25 km south of Durban)	81	60	40	
Umkomaas (47 km south of Durban)	86	44	56	
(c) from moored current buoys 1 km off Umlaas Canal, May 1963-January 1964 (Anderson 1965)				
Durban (Umlaas Canal)	123 days	63*	30	7**
(d) tracked floats between 1-5 km offshore, June 1962-July 1963 (Anderson 1965):				
Durban (Bluff)	107	45	36	19
Durban (Umlaas Canal)	82	49	28	23

* During May and June the current was north-going 23 out of 25 days.
** Onshore or offshore.

The reversing nature of the currents off this region of the coast is interesting and has been intensively studied, especially off Durban (Pearce 1977). The generalised regime suggested by Anderson (1965) is that the current 3-8 km offshore flows northwards for three days, then reverses, flows southwards and reverses again, each of the latter processes lasting a day - making the periodicity six days. Closer inshore the reversing process takes only a few hours, and the north-going and south-going elements of the regime are extended to four and two days respectively. The duration of the elements of the reversing process are in practice very variable. In general the current direction reverses over the whole depth of the water column.

There is some reason to believe that the current reversals are associated with the winds and atmospheric pressure systems. North-going currents are generally associated with north-going winds or with pressures high at Durban compared with those at St Lucia. Local topography may cause departures from this rule. The meandering of the Agulhas Current and its effect on the induced vortex in the cyclonic shear region between it and the coast are no doubt other factors which are not so wind/pressure dependent. Wind roses for Durban are shown in Figure 12.

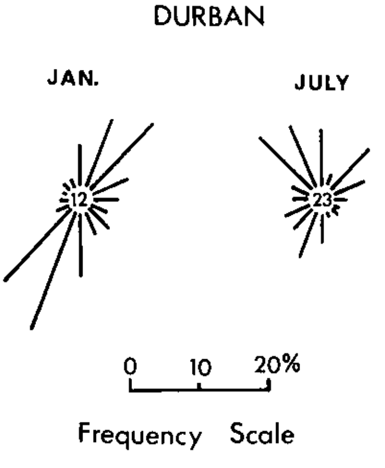


Figure 12. Wind roses for Durban (Royal Navy and South African Air Force 1942).

Figure 13 shows the frequency of current velocities and directions at 1, 3 and 5 km off Durban (Umlaas Canal) in the form of roses. They have been constructed from the table in Figure 11 of Andersons's report (1965). Evidently there is a decrease in the predominance of north-going currents with distance offshore. This trend is illustrated in Figure 14 where the ratio of the percentage frequency of north- to south-going currents has been plotted against distance offshore. The ratios for distances greater than 5 km (average of two lines) are taken from Pearce (1977) who reports that the ratio is about one at 15-20 km, and that it has been estimated by Anderson that the currents at about 35 km may be almost exclusively south-going. The graph in Figure 14 must be regarded as rather tentative, but it is consistent with the concept of a vortex (the Natal Gyre) in the mean circulation between Durban and the Agulhas Current. The equivalent curve for Richards Bay has been included in Figure 14 for comparison.

Onshore currents between $\pm$ 45° to the normal to the coast occur with the following percentage frequency:

Table 8. Onshore currents at Durban (percentage frequency).

Distance offshore km	% Durban (Bluff)	% Durban (Umlaas)	% Umkomaas
1	12,5	5	15,4
2	10	12,6	13,3
3	8	12	14,3

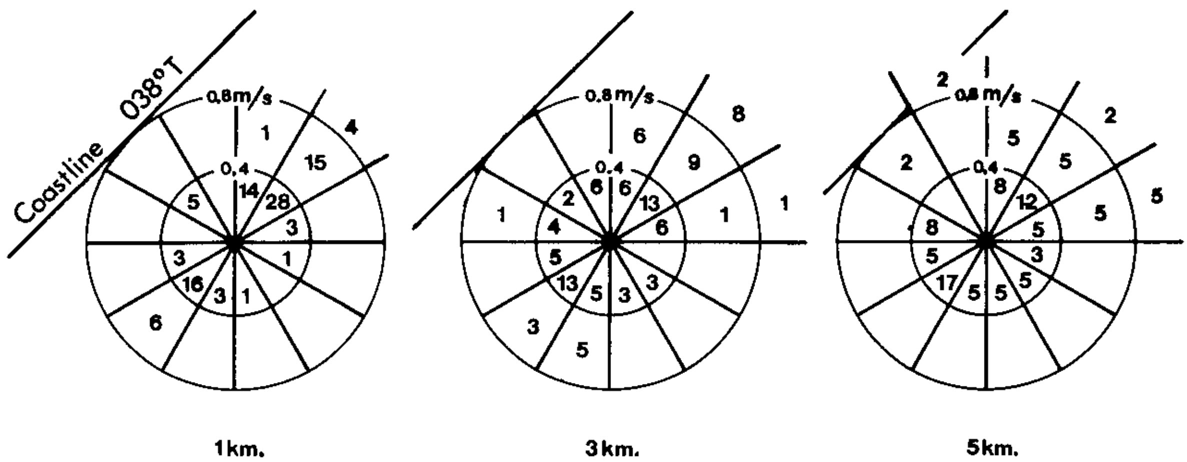


Figure 13 Current roses for indicated distances off Durban (Umlaas Canal) (data from Anderson 1965 with permission)

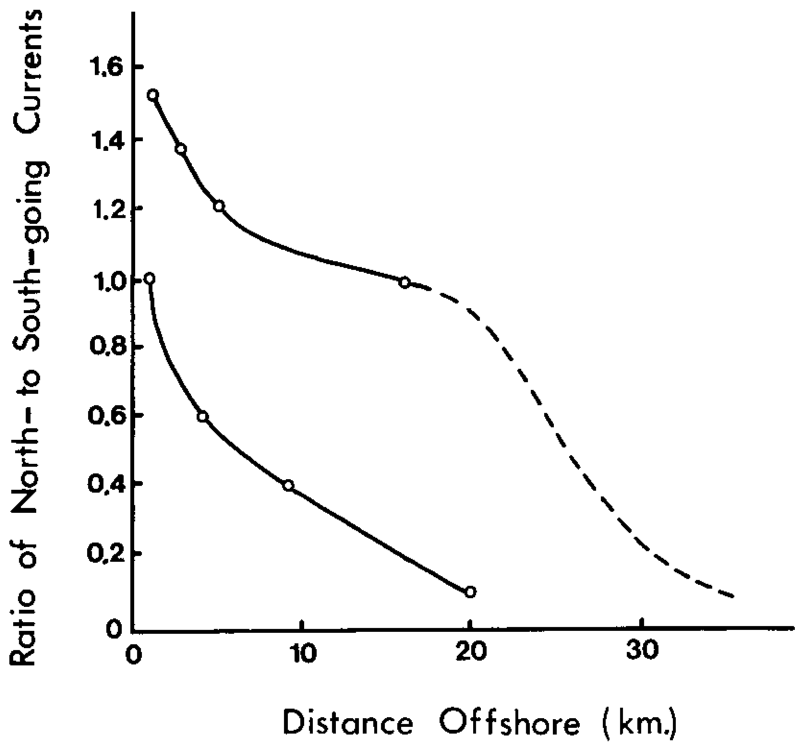


Figure 14 Approximate mean ratio of frequencies of north- to south-going current direction, with distance offshore for Durban (upper) and Richards Bay (lower).

Umkomaas

Measurements made close to Green Point at Umkomaas (Stavroupoulos 1964) were obtained mainly from tracked floats. The results are shown in Table 9 and in the current roses (Figure 15) which cover the period May 1962 to April 1963.

Table 9. Surface currents off Umkomaas.

Distance offshore km	No. of observ= ations	north-going %	south-going %	onshore %	slack water %
1	71	42	51	7	0
2	66	39	43	9,1	1,5
3	68	47	50	1,5	1,5
4	52	50	44	3,8	1,9
5	28	40	50	7,1	0

There is a slight but hardly significant preponderance of south-going currents and no clear trend of the ratio of current directions with distance offshore.

The current roses also give the frequency of occurrence of surface current velocities with directions, and indicate a tendency of increasing velocity with distance offshore. This tendency is illustrated in Figure 16 (Stavropoulos 1964)

Beesley (personal communication 1978) has recently made observations of the surface currents at Umkomaas over a period of three years. His sample is therefore a large one. He found that the north-going flow was the more frequent.

Limited data from moored current buoys (Stavropoulos 1964) suggest that the current direction reverses frequently. For 50% of the data the persistance of direction is less than a day, and for 70% less than two days. For 5% it was 4-5 days.

During the study (Stavropoulos 1964) a limited number of measurements were made of bottom currents (about 0,3 m from the sea floor) using a Carruthers jelly bottle. Current velocities were usually 0,1-0,2 m s^{-1} with an occasional value of up to 0,3 m s^{-1}. Directions at 5 km offshore were mainly parallel to the shore, and there was a suggestion that directions were more variable closer inshore. The data are for May to August 1962.

The conclusions to be drawn from the Umkomaas data are that once again the surface currents within a few kilometres of the shore are mainly parallel to the coastline, and that the direction alternates frequently. As will be evident from the next sector, Umkomaas is situated near to a transition point in the current system, where the Natal Gyre is giving way to a more direct influence of the Agulhas Current.

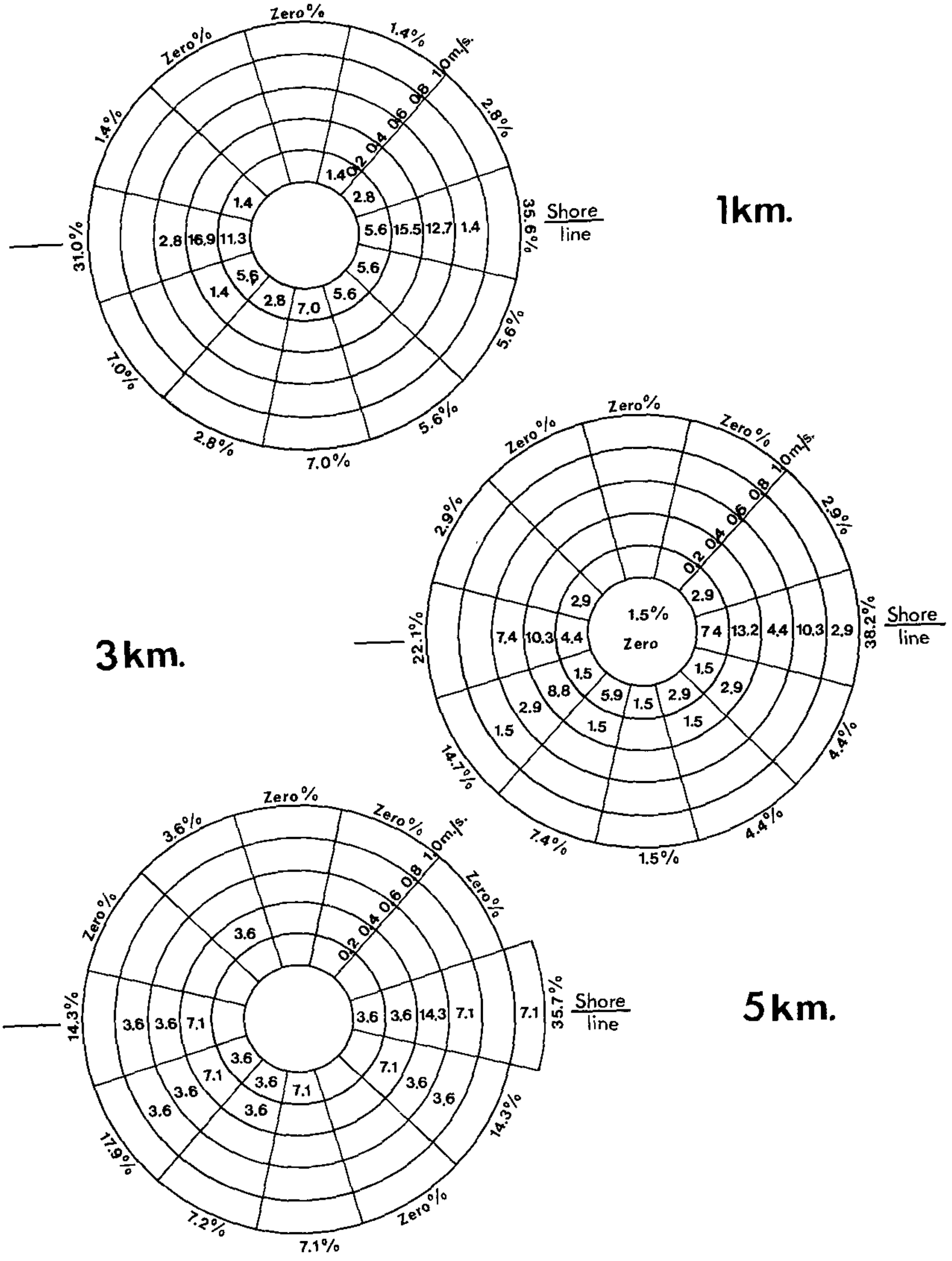


Figure 15 Current roses for 1, 3 and 5 km off Umkomaas (Stavropoulos 1964 with permission).

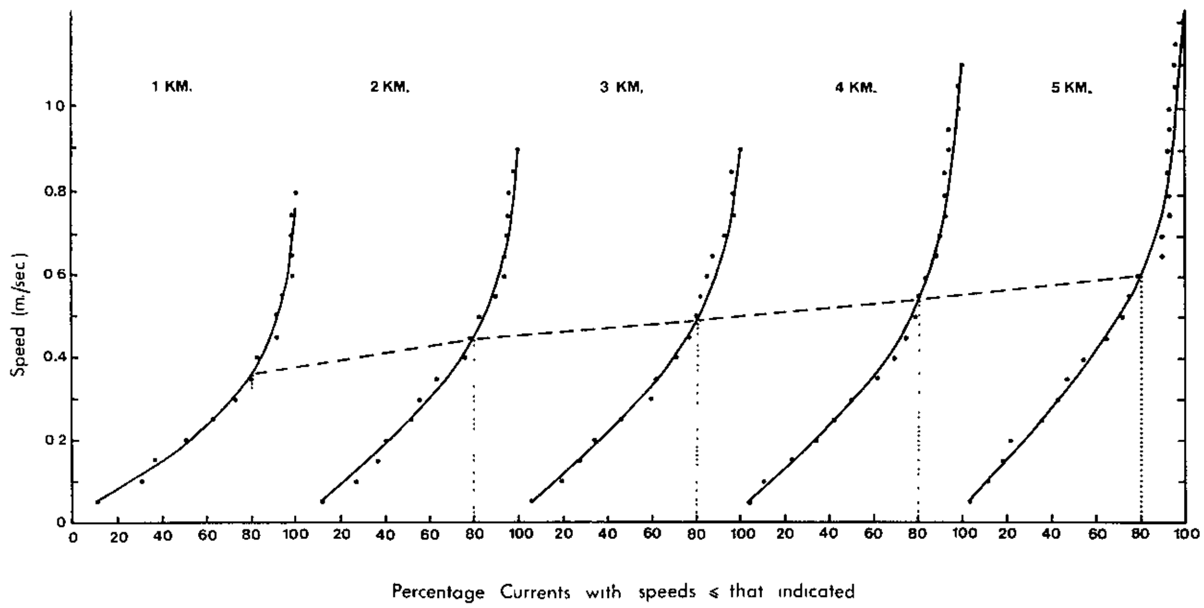


Figure 16 Percentages of currents off Umkomaas having velocities less than or equal to those indicated, for 1-5 km offshore. Note increase in velocity with distance from the shore. (Stavropoulos 1964 with permission).

Wave Currents

Currents generated by surface gravity waves have been studied off a number of beaches in this sector, and their characteristics are fairly clear. Further, the relatively straight coastline and hence similarity of long stretches of the coast, enable findings to be readily transferred to circulations off beaches not previously studied.

Broadly speaking the surf zones are not wide - perhaps ordinarily about 100-200 m. The circulations can be divided into three main types which are illustrated in Figure 17.

In the symmetrical cellular type of circulation with breakers parallel to the shore, longshore currents about 30 m wide will flow in opposite directions (within a cell) with velocities of 30-50 cm s^{-1} and feed into rip currents flowing out at right angles to the coast. These rip currents which are also about 30 m wide, and separated by about 500 m, carry surf zone water out to a distance of several surf widths beyond the first breakers. Their flow is intermittent. Between the rip currents, water is advected shorewards under wave action. The whole forms a cell of circulation. Exchange with water seaward of the cell is slow.

Another type is the alongshore system which arises because of obliquity of breaker approach to the shore. The longshore current so generated is unidirectional (down wave) and continuous. Velocities of over 1 m s^{-1} have been measured. At headlands these currents often slant out seawards. The third type, the asymmetrical cellular circulation, is intermediate between the two others described.

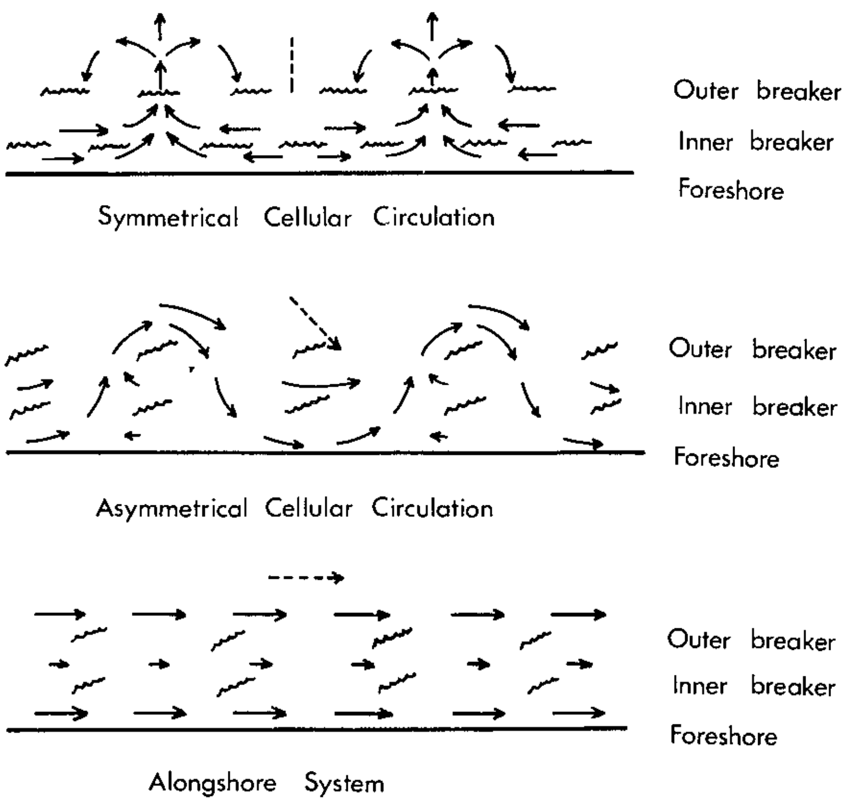


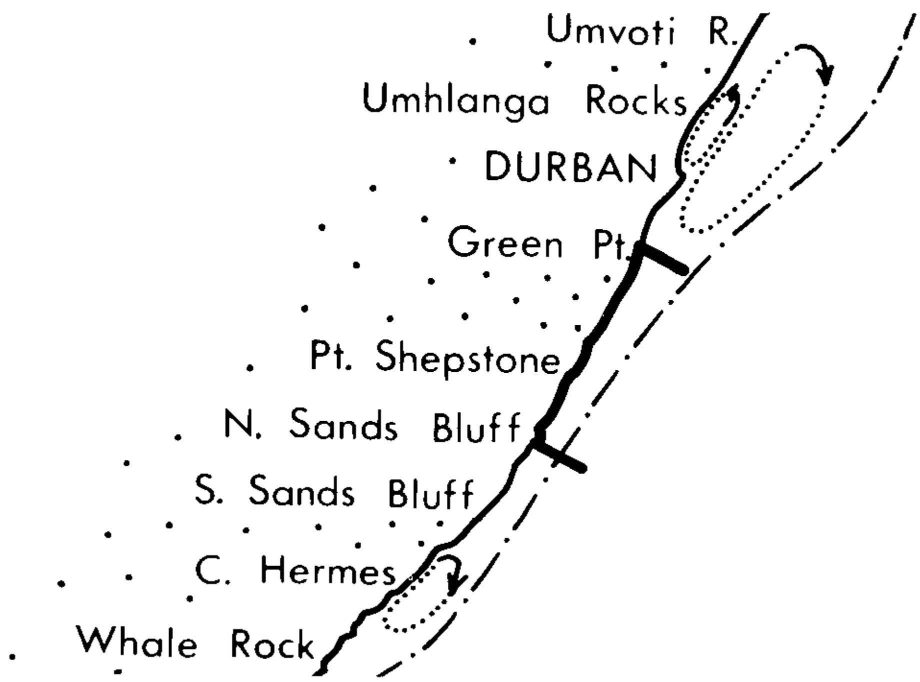
Figure 17. Schematic diagrams of three types of nearshore circulations (Natal Town and Regional Planning Commission and CSIR 1969 with permission)

Some indication of the frequency of occurrence of the 3 circulation types is to be had from 53 observations at Virginia Beach just north of Durban. The asymmetrical type occurred on 52% of the occasions, the symmetrical 38% and the longshore 10% (CSIR 1965a).

Nearshore circulations are independent of the currents in deeper water. They depend largely on the wave characteristics, but may be influenced by the wind. Figure 11 is a photograph taken off Durban Harbour and shows river silt near the surf, being moved northwards by oblique waves, and feeding into a south-going coastal current after reaching the end of the pier.

Since the nearshore drift along the coast is generated by wave obliquity, its net direction of flow will depend on the angle which the incident waves make with the coastline. On a coast with marked coastal discontinuties where the shoreline changes direction, the direction of drift may be locally determined. On the Natal coast however, in the sector under consideration, the coast is relatively straight, and there is some evidence that generally the net drift is from south to north.

1.5 GREEN POINT TO NORTH SANDS BLUFF



In this region the depth contours converge on the coast, and the Agulhas Current directly influences the coastal water, the influence increasing in the direction of North Sands Bluff. The growing tendency for south-going currents to dominate is illustrated by the following ships' drift data measured within a few kilometres of the shore (Harris 1964):

Table 10. Current directions (ships' drifts), Green Point to North Sands Bluff.

	No. of observ= ations	% north- going	% south- going	% slack water
Green Point to Port Shepstone	119	18	63	19
Port Shepstone to North Sands Bluff	111	9	80	11

The percentage frequency of south-going currents at North Sands Bluff is once again as high as it was at Cape St Lucia, and it is assumed that the influence of the Natal Gyre has abated. The variation of velocity with distance offshore is shown in Figures 18 and 19.

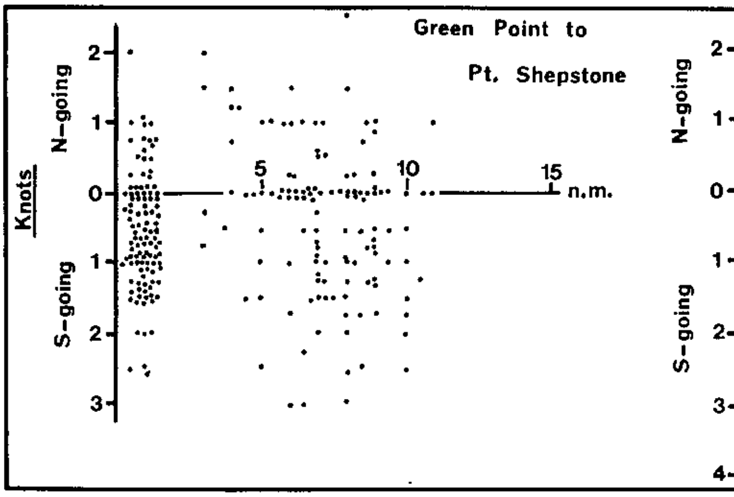


Figure 18. Distribution of current velocity with distance off-shore between Green Point and Port Shepstone (data from Bray 1955-1961).

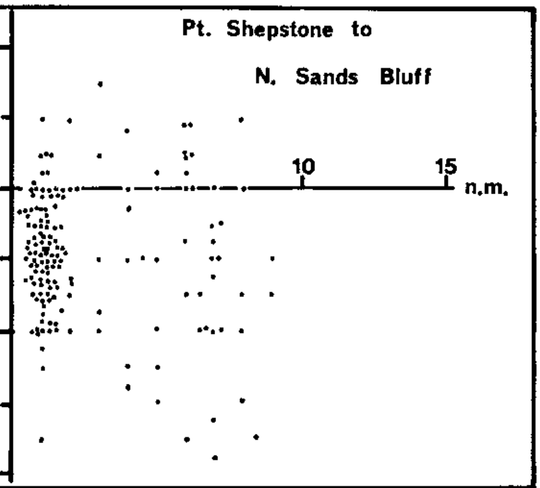


Figure 19. Distribution of current velocity, with distance off-shore between Port Shepstone and North Sands Bluff (data from Bray 1955-1961).

Notable is the high proportion of slack water between 5 and 10 miles offshore in the Green Point - Port Shepstone region. This of course is only in respect to currents parallel to the coast. Of particular interest therefore are the direct current measurements made by Schumann (personal communication 1978) off Umzinto (between Green Point and Port Shepstone). His results are yet to be published but a time series during June - August 1977, shows currents flowing towards the shore while simultaneous measurements made off Port Edward (near North Sands Bluff) and near Durban show currents going respectively southwards and northwards. Schumann's measurements were made at 45 and 155 m in 195 m of water at Umzinto, at 22 m in 25 m at Port Edward, and at 26 in 29 and 70 in 245 m of water near Durban.

1.6 SUMMARY OF SECTOR I PTA DE OURO TO NORTH SANDS BLUFF

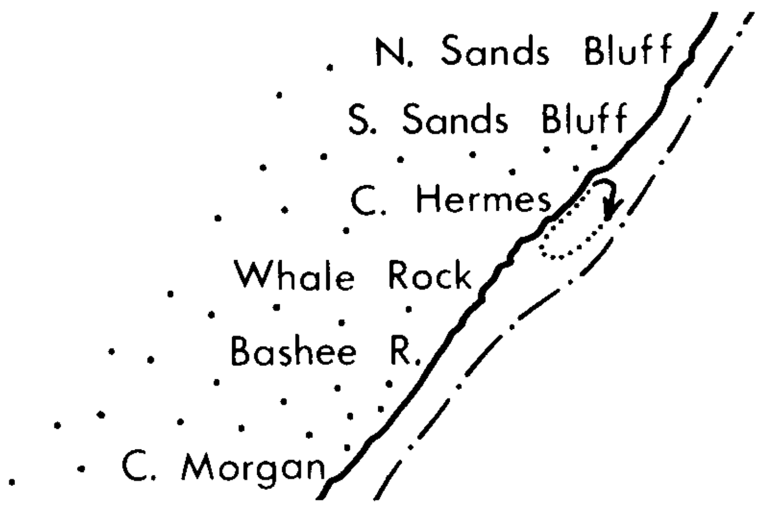
The circulation in sector I as suggested by Pearce (1977) seems to fit the known facts satisfactorily. Between Pta de Ouro and Cape St Lucia the shelf is narrow and the currents within a few kilometres of the shore are strongly influenced by the Agulhas Current. South of St Lucia the coast and the current separate and it is not until south of Green Point that the Agulhas

Current re-asserts its influence. Between these two regions there is, at least at times, a counter flow constituting part of the Natal Gyre. Inshore currents are more frequently north-going between Green Point and Durban. Just north of Durban there is a counter-counter flow caused by the coastal discontinuity of the Durban Bluff. Northwards up to Richards Bay the currents tend to be weak and may well be mainly wind driven.

The main difficulty in making current predictions in this sector is the lack of understanding of the circumstances which control the oscillation onshore and offshore of the Agulhas Current and how this displacement activates the Natal Gyre. When the main current meanders offshore the coastal currents probably follow the wind fairly closely. Better understanding of the precise response of the water to a variable wind stress is also required.

The surf zone and therefore the nearshore circulation on this part of the coast is comparatively narrow - probably less than a kilometre. The wave-driven currents are thus confined to a narrow strip. Because the coast is relatively uniform, strong longshore currents in response to oblique waves can be quite an important feature.

SECTOR II NORTH SANDS BLUFF TO CAPE MORGAN



The dominance which the Agulhas Current imposed on the system southwards of Port Shepstone is sustained in the sector stretching to Cape Morgan, (north of East London) except in the vicinity of the embayments at Cape Hermes (Port St Johns) and Cape Morgan where there is a local tendency for south-going currents to be less frequent (see Figure 20). Further offshore however, at about 10 km distance, the currents are nearly always south-going.

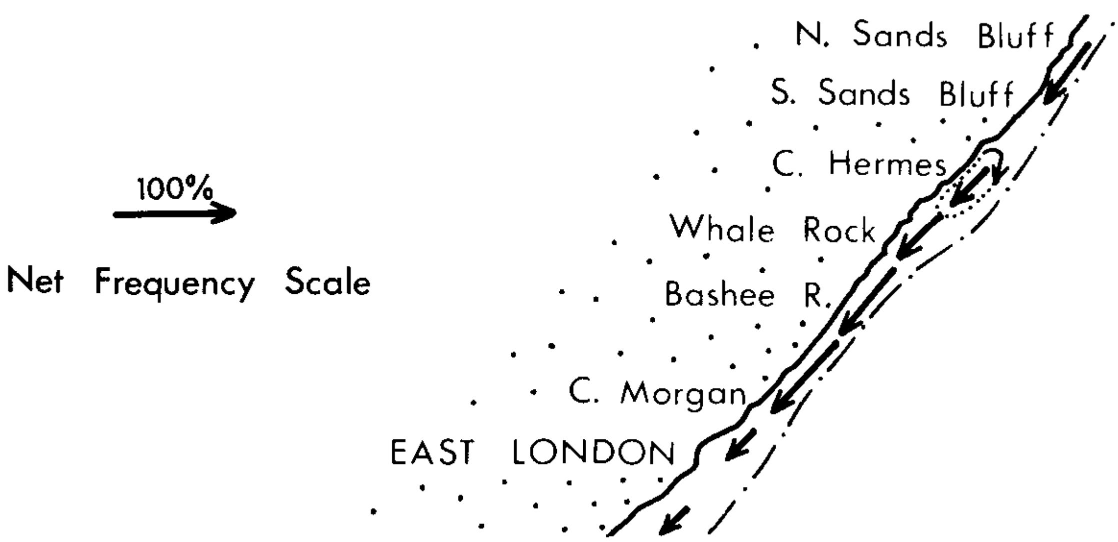
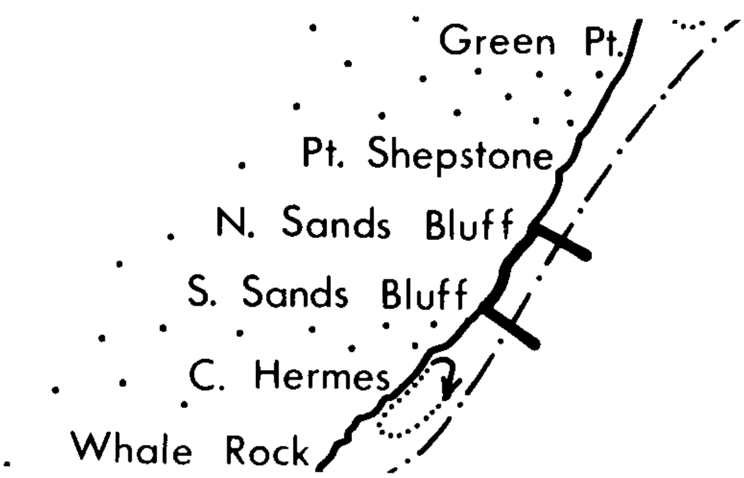


Figure 20. Net percentage frequency of current direction (data from Bray 1959-1964) at 2 km offshore (arrow length is proportional to frequency).

There is evidence from satellite infra-red imagery that, although the depth contours run approximately parallel to the shore, the trajectory of the Agulhas Current may be sinuous. This results in oscillatory on- and offshore modes of the current, and it is possible that the occurrence of north-going coastal currents are associated with the offshore mode of the regime.

Another factor almost certainly influencing the current regime is the confluence of another tributary with the Agulhas Current off this section of the coast. Its contribution is probably intermittent, and while the exact way in which it affects the system is not yet understood, it would be surprising if the wave trajectory is not in some way asssociated with it.

2.1 NORTH SANDS BLUFF TO SOUTH SANDS BLUFF



The ships' drift data of measurements made within 2 kms of the coast are as follows (Harris 1964):

Table 11. Current directions (ships' drifts), North Sands Bluff to South Sands Bluff.

No. of observations	% north-going	% south-going	% no current
113	10	76	14

The south-going Agulhas Current appears to be the dominating influence. The distribution of current velocity with distance offshore is shown in Figure 21. This includes the results of 9 cruises carried out by the CSIR in April 1974 to February 1975 off Port Edward near North Sands Bluff. Currents were measured directly (Lundie 1976).

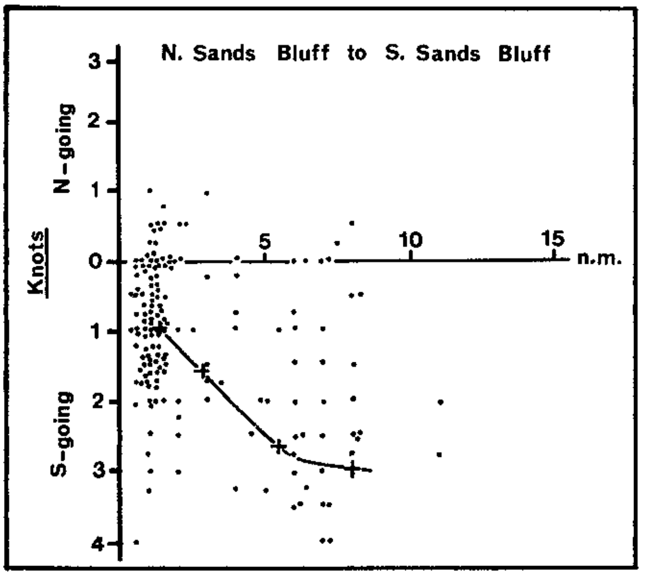


Figure 21. Distribution of current velocity with distance offshore (data from Bray 1955-1961), between North Sands Bluff and South Sands Bluff. Dots are ships' drift observations. Full line is the 0-100 m depth-averaged velocity parallel to the coast measured by the CSIR (Carter 1977).

Other ships' drift data analysed by Tripp (1967) are set out below. They are not strictly comparable with the above, because they cover a larger region and 3% of the wind has been subtracted. The mean velocities quoted have been arrived at by taking the weighted mean of the seasonal averages reported.

Table 12. Current directions (ships' drifts, wind subtracted), Port Shepstone to South Sands Bluff (percentages as in Figure 22).

	S	SI	NI	N	NO	SO	Slack
No. of observations	36	9	6	10	3	1	9
Mean velocity (m s^{-1})	0,60	0,35	0,23	0,35	0,20	0,16	

The high proportion of south-going currents between North Sands Bluff and South Sands Bluff is indicative of the Agulhas Current approaching close to the coast in this region. There is also the biological evidence reported by Carter (1977), that the neritic community (i.e. over the shelf) is more restricted near Port Edward than for example, at Durban.

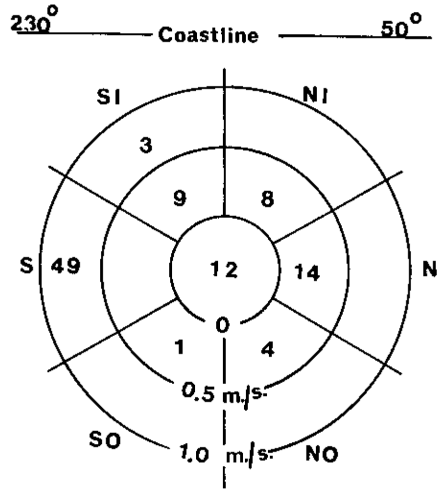
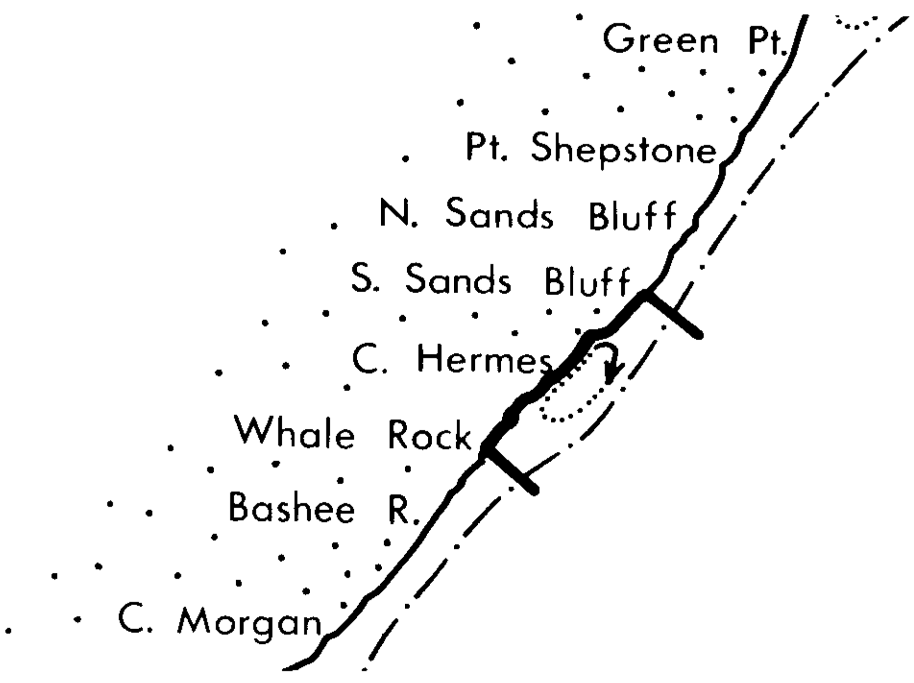


Figure 22. Current rose - wind subtracted - for Port Shepstone to South Sands Bluff - percentages (data from Tripp 1967).

2.2 SOUTH SANDS BLUFF TO WHALE ROCK

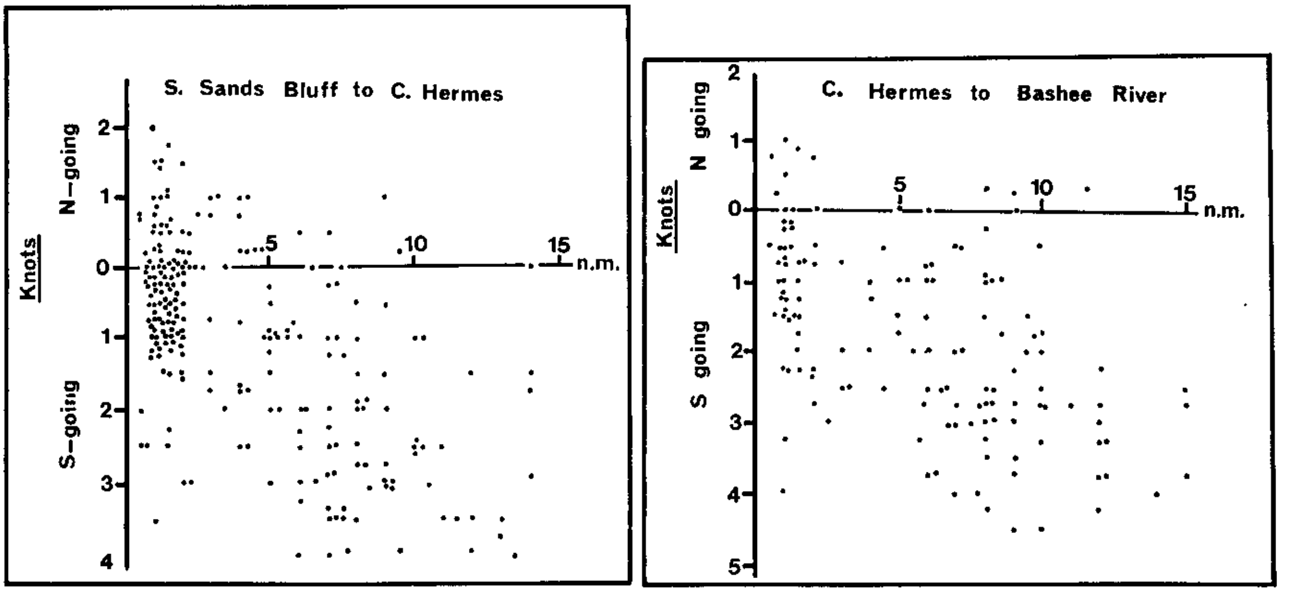


The Agulhas Current remains a direct influence, but this region includes a slight coastal discontinuity - a shallow embayment, between South Sands Bluff and Whale Rock, which is apparently sufficient to affect the currents near the shore. The ships' drift data (Harris 1964) within 3 km of the coast are as follows:

Table 13. Current directions (ships' drifts), South Sands Bluff to Whale Rock.

	No. of observ= ations	% north- going	% south- going	% slack water
South Sands Bluff to Cape Hermes	122	28	57	15
Cape Hermes to Whale Rock	91	23	67	10

The increase, compared with the regions to the north, of the north-going currents is notable, and arises perhaps because of a cyclonic circulation set up as the Agulhas Current separates from the coast just south of South Sands Bluff. The distribution of velocities with distance offshore is given in Figures 23 and 24.



Figures 23 and 24 Distribution of velocity with distance offshore (data from Bray 1955-1961) between (Figure 23) South Sands Bluff and Cape Hermes and (Figure 24) Cape Hermes and Bashee Point.

For the northern part of this region (South Sands Bluff to Cape Hermes) data about the direction and velocity of the currents within a few kilometres of the shore are reported by Tripp (1967) (as before it is noted that he reduced the current vectors by 3% of the wind velocity).

Table 14. Current directions (ships' drifts, wind subtracted), South Sands Bluff to Cape Hermes (percentages as in Figure 25).

		S	SI	NI	N	NO	SO	Slack
No. of observations	53	21	2	4	18	-	1	7
Mean velocity (m s^{-1})		0,70	0,24	0,41	0,42	-	0,35	

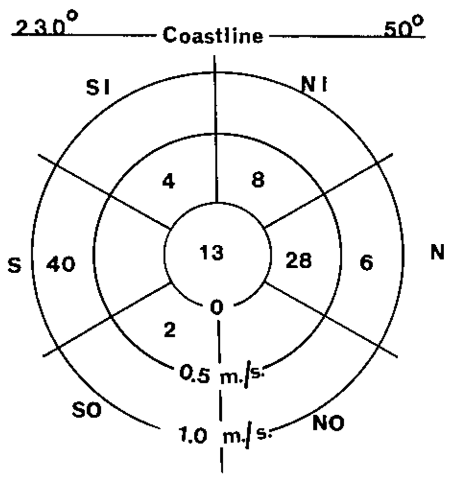


Figure 25. Current rose - wind subtracted - for South Sands Bluff to Cape Hermes - percentages (data from Tripp 1967).

Tripp's data (1967) cover Cape Hermes to the Bashee River, which bridges this region and the next. His analysis is therefore included here, and is as follows:

Table 15. Current directions (ships' drifts, wind subtracted), Cape Hermes to Bashee River (percentages as in Figure 26).

	Total	S	SI	NI	N	NO	SO	Slack
No. of observations	72	35	6	3	16	-	1	11
Mean velocity (m s^{-1})		0,68	0,27	0,42	0,35	-	0,2	

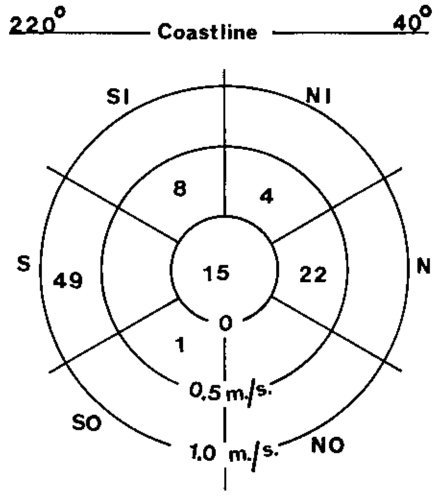
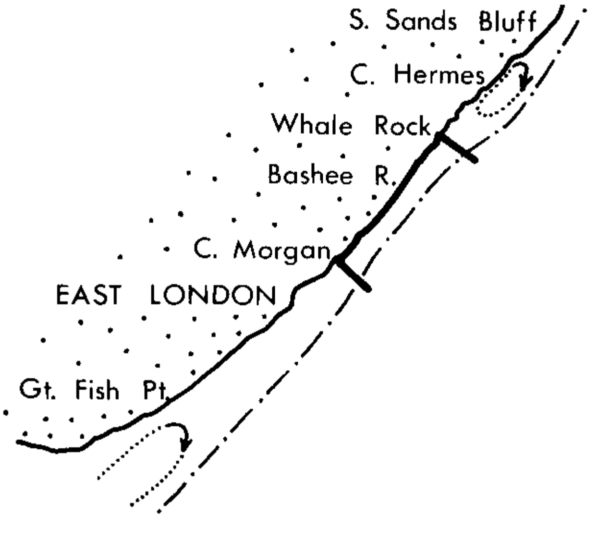


Figure 26. Current rose - wind subtracted - for Cape Hermes to Bashee River - percentages (data from Tripp 1967).

2.3 WHALE ROCK TO CAPE MORGAN



The dominance of the south-going currents near the shore is again established after Whale Rock, and is sustained until Cape Morgan. The following drift current data (Bray 1959-1964) (measured within 3 km of the coast) support this view (Table 16)

Table 16. Current directions (ships' drifts), Whale Rock to Cape Morgan.

	No. of observ= ations	% north-going	% south-going	% no current
Whale Rock to Bashee Point	87	13	78	9
Bashee Point to Cape Morgan	113	9	80	11

The distribution of velocity with distance from the shore is given in Figure 27.

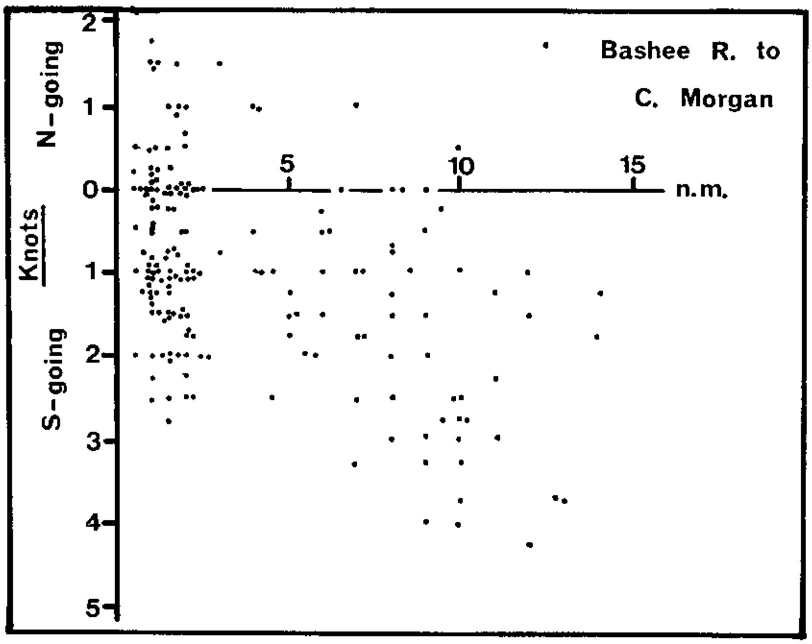


Figure 27. Current velocities with distance offshore (data from Bray 1955-1961) between Bashee Point and Cape Morgan.

Tripp's data for the latter or southern part of the region are as follows:

Table 17. Current directions (ships' drifts, wind subtracted) Bashee to Cape Morgan (percentages as in Figure 28).

	Total	S	SI	NI	N	NO	SO	Slack
No. of observations	62	36	7	7	5	-	2	5
Mean velocity (m s^{-1})		0,68	0,42	0,29	0,72	-	0,49	

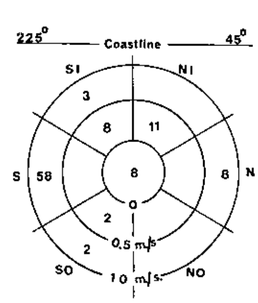


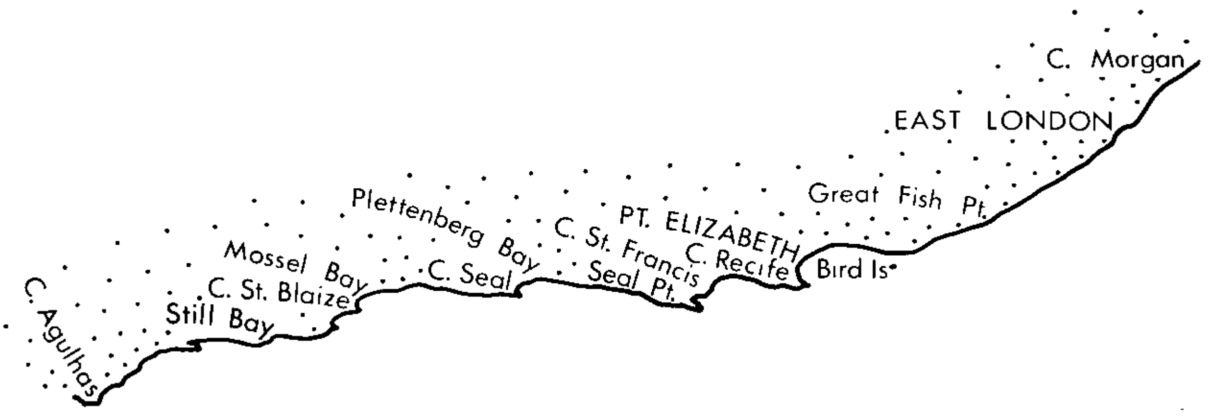
Figure 28. Current rose - wind subtracted - for Bashee Point to Cape Morgan - percentages (data from Tripp 1967).

2.4 SUMMARY SECTOR II NORTH SANDS BLUFF TO CAPE MORGAN

In this sector the shelf is narrow and the Agulhas Current is found quite close to the shore. The currents 5-10 km offshore are almost exclusively south-going and may reach very high velocities - 3 knots being common and 5-6 knots have been reported.

Currents within 2-3 km of the shore are predominantly south-going having their highest percentage frequency of occurrence between North Sands Bluff and South Sands Bluff, and between Whale Rock and Cape Morgan. There is a suggestion that the coastal discontinuity between South Sands Bluff and Cape Hermes causes an increase in the frequency of north-going currents. Velocities of the inshore currents may attain quite high values - the south-going ones reaching 3,4 knots on occasions. Slack water is comparatively rare (9-15%). Shoreward directed currents ($\pm$ 60^{o} to the perpendicular to the coast) are infrequent (about 12%) except at either end of the sector where they rise to 20%.

SECTOR III CAPE MORGAN TO CAPE AGULHAS



Downstream of Cape Morgan the Agulhas Current gradually separates from the coast - following the sea floor depth contours - until at Cape Agulhas it is of the order of 350-400 km distant from the shore. Inshore of it the Agulhas Bank, a shallow shelf of some 100 m mean depth, widens accordingly. As the Agulhas Current separates from the coast its upper layers are no longer restrained by a 'western' boundary and assume the properties of a jet which is rather unstable. The trajectories of this warm jet are clearly visible in NOAA satellite infrared images. A random selection of these, shown in Figure 29 indicates the variability of the paths followed, sometimes relatively straight and sometimes deflecting sharply offshore (the actual image for 76.11.30 is reproduced in Figure 30). It will be noted that there are occasions when current branches move in over the shallow shelf towards the shore - perhaps especially in the region between Cape St Francis and Mossel Bay. There is also the evidence from a satellite drifter which came ashore just east of Cape Agulhas. Its trajectory (No. 1116) is shown in Figure 48.

At the eastern (Port Elizabeth) end of this section one may expect to find entrainment of coastal waters in the Agulhas Current jet, with a tendency for vortices to form over the shelf.

In addition to the intrusion of the Agulhas Current over the shelf, the winds appear to have an important influence on the currents in parts of this sector. Following the account given in 'Weather on the Coasts of Southern Africa' (Royal Navy and South African Air Force 1942), it is noted that this part of the coast is subject to strong winds at all seasons of the year and that the prevailing winds are generally parallel to the coast. The 'Southeaster' well known on the southwest coast in the summer, affects the coast as far as Mossel Bay, but does not often extend to Port Elizabeth. At East London - perhaps the windiest place on the coast - the prevailing winds are northeast, southwest.

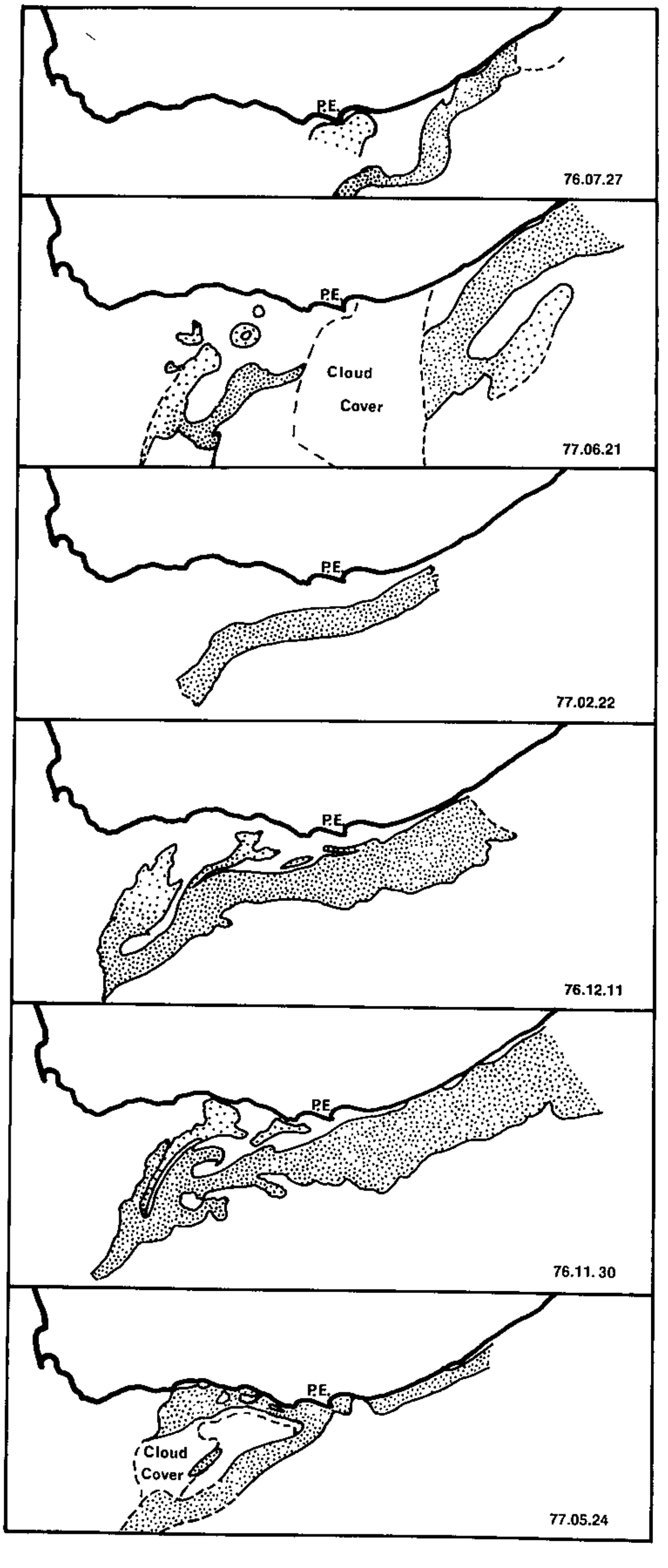


Figure 29. Sketches from NOAA infrared images of Agulhas Current trajectories. Warmer water dotted.

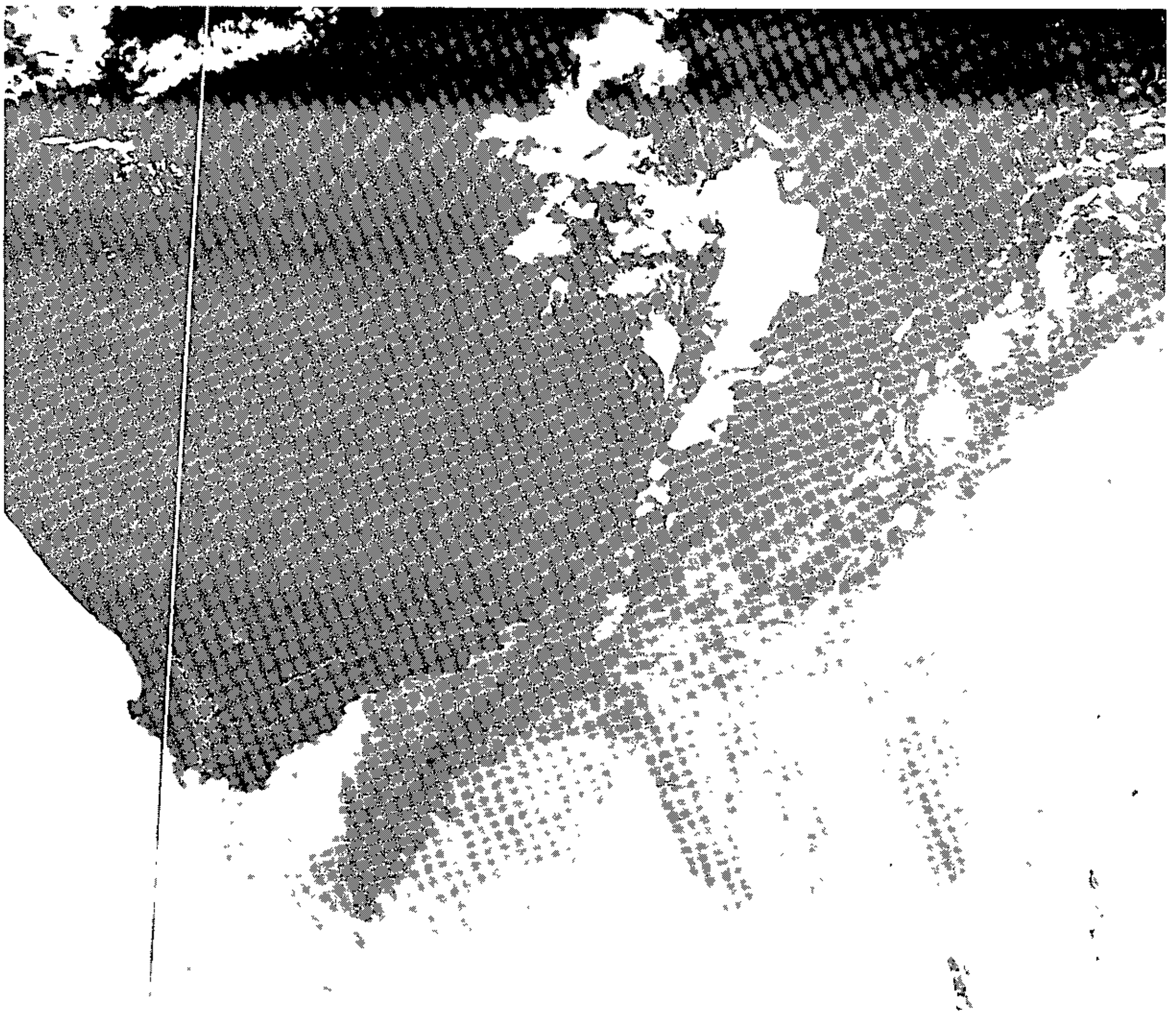


Figure 30. NOAA infrared satellite image showing Agulhas Current separating from the coast at Port Elizabeth. Elements of warmer water (darker grey) have invaded the Agulhas Bank, nearly as far west as Mossel Bay. Image should be tilted clockwise for true north - south orientation.

The main difference between winter and summer between Cape Agulhas and Port Elizabeth, is the higher frequency of easterly winds in the summer season. The westerly winds show little seasonal variation apart from a tendency to become south-southwesterly in the summer - an onshore wind.

Wind diagrams for Cape Agulhas, Port Elizabeth and East London, for December to February and June to August are given in Figure 31. These have been constructed in terms of miles of wind, calculated as the product of frequency and velocity. The tacit assumption that percentage frequency of occasions is equivalent to percentage frequency of time is not necessarily true however.

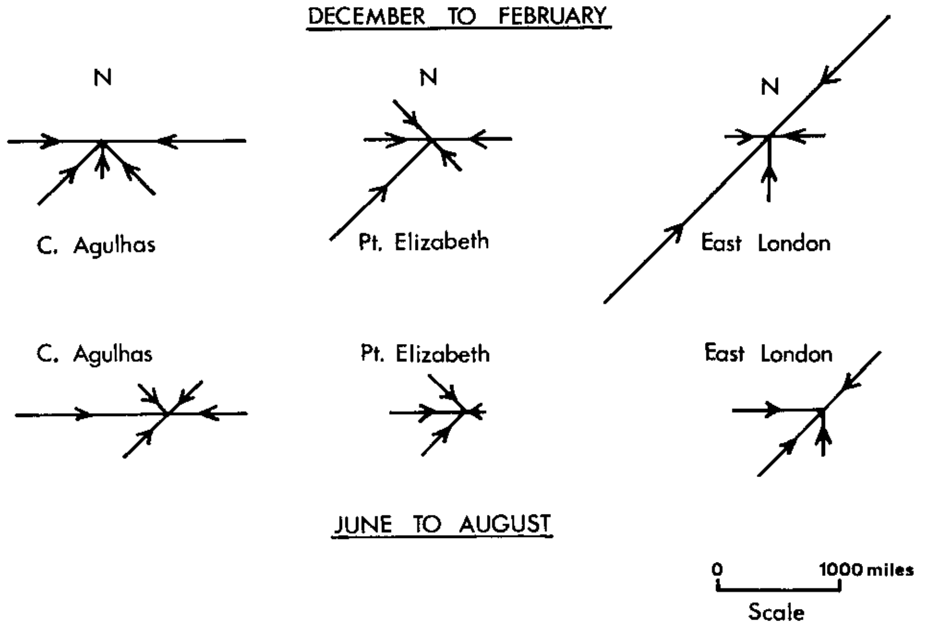


Figure 31. Miles of wind: Sum of the product of velocities and frequencies for 08h00, 15h00 and 20h00 (blows of less than 150 miles have been neglected) (data from Royal Navy and South African Air Force 1942).

The diagrams for the summer show the higher mileages of the easterly (or northeasterly at East London) winds but they do not appears to be greater than those with a westerly component, except perhaps at Cape Agulhas. The onshore southwesterly winds at Port Elizabeth and the resultant southerly winds at Cape Agulhas are notable features.

In the winter months the mileage from the west or southwest appears to be dominant.

The section is not one in which there is a great quantity of data. Apart from ships' drifts there have been some drift card studies (Baird personal communication 1978), and Bang (1972) carried out a number of bathythermograph studies during 'box' cruises in the area. Figure 32 is his diagram (Bang 1972) showing current inferences based on isotherms.

Figure 33 shows the net percentage frequency of current direction parallel to the coast as deduced from the drifts of ships within 30 km of the shore. This frequency is indicated by an arrow of length proportional to frequency. There are two arrows in each region. One is from the ships' drifts (Bray 1959-1964) and the other from the ships' drifts less 3% of the wind vector (Tripp 1967) (only east- and west-going data have been used). The numbers below the arrows represent the percentage of occasions when the current was against the local wind (top for west-going currents; lower for east-going). The high percentage of west-going current between Cape St Francis and Mossel Bay, which were contrary to the wind, is notable.

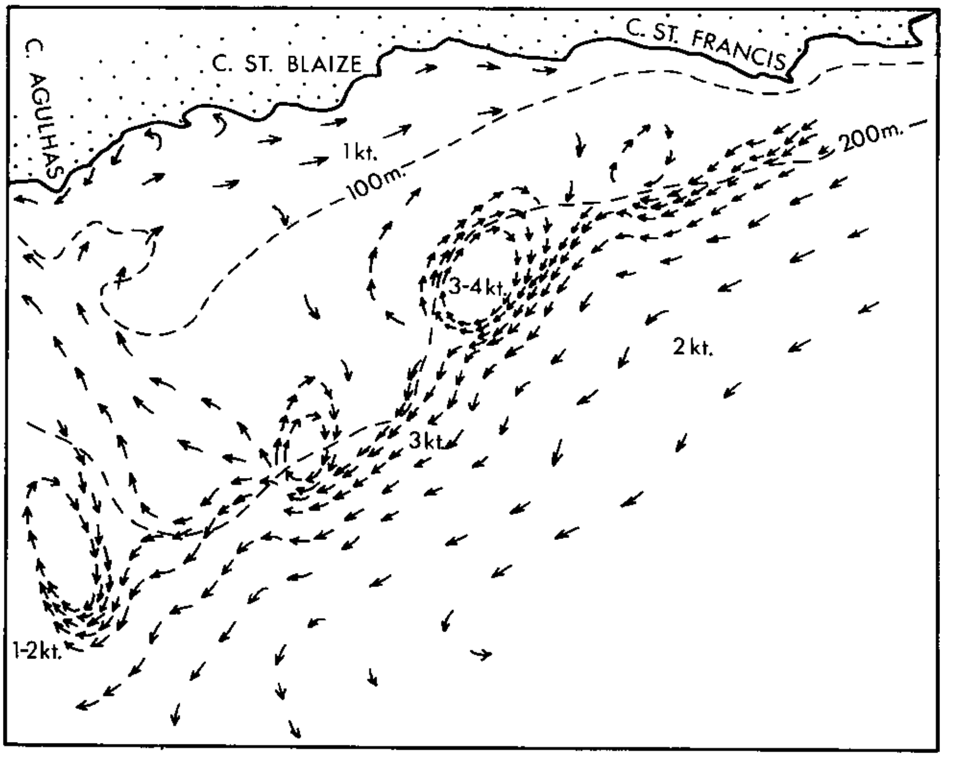


Figure 32. Current circulation inferred from bathythermograph data (Bang 1972).

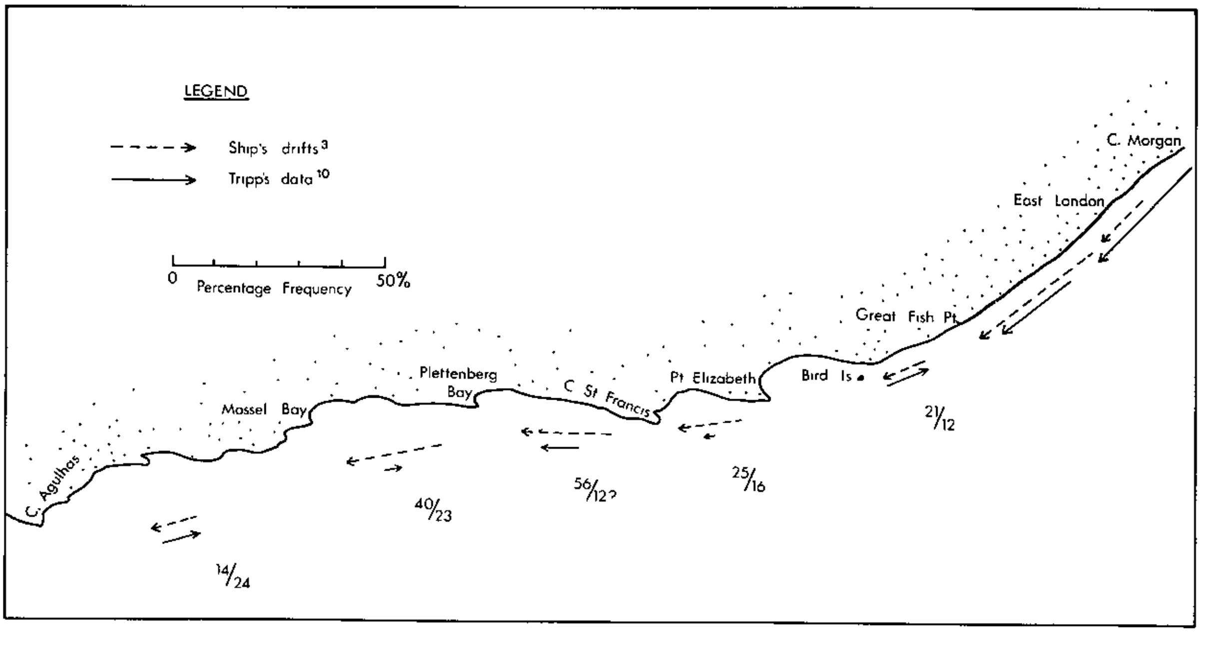


Figure 33. Net percentage of current direction of inshore currents (annual) for ships' drift (data from Bray 1959-1964) and Tripp's data (1967). Numbers are percentage frequencies of current against wind (top west-going currents, lower east-going).

In view of the higher frequency of easterly winds in the summer, it is desirable to divide the current directions into seasons. Tripp's data are not extensive enough to justify this but those for the other ships' drift data have been so divided into two periods, May to September and October to April. The net percentage frequency of direction for each period is represented in Figure 34 for the region Cape Agulhas to Great Fish Point.

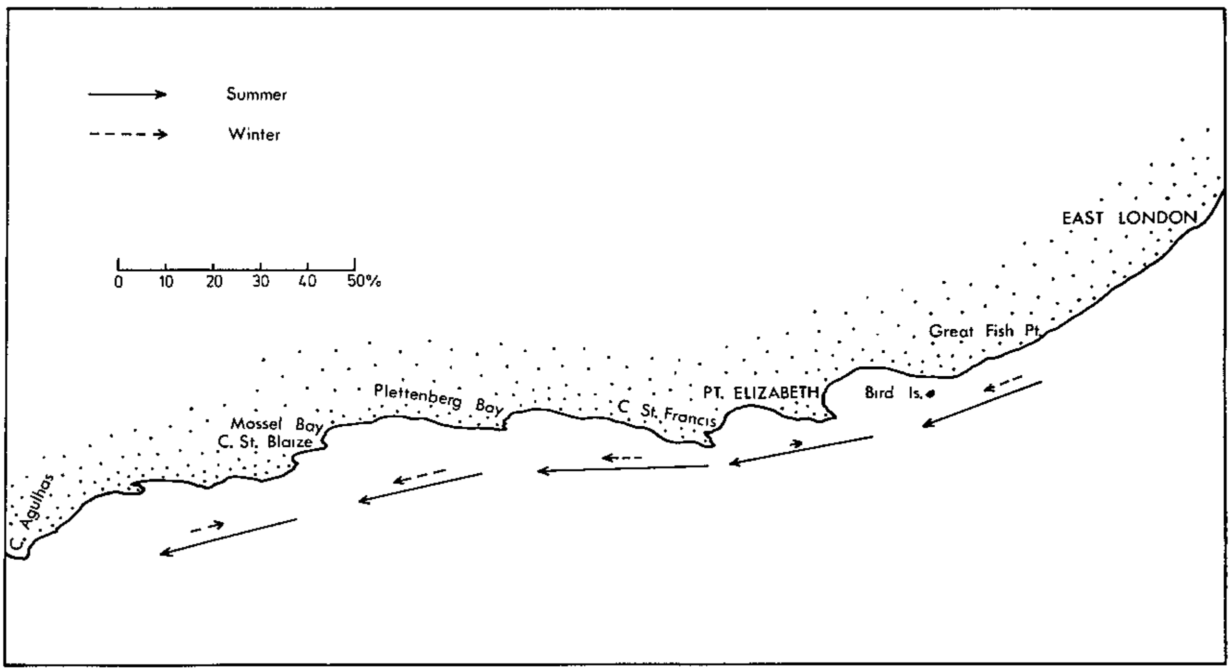


Figure 34. Net percentage frequency of current direction from ships' drift (data from Bray 1959-1964) for 'summer' and 'winter' months, Great Fish Point to Cape Agulhas.

For the winter months there is little difference in the frequency of directions except at the Cape Agulhas end but in the summer there is a greater tendency for west-going currents to be encountered.

The histograms in Figure 35 contain the ships' drift inshore velocities measured in the regions Great Fish Point - Bird Island and Cape Recife - Cape St Francis at the eastern end of this sector, and Cape St Blaize to Cape Agulhas at the western end. The stronger currents, both east- and west-going, are noted in the former.

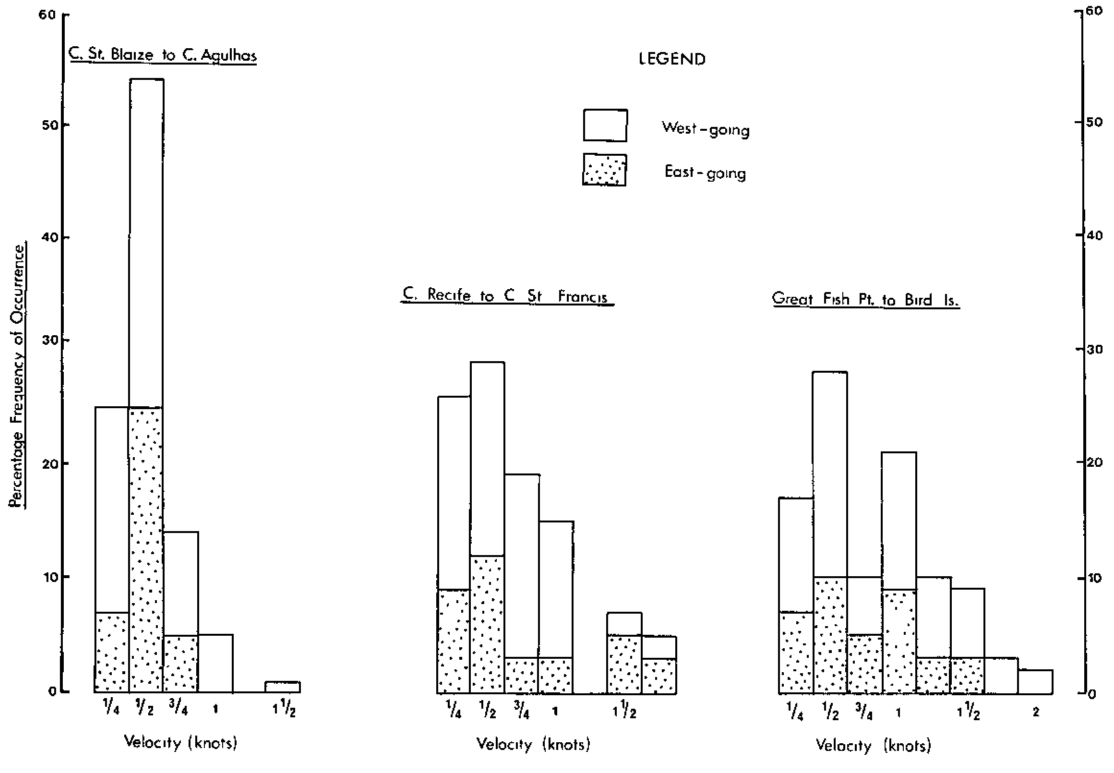


Figure 35. Histograms of the percentage frequency of occurrence of east- and west-going current velocities close to the coast for the regions indicated. Centre and right hand histograms show higher velocities (data from Bray 1959-1964)

3.1 CAPE MORGAN TO GREAT FISH POINT

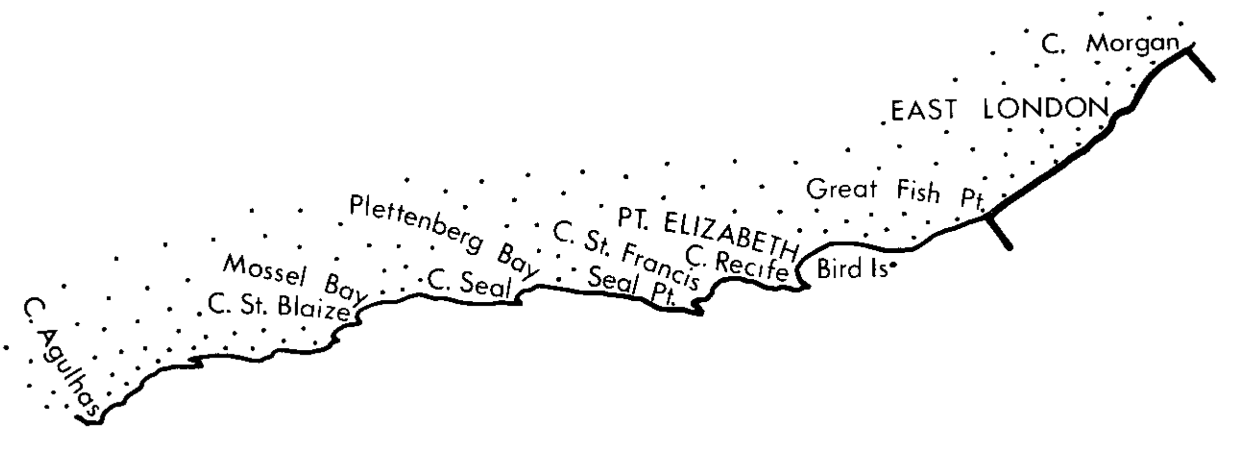


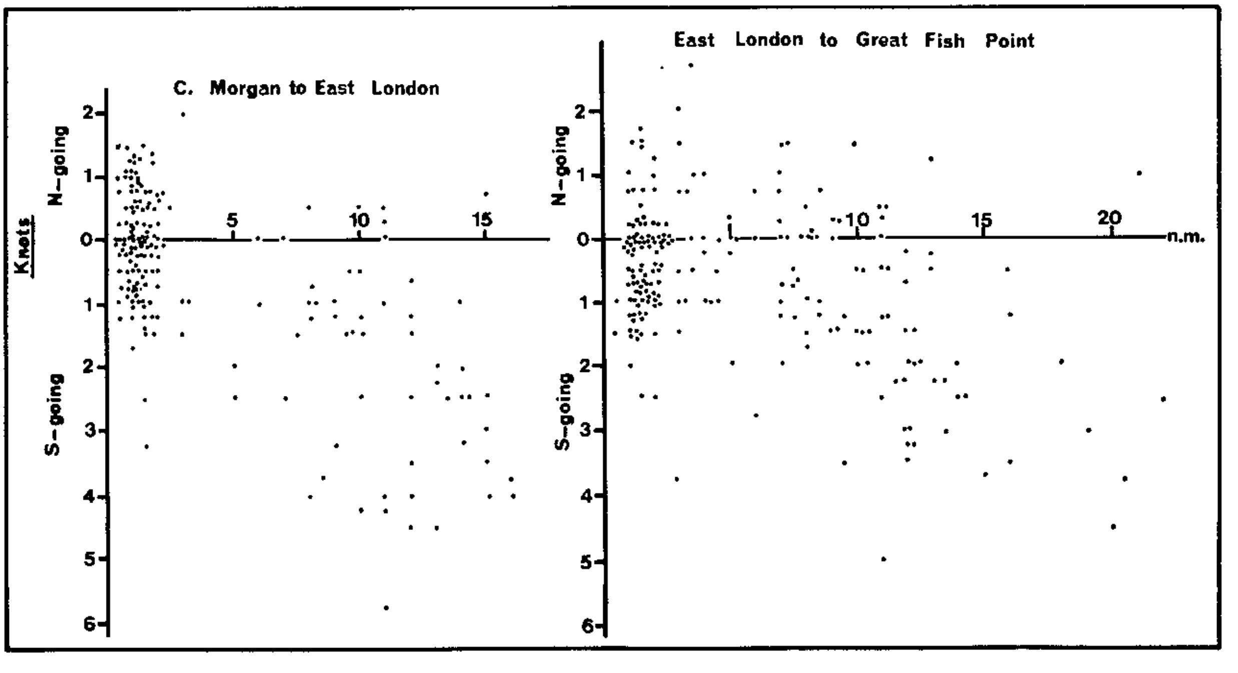
Figure 33 shows that the net percentage frequency of the direction of the current close to the shore is diminishingly south-going after Cape Morgan, indicating the reduction in the direct influence of the Agulhas Current on the coastal waters. There may be a cyclonic vortex at the discontinuity just south of Cape Morgan.

The percentage frequency of directions of currents within 3 km of the shore as indicated by ships' drifts (Bray 1959-1964) is as follows:

Table 18. Current directions (ships' drifts) within 3 km of the coast, Cape Morgan to Great Fish Point.

	No. of observ= ations	% north-going	% south-going	% slack water
Cape Morgan to East London	118	34	47	19
East London to Great Fish Point	108	23	56	21

The distribution of velocity with distance offshore is given in Figures 36 and 37.



Figures 36 (left) and 37. Distribution of current velocity with distance offshore (data from Bray 1955-1961) between Cape Morgan and East London (left) and East London and Great Fish Point (right).

Based on Tripp's data the currents were as follows:

Table 19. Current directions (ships' drifts, wind subtracted), Cape Morgan to East London (percentages as in Figure 38).

	Total	S	SI	NI	N	NO	SO	Slack
No of observations	56	25	8	6	8	1	2	6
Mean velocity (m s^{-1})		0,5	0,25	0,31	0,45	0,13	0,26	

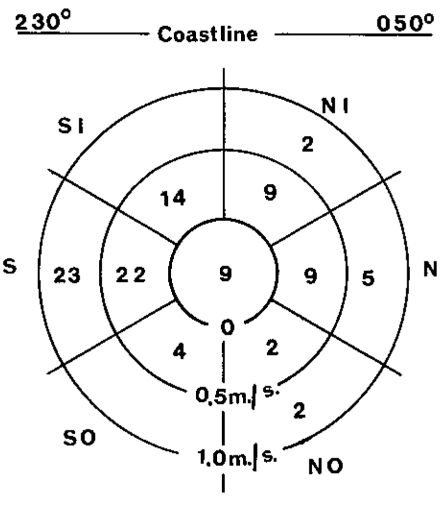


Figure 38. Current rose - wind subtracted - for Cape Morgan to East London - percentages (data from Tripp 1967).

Comparing Tripp's data with those of Bray suggests that the removal of the wind effect has increased the proportion of south-going currents.

Table 20. Current directions (ships' drifts, wind subtracted), East London to Great Fish Point (percentages as in Figure 39).

	Total	S	SI	NI	N	NO	SO	Slack
No of observations	50	21	-	8	11	3	1	6
Mean velocity (m s^{-1})		0,45	-	0,31	0,5	0,23	0,13	

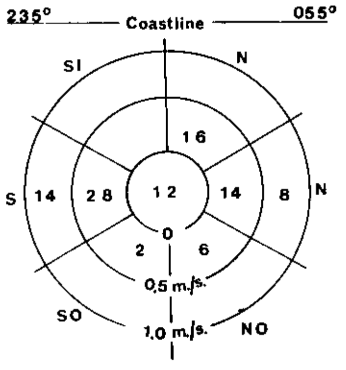


Figure 39. Current rose - wind subtracted - for East London to Great Fish Point - percentages (data from Tripp 1967).

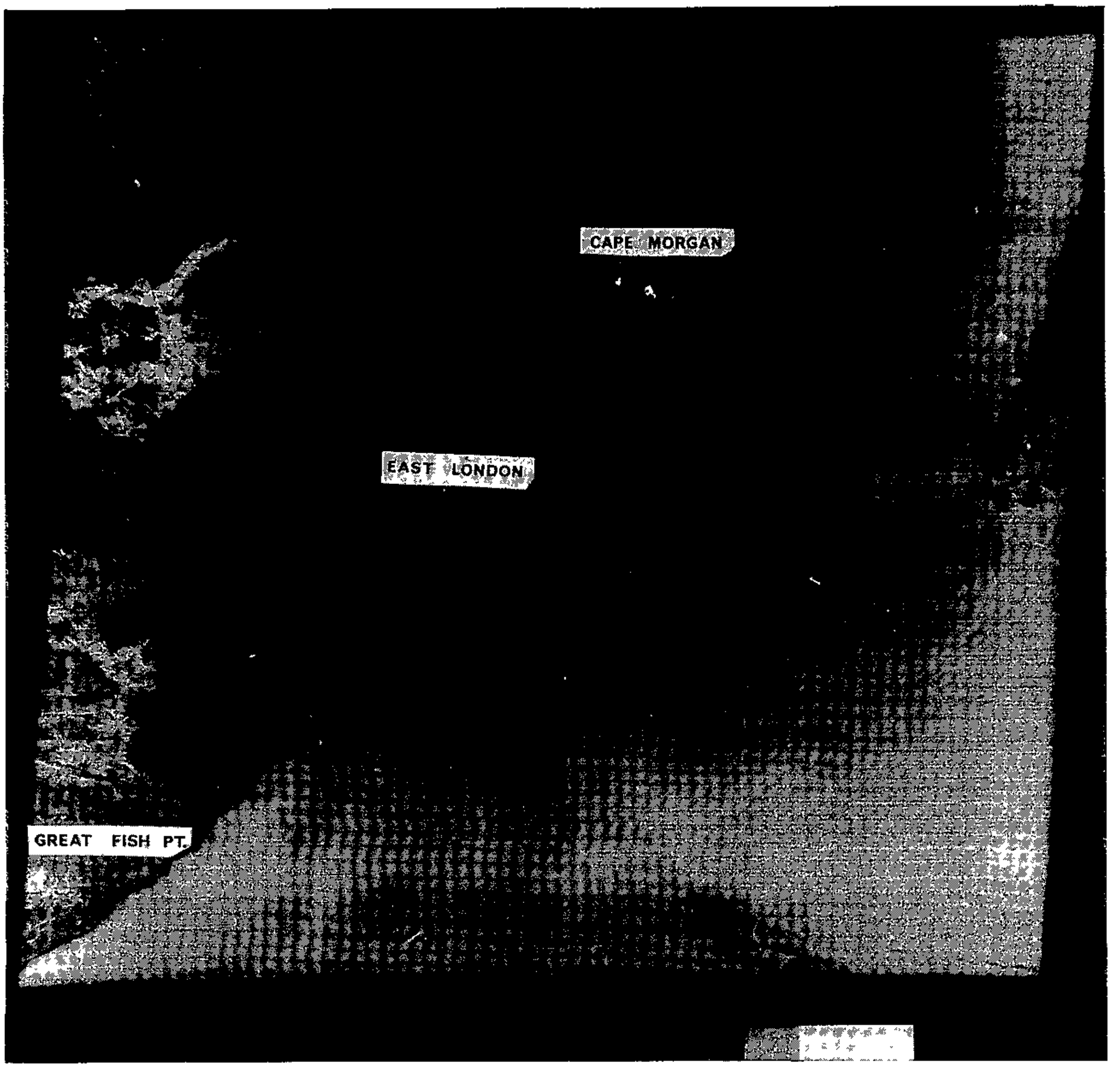


Figure 40. Landsat (band 4) image of the region Cape Morgan to the Great Fish River 72.10.15. River silts mark vortices along the inner edge of the Agulhas Current 5-10 km offshore. Cloud patterns and silt suggest a sharp offshore deflection of the current off Great Fish Point (image supplied by CSIR).

A satellite image in Figure 40 affords a brief brush with the realities of the currents in this region. It shows what are presumably vortices 5-10 miles from the coast, caused by the large horizontal velocity shear, and shown up by river silts. The image was made on 72.10.15 and there had been rain on the 72.10.13. There is a suggestion of the cyclonic vortex in the coastal embayment just south of Cape Morgan.

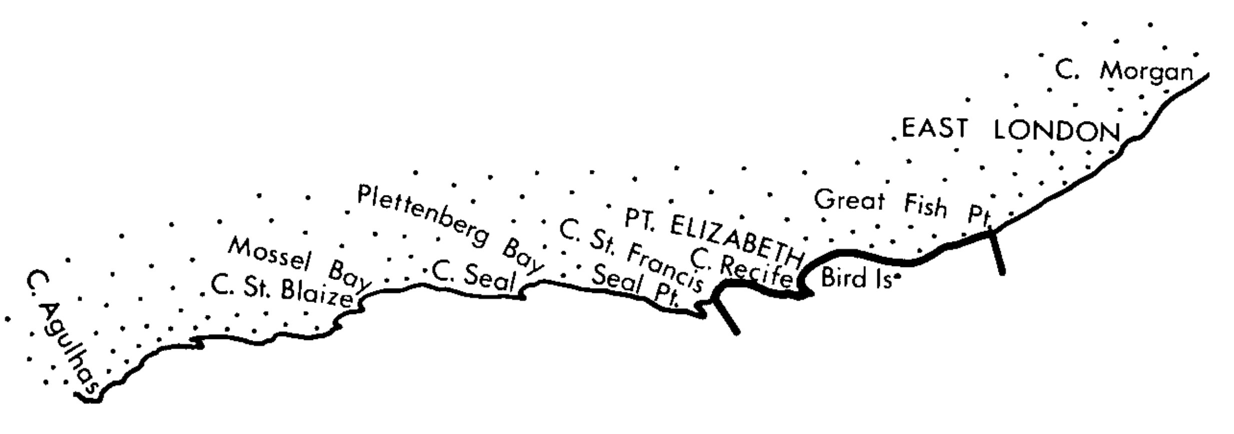
Though the image is not quite distinct enough for certainty, there does appear to be a sharp deflection offshore of the discoloured water and cloud line, near Great Fish Point - perhaps similar to that shown in Figure 29 for 76.07.27.

East London

A study of the currents within about 1 km of the shore was reported by Whillier (1962). He used several current measuring methods including floats, dyes and also carried out model studies. Incorporating the results of earlier work undertaken by the harbour authorities he came to the conclusion that cyclonic vortices occur between the harbour and Nahoon Point, and the harbour and Hood Point, and cause a northward drift close to the coast.

The opinion of the East London City Engineers Department based on its own experience is that the regime consists of, 'under conditions of wind with a southerly bearing, a north-flowing inshore drift interrupted and deflected by promontories: this north-flowing drift may be restricted or reversed by wind with another bearing' (Keppie personal communication 1978).

3.2 GREAT FISH POINT TO CAPE ST FRANCIS



In this region the percentage frequency of the northeast-going (or east-going) currents becomes more nearly equal to the southwest (west-going) currents. If the wind's contribution is subtracted the northeast-going (east-going) currents are slightly the more frequent. This is possibly because, as mentioned above, the separation of the

Agulhas Current from the coast not only diminishes its direct influence but also induces a cyclonic separation vortex increasing the frequency of basic northeast-going currents near the coast.

The ships' drift data (Bray 1959-1964) measured at a mean distance offshore of 4 km are as follows:

Table 21. Current directions 4 km offshore (ships' drifts), Great Fish Point to Cape St Francis.

	No. of observ= ations	% east-going	% west-going	% slack
Great Fish Point to Bird Island	120	29(24) (25)	38(51) (33)	33(25) (42)
Cape Recife to Cape St Francis	89	29(19) (44)	44(50) (42)	27(31) (14)

(Numbers in brackets are the percentages for summer (top) and winter).

The percentage frequency of slack currents is now significantly large.

The distribution of velocities for the regions Great Fish Point to Bird Island are shown in Figure 41.

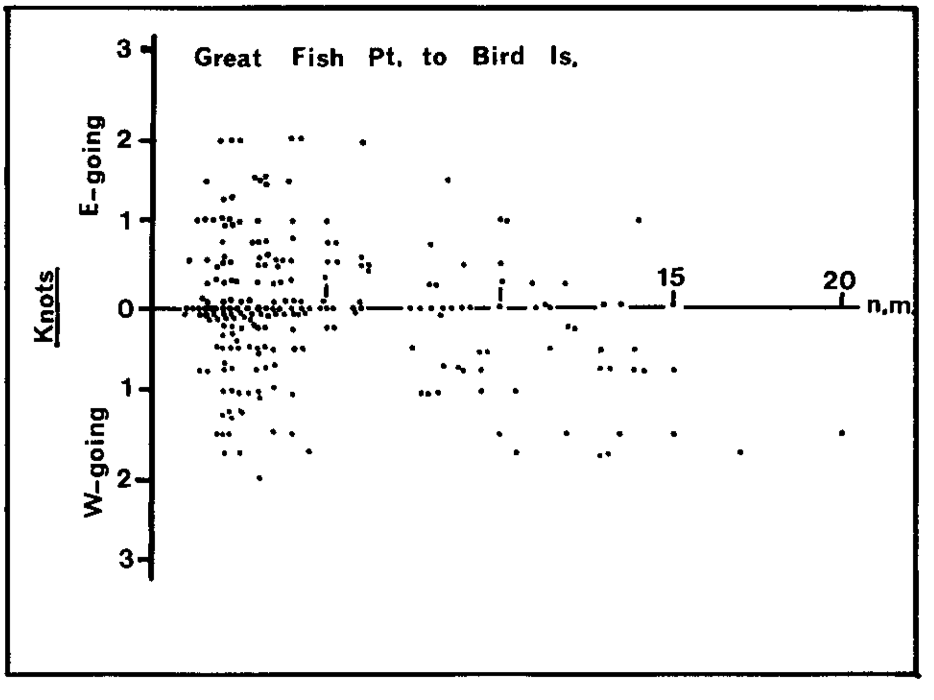


Figure 41. Distribution of current velocity with distance offshore (data from Bray 1955-1961) for Great Fish Point to Bird Island.

The data from Tripp's (1967) analysis are set out below:

Table 22. Current directions (ships' drifts, wind subtracted), Great Fish Point to Bird Island (percentages as in Figure 42).

	Total	W	WI	EI	E	EO	WO	Slack
No. of observations	54	13	5	12	18	-	1	5
Mean velocity (m s^{-1})		0,35	0,25	0,29	0,41	-	0,38	

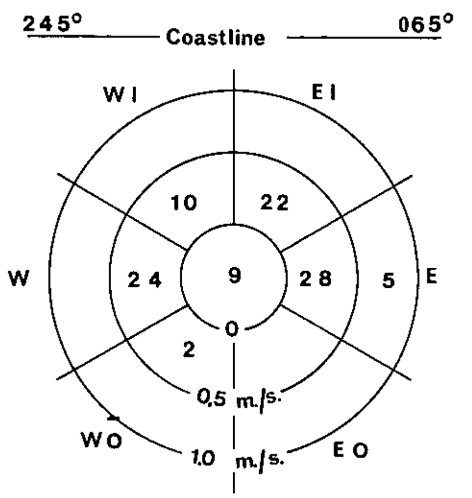


Figure 42. Current rose - wind subtracted - for Great Fish Point to Bird Island - percentages (data from Tripp 1967).

Algoa Bay

Algoa Bay is shallow, having a maximum depth across its mouth of about 40 fathoms (73 m). Its otherwise regular topography is disturbed by the presence of Bird and St Croix Islands (see Figure 43).

Information about the currents comes from ships' drift between Bird Island and Port Elizabeth and float studies made by the City of Port Elizabeth (City and Water Engineer, unpublished report). A drift card study is at present in progress (Baird personal communication 1978).

The ships' drift data (Bray 1959-1964) are as follows:

Table 23. Current directions (ships' drift) Bird Island to Port Elizabeth.

No. of observations	% east-going	% west-going	% slack
118	24	26	50

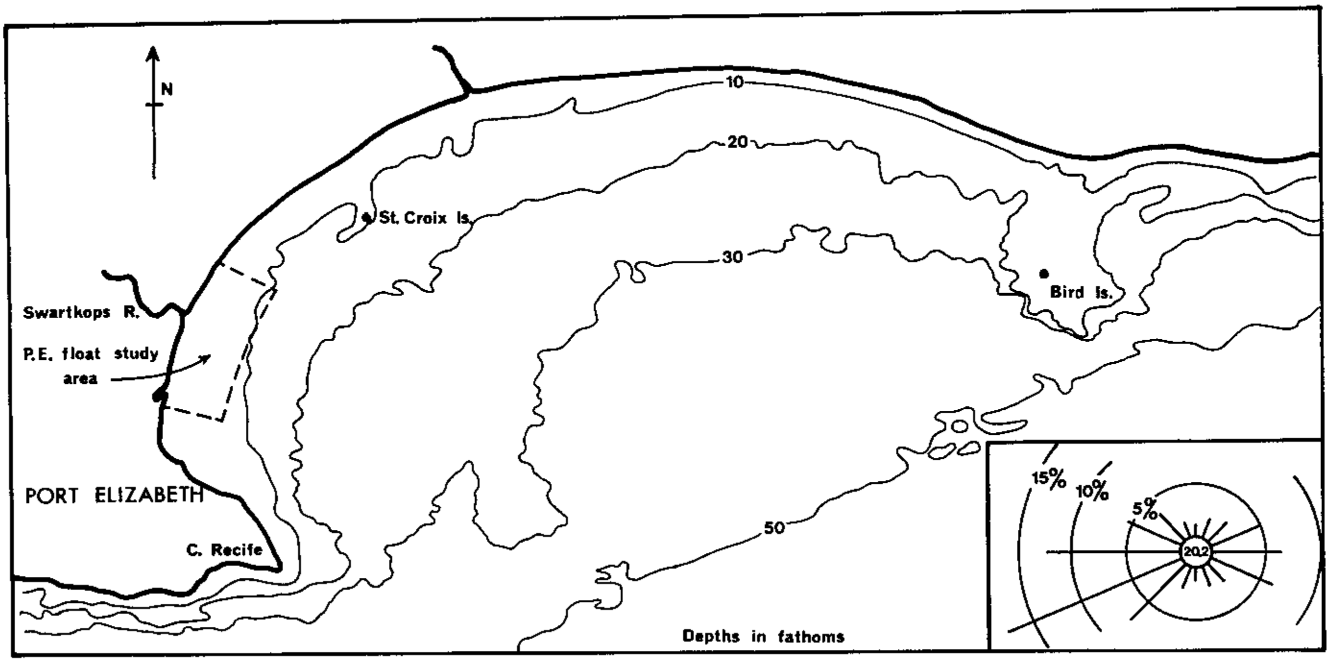


Figure 43. Algoa Bay, its bathymetry, the site of float studies, and (inset) annual wind rose showing frequencies of wind and calms (centre figure).

Tripp's data (1967) for the same passage are given below.

Table 24. Current directions (ships' drift, wind subtracted), Bird Island to Port Elizabeth (percentages as in Figure 44).

	Total	W	WI	EI	E	EO	WO	Slack
No. of observations	51	11	6	13	12	2	3	4
Mean velocity (m s^{-1})		0,3	0,38	0,35	0,37	0,22	0,28	

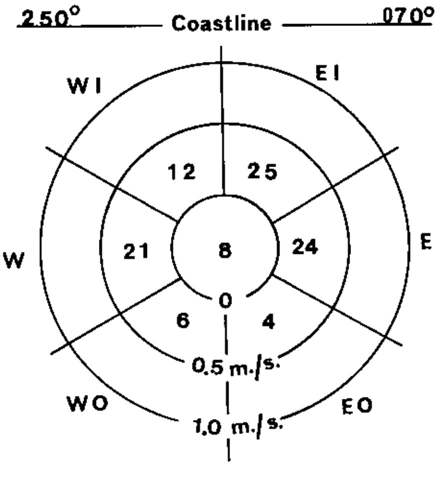


Figure 44. Current rose - wind subtracted - for Bird Island to Port Elizabeth - percentages (data from Tripp 1967).

Of the current velocities measured by the ships' drift about 20% were greater than 1 knot (about 0,5 m s^{-1}). East-going currents were almost always in sympathy with the wind whereas there was a significant number of occasions when the west-going ones were contrary to the wind (about 20%).

During the year August 1964 to July 1965 studies were carried out by the City of Port Elizabeth on the coastal currents in the vicinity of the town (see Figure 43 for location). Both drift cards and tracked floats (with drogues at 10 feet) were released along a number of lines out to a distance of about 4 km (City of Port Elizabeth undated). Figure 45 shows the end points of floats which had been released about 3 km offshore just south of the Swartkops River. The positions indicated are those reached after six hours travel. The frequency of the wind during tracking is shown in the adjacent rose.

The study revealed that floats travelled broadly downwind though there were exceptions. The flow was generally parallel to the coast. In view of the directions of the prevailing wind, the current directions appear to be a little to the left of the wind. Those associated with winds from the south to southeast were exceptions in that they went either north or south.

North-going currents were more frequent than south-going in the ratio of 31% to 17%. Onshore currents with directions $\pm$ 45° to the perpendicular to the coast occurred on 19% of the occasions. Average velocities were 33 cm s^{-1} maximum, 3 cm s^{-1} minimum and mean 11 cm s^{-1}.

In the shallower portion of the bay there will be some current generation by the larger, longer waves.

Baird's (personal communication 1978) preliminary results for Algoa Bay seem to confirm that there is a predominantly cyclonic circulation in the inner region, though not necessarily in the outer part near Cape Recife.

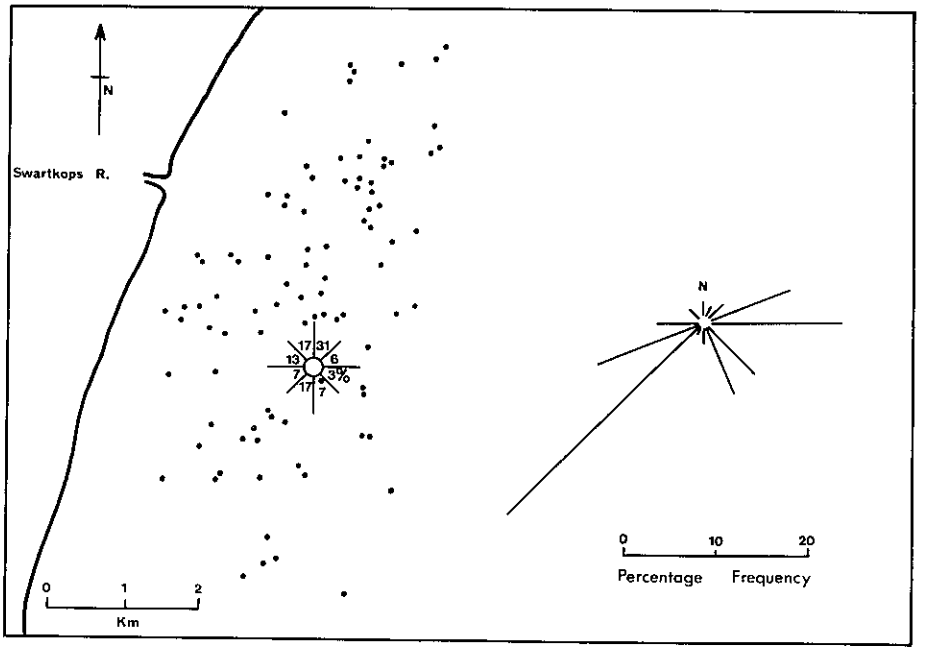


Figure 45. Positions of floats 6 hours after release at the centre of the current rose off Swartkops River. Tracks are mainly parallel to the coast. The frequency of the winds during the tracking is shown on the right (data from City of Port Elizabeth undated, with permission).

Cape Recife to Cape St Francis

The distribution of current velocities with distance from the shore in this region is given by the ships' drift observations. These are presented in Figure 46.

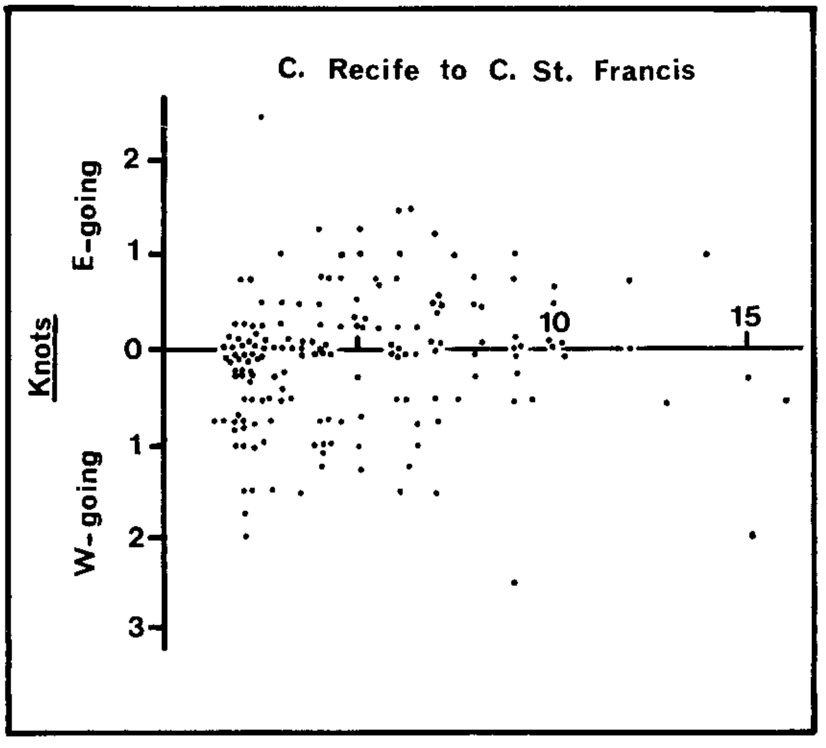


Figure 46. Distribution of current velocity with distance offshore (data from Bray 1955-1961) for Cape Recife to Cape St Francis.

Tripp's analysis (1967) shows the following distribution of currents with direction.

Table 25. Current directions (ships' drift, wind subtracted), Cape Recife to Cape St Francis (percentages as in Figure 47).

	Total	W	WI	EI	E	EO	WO	Slack
No. of observations	75	15	7	11	13	11	10	8
Mean velocity (m s^{-1})		0,42	0,37	0,30	0,49	0,28	0,35	

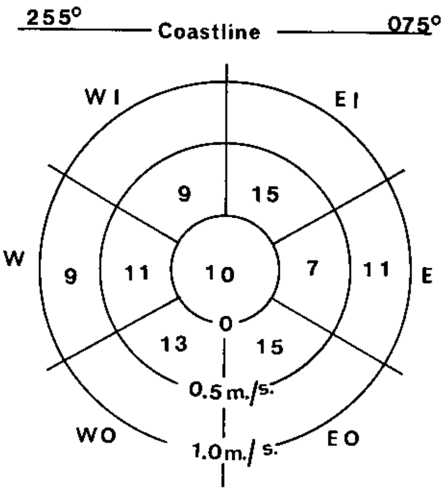
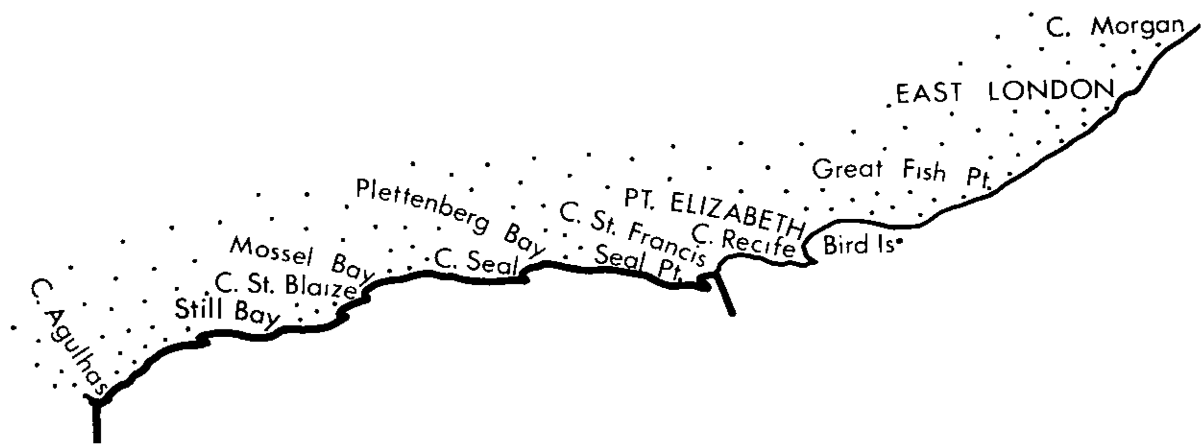


Figure 47. Current rose - wind subtracted - for Cape Recife to Cape St Francis - percentages (data from Tripp 1967).

3.3. CAPE ST FRANCIS TO CAPE AGULHAS



Within this region the Agulhas Bank widens considerably. Using the 200 m contour as its outer boundary, the Bank is about 50 km wide at Cape St Francis and about 300 - 400 km at Cape Agulhas. The mean path of the Agulhas Current is to be found at corresponding distances. It is now relatively remote from the coastal water. Nevertheless it is clear from the evidence adduced above that Agulhas Current water does spill over the Agulhas Bank probably drawn in by the entrainment vortices caused by the separation of the current from the coast or by instability of waves in the current. However, whereas the Agulhas Current maintains some influence over the coastal waters, the velocity of the currents it induces are usually less than 0,5 m s^{-1} (1 knot) and consequently wind effects may be equally or more important. For example, assuming the wind drift current to be 3% of the wind speed, a steady wind of just over 30 knots (15 m s^{-1}) would generate a surface current of approximately 1 knot (0,5 m s^{-1}).

It will readily be appreciated that the combination of two forcing mechanisms of nearly equal effectiveness, and not necessarily correlated (having different time scales), will produce very complex current circulations. This is undoubtedly true of the region, and simple statements about the currents are difficult to make.

The complexity of the currents over the Agulhas Bank in this region is illustrated by the trajectory of a satellite tracked drifter (Grundlingh 1977) (No. 1116), shown in Figure 48. Superimposed is a progressive vector diagram of wind stress as represented by the square of the wind velocity, and the diagram slewed through an angle of 35° to the left to account roughly for the Ekman deflection. The stress diagram has been arbitrarily made to fit the length of the trajectory. There are sufficient similarities between the two paths to justify an assumption that the wind was an important contributory forcing mechanism. On the other hand there are important differences suggesting the presence of basic currents, perhaps generated by a pressure gradient between the warmer water invading the Agulhas Bank and the colder water inshore of it.

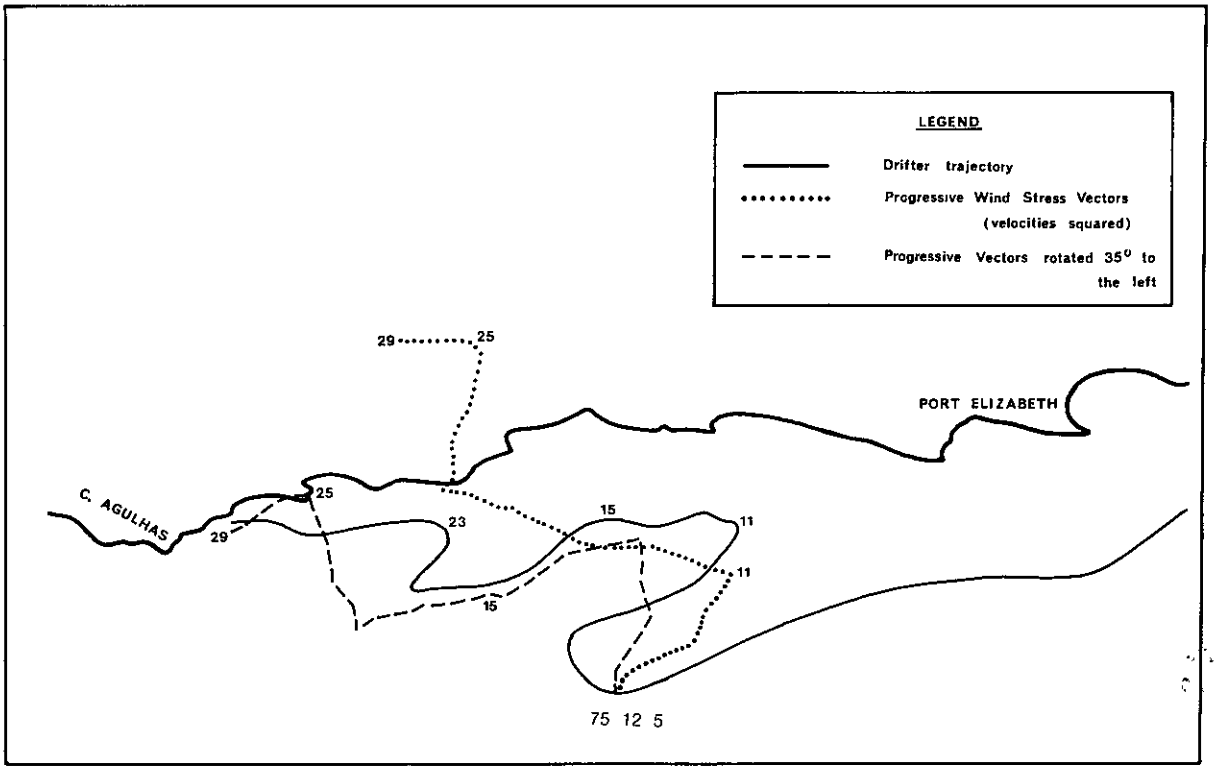


Figure 48. Trajectory of a satellite tracked float (No. 1116) showing its passage down the Agulhas Current and subsequent mean= ders over the Agulhas Bank before grounding just east of Cape Agulhas. Superimposed are the progressive wind stress diagram and the same diagram slewed anticlockwise through an arbitrary 35°, (drifter trajectory from Grundlingh 1977, wind data from the Weather Bureau's synoptic pressure charts).

The data from the ships' drifts (Bray 1959-1964) are as follows: (It should be noted that in this region ships' courses tend to vary and their distances from the shore are therefore much more variable than they were along the Natal and Transkei coasts. In general they range from 5 km off Cape St Francis to up to 30 km off the western end of the sector in the region of Mossel Bay).

Table 26. Current directions (ships' drifts), Cape St Francis to Cape Agulhas.

	No. of observations	mean distance from shore km	% east going	% west going	% slack
Cape St Francis to Plettenberg Bay (Cape Seal)	86	7	23(20) (30)	44(56) (38)	32(24) (32)
Plettenberg Bay to Mossel Bay (Cape St Blaize)	87	15	24(25) (27)	47(52) (38)	29(23) (35)
Mossel Bay to Cape Agulhas	91	22	24(18) (35)	36(47) (28)	40(35) (37)

(The figures following the brackets are the percentages for summer (top) and winter).

The high precentage frequency of slack water, especially in the Mossel Bay - Cape Agulhas region is to be noted. On the basis of this data (and the sample is rather small) there is a net frequency of west-going currents of about 10% to 25% over the year, but higher in the summer months.

Tripp's (1967) analysis of other ships' drift data is as follows: (3% of the wind velocity has been subtracted).

Table 27. Current directions (ships' drift, wind subtracted), Cape St Francis to Plettenberg Bay (percentages as Figure 49).

	Total	W	WI	EI	E	EO	WO	Slack
No. of observations	52	15	5	8	11	3	3	7
Mean velocity (m s^{-1})		0,34	0,31	0,29	0,20	0,47	0,23	

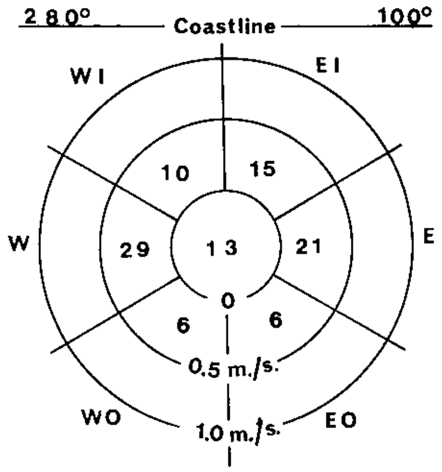


Figure 49. Current rose - wind subtracted - for Cape St Francis to Plettenberg Bay - percentages (data from Tripp 1967).

Table 28. Current directions (ships' drift, wind subtracted), Plettenberg Bay to Mossel Bay (percentages as in Figure 50).

	Total	W	WI	EI	E	EO	WO	Slack
No. of observations	35	6	5	9	7	-	2	6
Mean velocity (m s^{-1})		0,26	0,31	0,39	0,29	-	0,32	

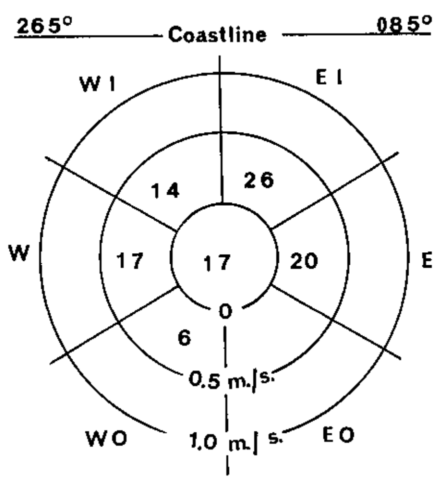


Figure 50. Current rose - wind subtracted - for Plettenberg Bay to Mossel Bay - percentages (data from Tripp 1967).

Table 29. Current directions (ships' drift, wind subtracted) Mossel Bay to Cape Agulhas (percentages as in Figure 51).

	Total	W	WI	EI	E	EO	WO	Slack
No. of observations	90	14	7	17	22	14	5	11
Mean velocity (m s^{-1})		0,3	0,27	0,22	0,32	0,28	0,24	

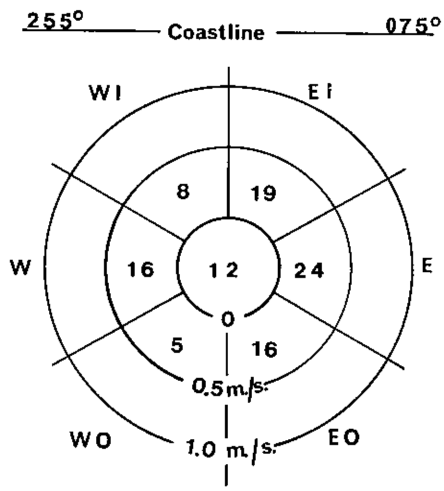


Figure 51. Current rose - wind subtracted - for Mossel Bay to Cape Agulhas - percentages (data from Tripp 1967).

The relatively high percentage frequency of currents flowing towards the shore is worthy of note (25-40%), the highest value being in the Plettenberg Bay - Mossel Bay region. (It may be coincidental but it was this region which received oil from the 'Venpet/Venoil' spill - see below).

As to the net frequency of current direction parallel to the coast both sets of ships' drift data indicate a small net westerly motion in the Cape St Francis - Plettenberg Bay region. In the other two regions the data are conflicting - with the wind included, the net frequency of direction is westerly, and with the wind effect removed, easterly. The underlying reasons for the difference are not clear. It may be that the samples were too small.

A case history arising from the oil spill consequent upon the collision of the 'Venoil/Venpet' off Plettenberg Bay in December 1977 is of some interest. The full report on the incident is not yet available and what follows is based on information supplied by Mr W Bricknell (personal communication 1978).

Figure 52 shows the position of the collision and a very tentative and schematic representation of the path followed by some of the oil. On the day following the oil spill (77.12.17) a wind from the east advected the oil to a position off Cape Seal. Five days of wind from approximately the southwest carried the oil into Plettenberg bay. On 77.12.24 a wind from the east reversed the trajectory of the oil and largely removed it from the bay. By 77.12.29 oil was deposited near Mossel Bay especially along the coast between the Klein and Groot Brak Rivers and in Victoria Bay. The wind had a strong onshore component from the 25th onward.

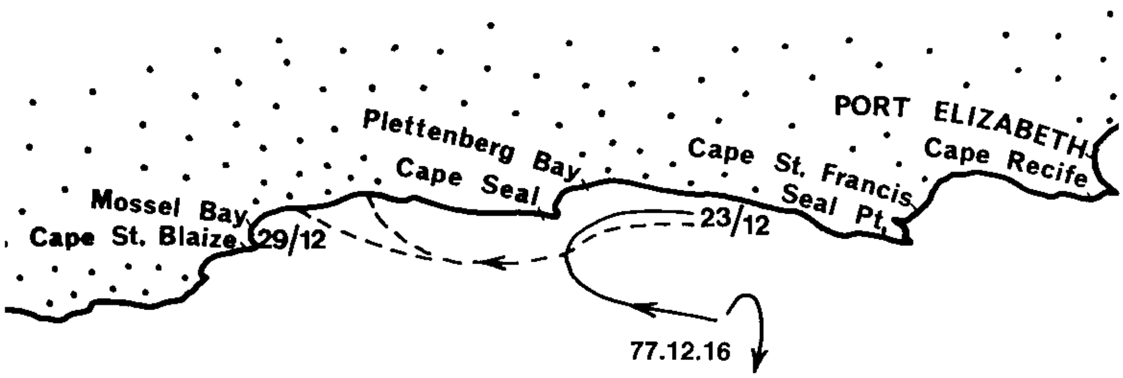


Figure 52. Diagramatic sketch of path taken by some of the oil from the 'Venoil/Venpet' collision at point X (data from Bricknell personal communication 1978).

Still Bay

The currents close inshore at Still Bay (about 75 km west of Mossel Bay) have been measured by means of moored current buoys during the period June 1969 to July 1971 (Universiteit van Stellenbosch 1976). The mooring was in 13 m of water about 1 km off Morris Point, a promontory at the western end of the bay. The currents were directed predominantly (75%) towards the north or northeast i.e. into the bay. About 15% were directed towards the south to southwest quarter. There is reason to believe that the north-going bias was imparted by wave currents developed over the shallow spit off Morris Point (Retief personal communication 1978).

3.4 SUMMARY CAPE MORGAN TO CAPE AGULHAS

The complexity of the circulation and the scarcity of the data means that any statements about the circulation in the sector must necessarily be very tentative and subject to later revision. The complexity arises for a number of reasons.

(a) The Agulhas Current, which had a strong influence in the previous sector now separates from the coast as it follows the edge of the Agulhas Bank. Its influence over the Bank is sometimes apparent but it is intermittent and may be vortex-forming. The time scales are not well known but they may be of the order of several weeks.

(b) The diminished influence of the Agulhas Current means that the wind stress now becomes more important. The time scale here is that of the passage of fronts - say 4-5 days. Furthermore there is a marked seasonal difference with the easterly winds being more frequent in the summer months. There is also a spatial difference in that the easterlies are more frequent at the western (Cape Agulhas) end.

(c) The Agulhas Bank is shallow (mean depth roughly 100 m). There is little scope for quasi-permanent pressure gradients to be set up below the depth influenced by the wind.

An important characteristic of this sector is the broadening of the shelf to form the Agulhas Bank. Whereas almost exclusively south-going currents are to be found at about 10 km off the Cape Morgan end, they would probably not be encountered within 300-400 km at the Cape Agulhas end. The current's departure from the coast is attended by considerable variability with deflections sometimes as much as 100 km offshore at Port Elizabeth.

Although the currents within a few kilometres of the coast are difficult to categorise, the evidence suggests the following tentative conclusions:

(a) The frequency of currents with velocities equal to or greater than a knot (which are unlikely to be purely wind-driven) decreases with distance westward and are rare in the Mossel Bay to Cape Agulhas region. This points to an increasingly greater wind influence to the west.

(b) Since those currents with velocities equal to or greater than one knot may be in either direction (parallel to the coast) the influence of the Agulhas Current either directly or indirectly by causing entrainment vortices and/or pressure gradients depending on its mode of behaviour, remains a possibility. The region Plettenberg Bay to Mossel Bay may be about the westward limit of these processes.

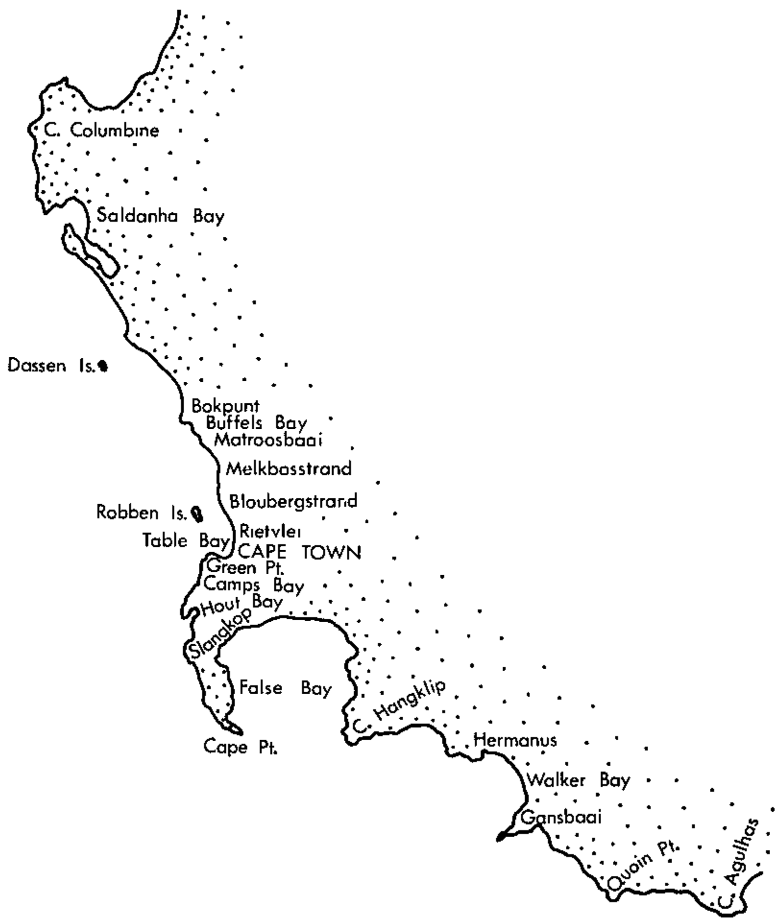
(c) There are seasonal differences. In the region Cape St Francis to Cape Agulhas, for example, west-going currents are more frequent than east-going by about 27-36%. In the winter months this tendency is slight - and in fact is slightly reversed in the Mossel Bay to Cape Agulhas region.

(d) In the region Cape St Francis to Cape Agulhas the percentage of occasions when the west-going currents were against the wind was significantly high (40-56%) in the eastern end of the region but diminished towards Cape Agulhas (14%).

(e) Currents directed shorewards occur relatively frequently in the sector between Plettenberg Bay and Cape Agulhas. Both the oil from the 'Venpet/Venoil', and the satellite tracked drifter beached here. There is a possibility that this is a region of current convergence.

Prediction of currents will only become possible when our understanding of the Agulhas Current regime and its influence over the Agulhas Bank water is more advanced.

SECTOR IV CAPE AGULHAS TO CAPE COLUMBINE



This sector of the coast is oriented approximately northwest - southeast, and contains several large coastal discontinuities such as Walker Bay, False Bay and Table Bay. The forcing mechanism for waters lying within 30-40 kms of the coast appears to be primarily the wind. However a branch of the Agulhas Current can be found further offshore when the winds are suitable - this current having rounded the tip of the Agulhas Bank. Bang (1973) has expressed the view that 'vestiges of Agulhas Bank or Agulhas Current water are almost always found off the Cape upwell cell'.

An impression of the prevailing winds can be got from Figure 53 which shows the resultants (Weather Bureau 1960) for January and July. Generally speaking the prevailing winds blow parallel to the local coastline (except at Cape Agulhas where the resultant is southerly). For most of the year the winds between east and south are dominant and their influence, which is of paramount importance, increases northwards. In the winter months (June - August) winds from the north and west are more frequent - increasing in frequency in the southern part of the sector.

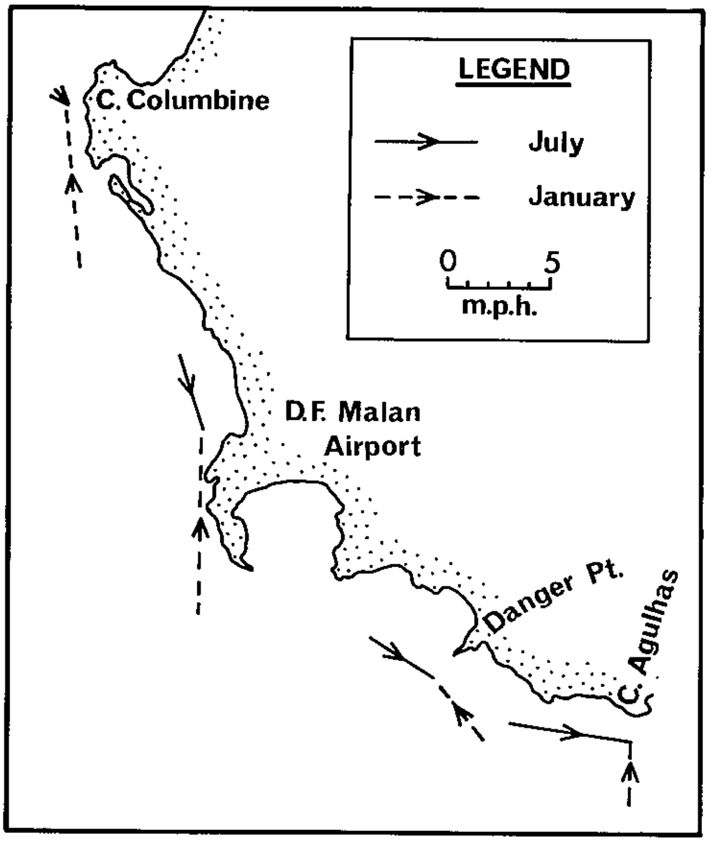


Figure 53. Resultant of winds measured at indicated sites for January and July (data from Weather Bureau 1960).

Quite generally when a wind blows parallel to a shore on its right (looking down wind in the Southern Hemisphere), the near-surface waters tend to be deflected offshore (to the left) on account of the earth's rotation, and upwelling occurs along the coast. This means that the deeper, colder water is brought towards the surface and warmer surface water is moved offshore. A subsidiary effect is the establishment of a slope to the sea surface, upwards offshore. It follows that apart from the currents generated by the direct stress of the wind on the near surface layers, there will be a so-called barotropic current superimposed because of the pressure gradient resulting from the sea surface elevation. The baratropic current will flow down wind. This, together with the direct wind stress, is an important forcing mechamism of the Benguela System. (The path of a satellite drifter launched off Cape Town and moving in the Benguela System is shown in the next sector - Figure 76).

The cold upwelled water can act as a tracer whereby the movements of the water may be tracked. Figure 54, obtained by Bang (1973) by measuring sea surface temperatures from a ship in the summer, shows several tongues of cold upwelled water. One is close to the coast between Cape Town and Cape Columbine. Another arises along the Cape Peninsula and travels parallel to the previous one. Further offshore there is a tongue of warmer (Agulhas?) water flowing parallel to the coast. The technique of using sea surface temperatures becomes particularly useful now that they may be remotely sensed by means of an infrared radiometer carried by an aircraft or satellite, yielding synoptic data over a wide area. Caution is however necessary in the interpretation.

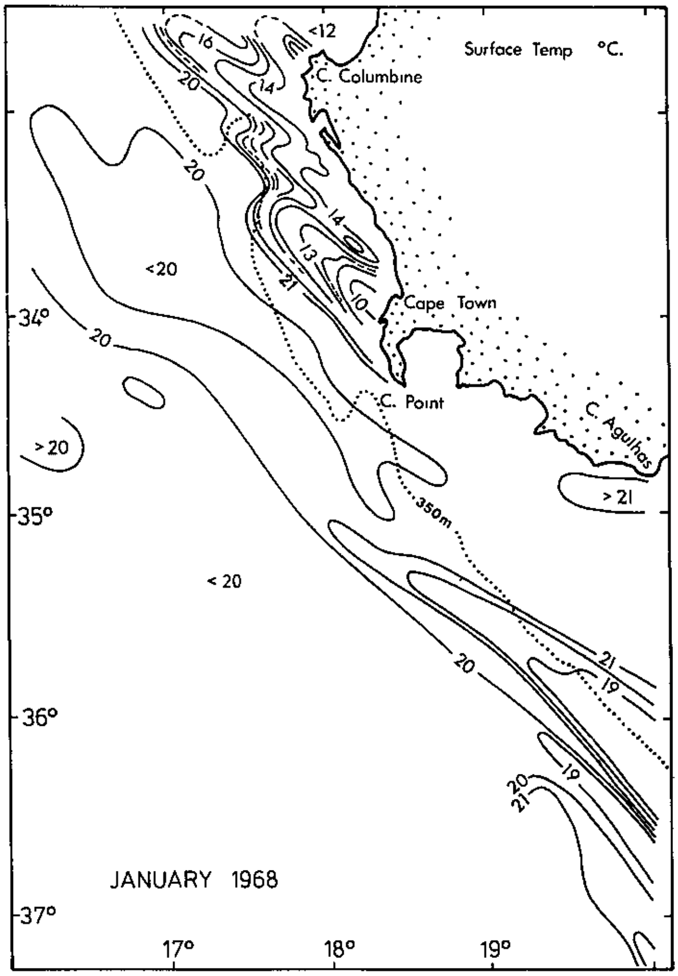


Figure 54. Sea surface isotherms for January 1968. Note tongues of cold upwelled water from the Cape Peninsula and from the coast south of Cape Columbine - also tongue of warm Agulhas water in the south (Bang 1973).

Figure 55 is a satellite infra-red image which shows the cold water in a lighter grey. On the occasion that it was made, the 'Southeaster' had just begun to blow and the cold upwelled water (whitish) can be seen between Cape Point and Cape Columbine, with plumes separating from the coast at coastal discontinuities. Warmer (darker) water in a branch of the Agulhas Current can be seen further offshore. Figure 56 depicts the situation after sustained southeasterly winds. The cold water is now being upwelled as far east as Cape Agulhas and has penetrated False Bay. Off Cape Town it has been advected to form a broad band with a fairly sharp gradient of temperature at its interface with the offshore Agulhas water. It is at such an interface that a north flowing jet has been identified. Surface velocities of about 0,7 m s^{-1} were measured in January 1973, at a distance of 75 km from Cape Town (Bang & Andrews 1974).

Two points about the system emerge. The wind dependence necessitates treatment of the problem seasonally, and the orientation of the coast to the wind must be taken into account.

The Sea Fisheries Branch has for many years studied the movements in the upwelled waters of the lower Benguela System and more recently local investigations have been undertaken by the University of Cape Town. In addition the ships' drift data are available as far as Cape Town. The various contributions will be dealt with in the appropriate regions.

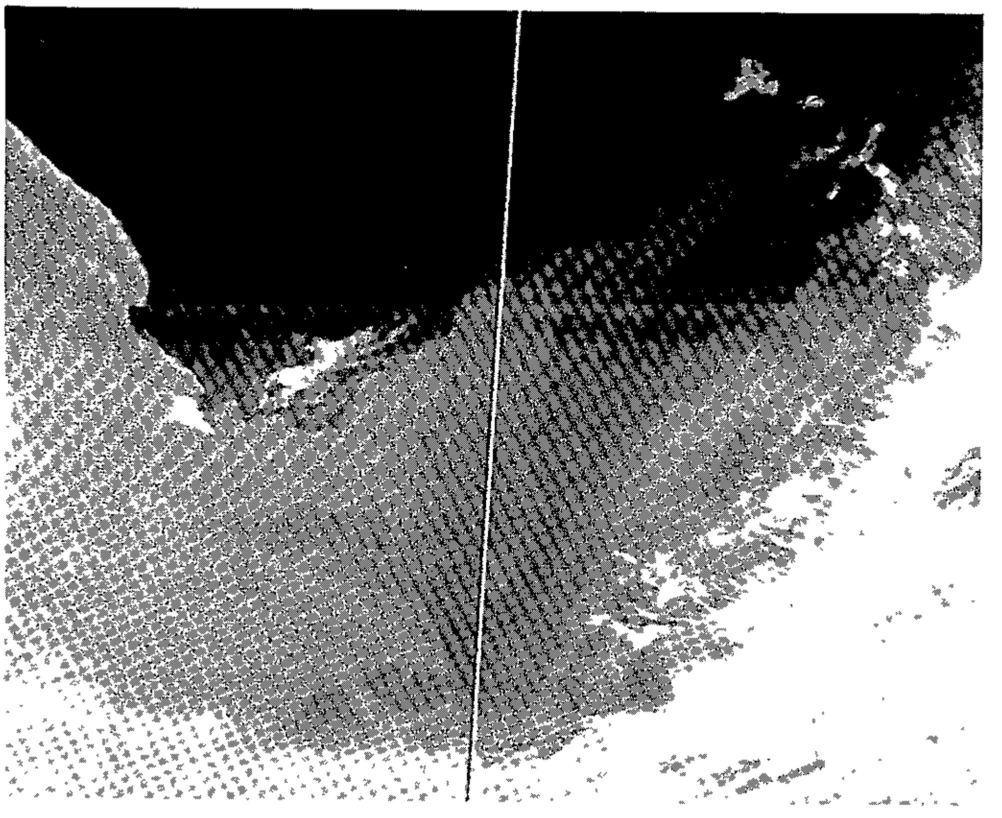


Figure 55. NOAA infrared image showing the start of upwelling, northwards of Cape Point (white) and the Agulhas Current with a branch flowing northwest (darker) on 76.12.11

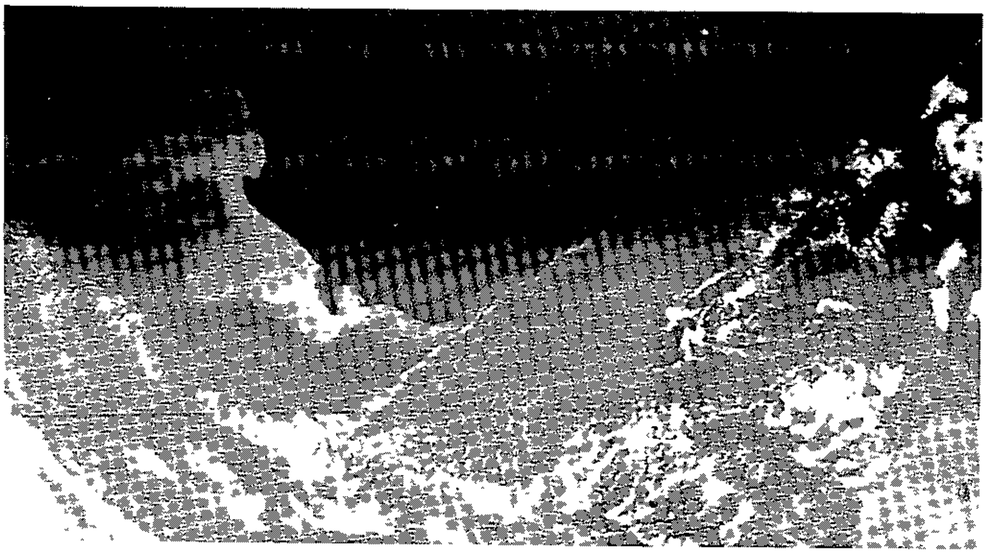
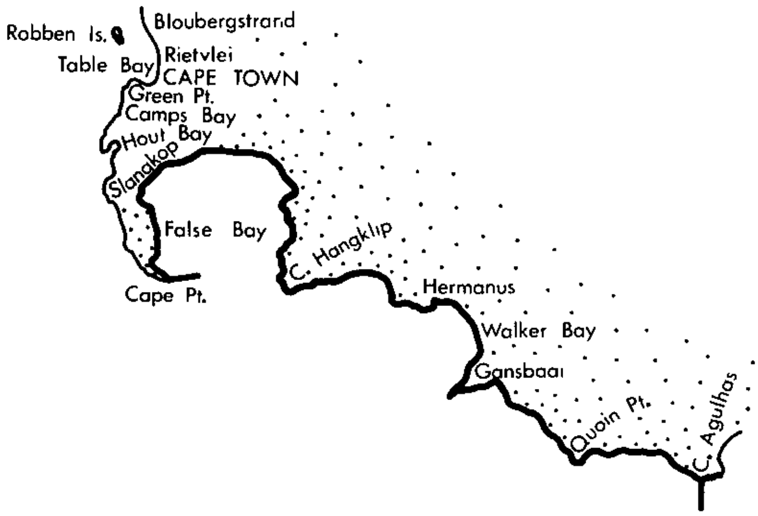


Figure 56. NOAA infrared image showing well developed upwelling as far east as Cape Agulhas (light grey) on 77.03.15.

4.1 CAPE AGULHAS TO CAPE POINT



The ships' drift data (Bray 1959-1964) are shown in the following table. They have been divided into two seasons: May to September and October to April - the latter being the period when the winds from the southeast prevail. The current directions are approximately parallel to the coast and have for convenience been labelled west- and east-going. Both 'up' and 'down' voyages have been used. Distances from the shore at 'fixes' were up to 12 km.

Table 30. Current directions (ships' drift), Cape Agulhas to Cape Point

	No. of observ= sations	mean distance from shore km	% west going	% east going	% slack water
Cape Agulhas to Quoin Point:					
Winter (May - Sept)	75	7	23	41	36
Summer (Oct - April)	102	7	60	17	23
Quoin Point to Danger Point:					
Winter (May - Sept)	74	9	19	41	41
Summer (Oct - April)	104	9	51	20	29
Danger Point to Cape Point:					
Winter (May - Sept)	74	12	38	27	35
Summer (Oct - April)	101	12	62	9	29

Notable points arising from these data are:

(a) the sample is biased towards the 'summer';

(b) there is a high frequency of slack currents especially during the 'winter' when it can be as high as 40%;

(c) there is a clear seasonal difference; west-going currents prevailing in the summer over the whole region and over the western part in the winter.

In Figure 57 the net percentage frequency of current direction (Bray 1959-1964) has been represented by arrows of length proportional to the difference between the frequency of occurrence of east- and west-going currents. The data suggest that the Benguela Current may be thought of as having a source as far east as Cape Agulhas in the summer, and probably further west in the winter.

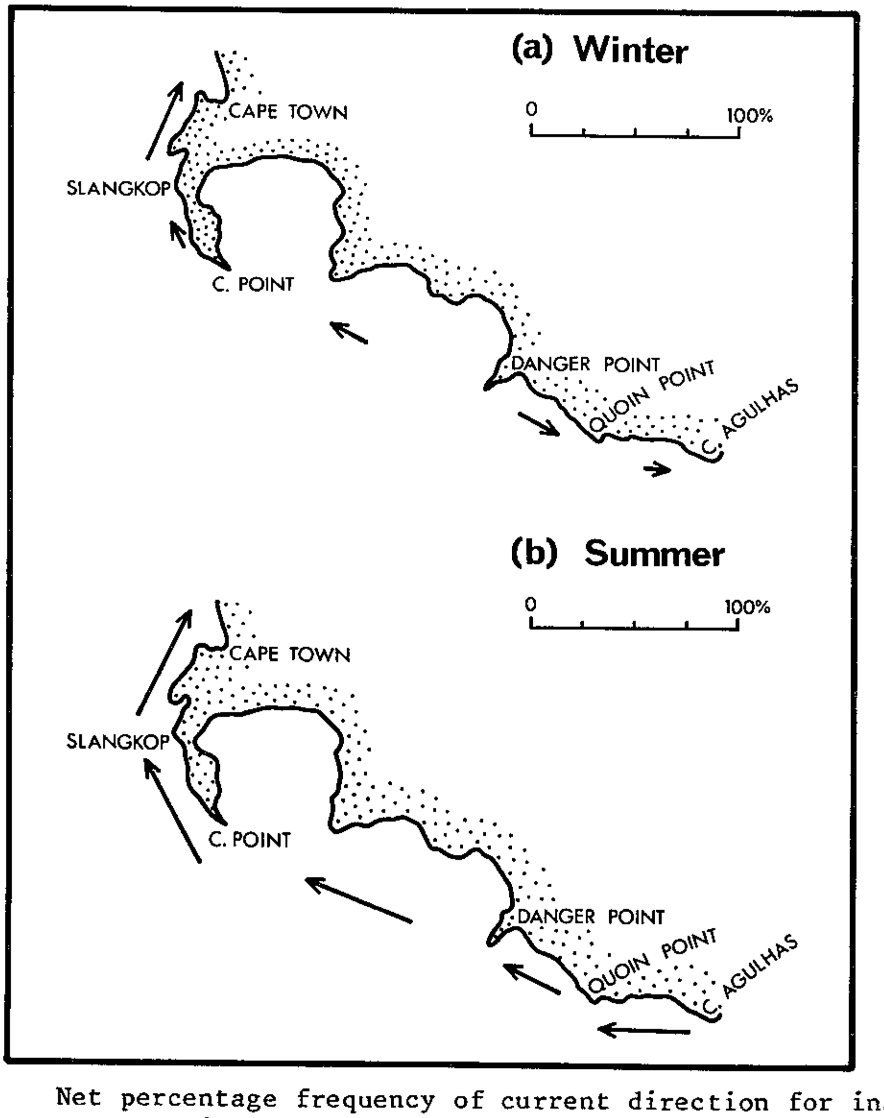


Figure 57. Net percentage frequency of current direction for inshore currents 'parallel' to the coast (a) in the winter months (May to September) and (b) the summer months (October to April) (data from Bray 1959-1964).

Examination of the current and wind directions between Danger Point and Cape Point shows that the west-going current had a favourable accompanying wind (between south and east) on 70% of the occasions. On 14% of the time the wind was contrary to the current (that is between west and north) usually in the summer months. The east-going currents were with the wind (between north and west) on 69% of the occasions, nearly all of which were in the winter months.

Data from Tripp's (1967) analysis follow in Table 31.

Table 31. Current directions (ships' drift, wind subtracted), Cape Agulhas to Quoin Point (percentages as in Figure 58).

	Total	W	WI	EI	E	EO	WO	Slack
Summer and autumn								
No. of observations	38	10	-	2	4	4	12	6
Mean velocity (m s^{-1})		0,32	-	0,23	0,28	0,38	0,30	
Winter and spring								
No. of observations	22	7	1	-	3	2	2	7
Mean velocity (m s^{-1})		0,31	0,20	-	0,33	0,31	0,38	

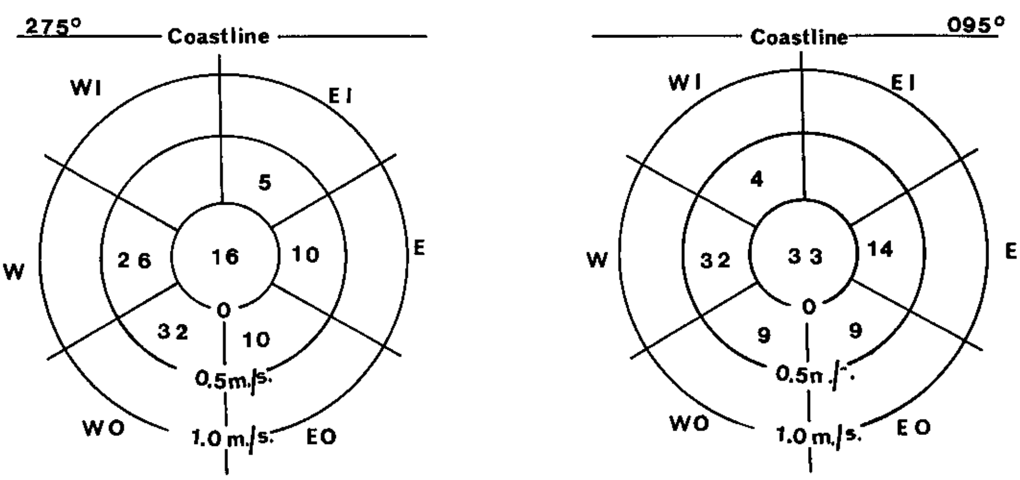
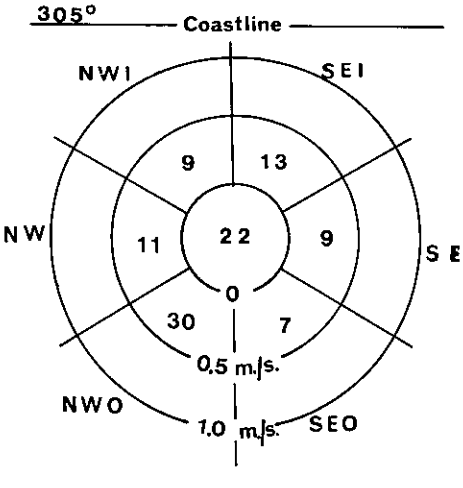


Figure 58. Current roses - wind subtracted - for Cape Agulhas to Quoin Point, (left) summer and autumn, (right) winter and spring (data from Tripp 1967).

Table 32. Current directions (ships' drift, wind subtracted), Quoin Point to Cape Point (percentages as in Figure 59).

	Total	NW	NWI	SEI	SE	SEO	NWO	Slack
Summer and autumn								
No. of observations	46	5	4	6	4	3	14	10
Mean velocity (m s^{-1})		0,33	0,37	0,27	0,26	0,37	0,34	
Winter and spring								
No. of observations	31	6	2	3	2	5	9	4
Mean velocity (m s^{-1})		0,45	0,36	0,36	0,48	0,23	0,25	



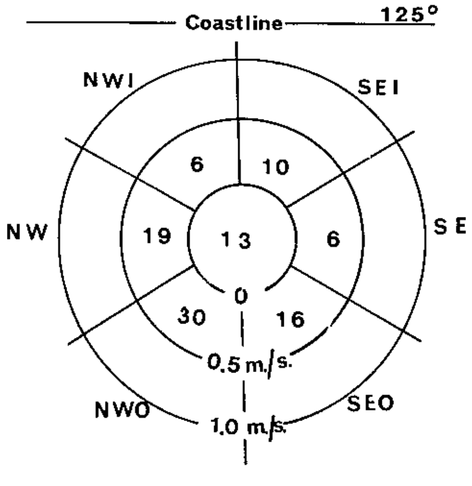


Figure 59. Current roses - wind subtracted - for Quoin Point to Cape Point, (left) summer and autumn, (right) winter and spring (data from Tripp 1967).

The directional roses above both show an excess of northwest-going over southeast-going currents for both seasons. It must be recalled that the data have had 3% of the wind speed vector subtracted and are not comparable with the other ships' drift data, but should represent a basic current in the absence of wind. It is interesting that the roses show a high percentage frequency of current flowing in a westerly direction in both seasons. However, the sample size is small.

Staff of the Sea Fisheries Branch (Tromp, et al 1975) occupied a grid of closely spaced stations in this region. Based on the distribution of density they made deductions about the current patterns. That, for the month of December 1975 on the density surface Sigma-t 26, is shown in Figure 60. The patterns for the winter months are much more complicated.

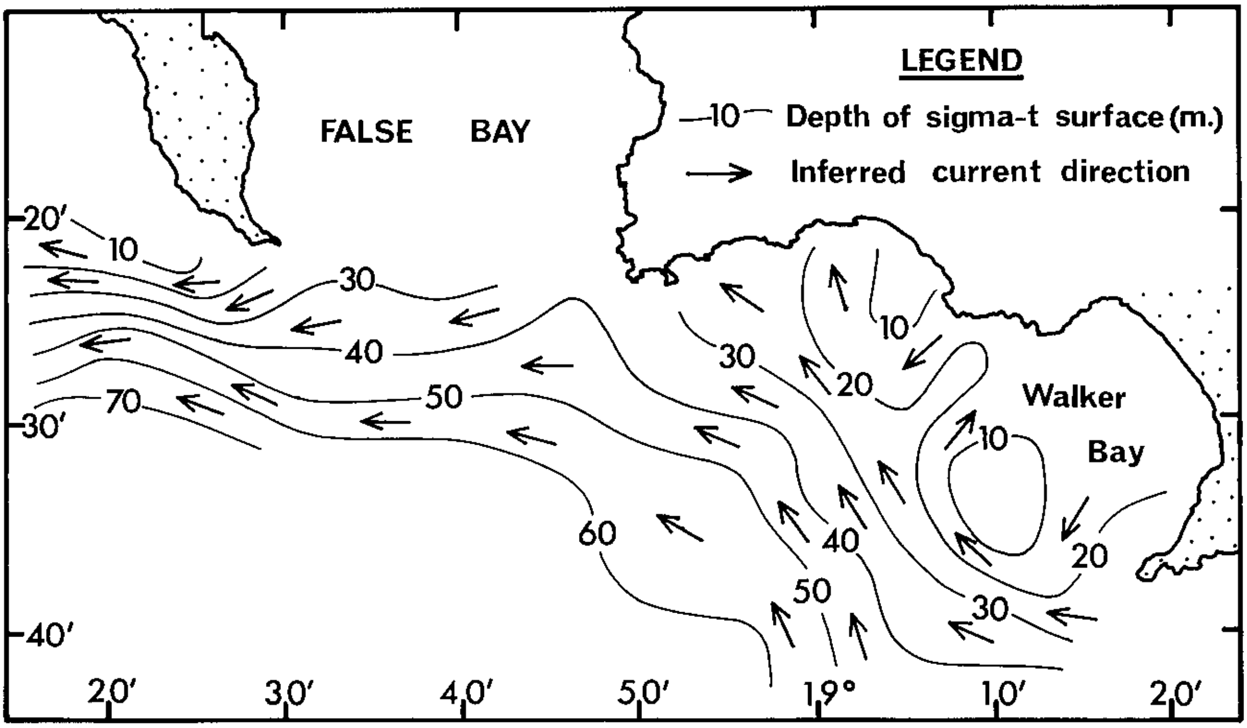


Figure 60 The pattern of currents for December 1975 deduced from the topography of the 26,0 sigma-t surface (Tromp et al 1975 with permission).

Walker Bay

Duncan and Nel (1969) of the Division of Sea Fisheries (now the Sea Fisheries Branch) used drift cards to study the surface currents in Walker Bay. During the period January - December 1963 over 600 cards were released at approximately monthly intervals in the vicinity of Hermanus and Gansbaai. Points of interest from their report are:

(a) In January and December cards were recovered in False Bay;

(b) In November cards moved from Hermanus to Cape Point and there was evidence of a small cyclonic eddy in Walker Bay;

(c) In December there was also evidence of a cyclonic vortex in Walker Bay;

(d) In the winter months there was a clear southeasterly current between Hermanus and Gansbaai with some cards rounding Danger Point, though in July and August the cards were confined to the bay.

False Bay

False Bay is the largest coastal bay on the South African coast. It is almost a square with sides about 30 km in length. It shoals regularly from a depth of about 80 m at its mouth.

A study of the winds and current patterns which prevail in the bay was undertaken by Atkins (1970). He reports that previous drift card work by the Division of Sea Fisheries had led to the suggestion that in the summer a west flowing current enters False Bay (probably on the Cape Point side). A few cards released north of Cape Town were reported from Buffels Bay and Simons Bay, having rounded Cape Point.

Atkins' method was to track floats (with drogues at 2 m depth), from an aircraft, over a period of 40 minutes. He made measurements at 11 stations (see Figure 61) on 13 occasions in 1964 - 1965. In addition in 1965 - 1966 measurements were made on 15 occasions close to the shore between Simonstown and Steenbras River. The earlier experiments enabled four different kinds of current patterns to be identified. These are illustrated by examples in Figure 61 and are as follows:

Type 1 is developed by easterly or southeasterly winds outside the bay in the region of Danger Point. The wind driven water enters the bay and forms a large cyclonic circulation with a small cyclonic or anticyclonic vortex off Gordons Bay.

Type 2 (one example only) is developed by a northwesterly wind. An easterly current enters the bay near Hangklip and follows the coastline of the bay until being influenced by winds within it.

Types 3 and 4 occurred after a period of calm and had slow-moving currents apparently of tidal origin, though in the deeper water velocities were higher than those calculated.

Circulation types 1 and 2 are apparently wind dependent. Notable is the fact that at Cape Point the southeasterly winds (generating Type I circulation) prevail throughout the year.

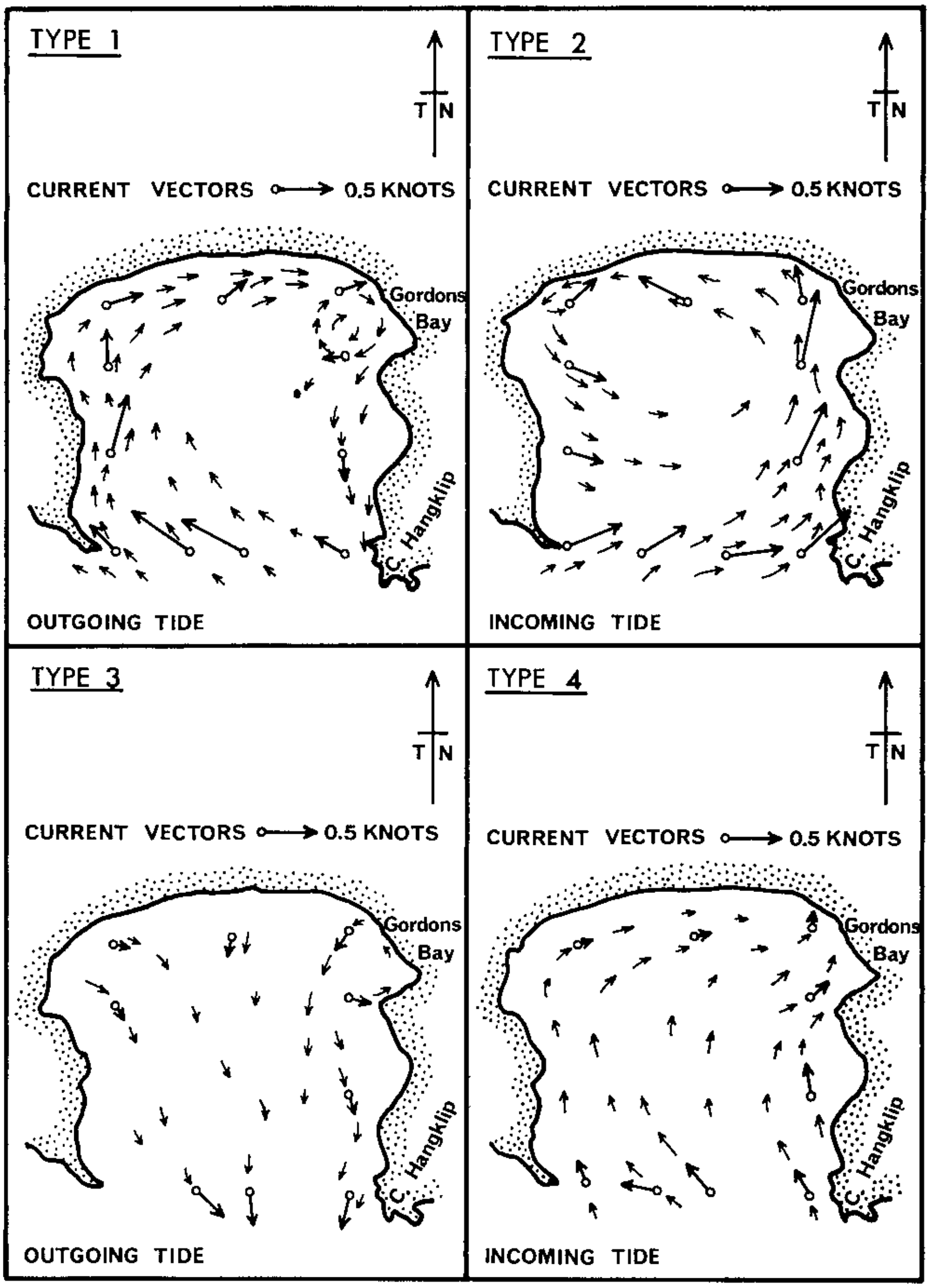
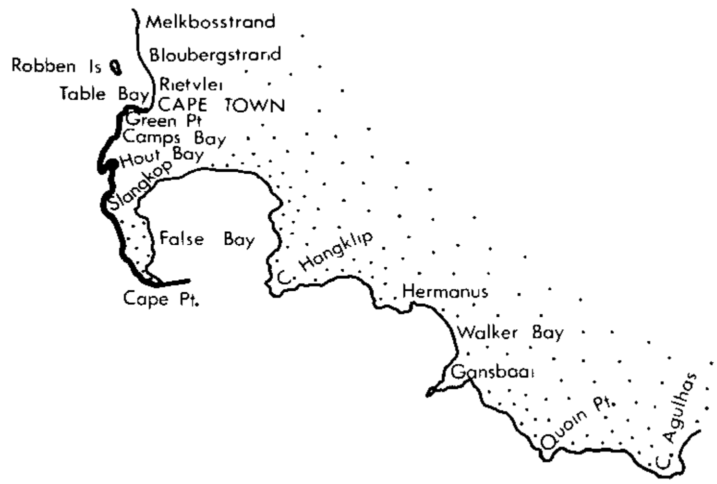


Figure 61 Representation of four types of current circulation found in False Bay (Atkins 1970 with permission).

4.2 CAPE POINT TO TABLE BAY



The orientation of the coastline in this region is roughly of two kinds. That between Cape Point and Slangkop is approximately southeast-northwest, while between Slangkop and Table Bay the coastline curves away to the east. The former is more closely aligned to the prevailing winds and the latter is, in part, athwart them. The difference has some influence on the currents close to the coast.

The currents in the region have been studied for many years by the Sea Fisheries Branch and more recently by the University of Cape Town.

Statistics as to the current directions within several kilometres of the shore are available from ships' drifts (Bray 1959-1964). They refer to currents within 10 km of the shore and are set out below:

Table 33. Current directions (ships' drift), Cape Point to Cape Town.

	No. of observ= ations	% north going	% south going	% slack
Cape Point to Slangkop				
Winter (May to September)	72	37	25	37
Summer (October to April)	103	61	7	32
Slangkop to Cape Town				
Winter (May to September)	36	50	8	42
Summer (October to April)	52	60	3	37

The seasonal pattern in the Cape Point - Slangkop region is similar to that which emerged for the previous region. However, between Slangkop and Cape Town the winter pattern is unusual, there being little difference between seasons, with currents mainly north-going or slack.

The Sea Fisheries Branch have recorded a very interesting series of measurements of the sea surface temperature, made by airborne radiation thermometer, under different wind conditions. The results have been presented as charts of surface isotherms. Figure 62 shows the situation after the 'Southeaster' had been blowing for several days. Very cold water has upwelled along the coast between Cape Point and just north of Hout Bay. A plume or tongue of cold water can be seen deflecting offshore and passing west of Robben Island.

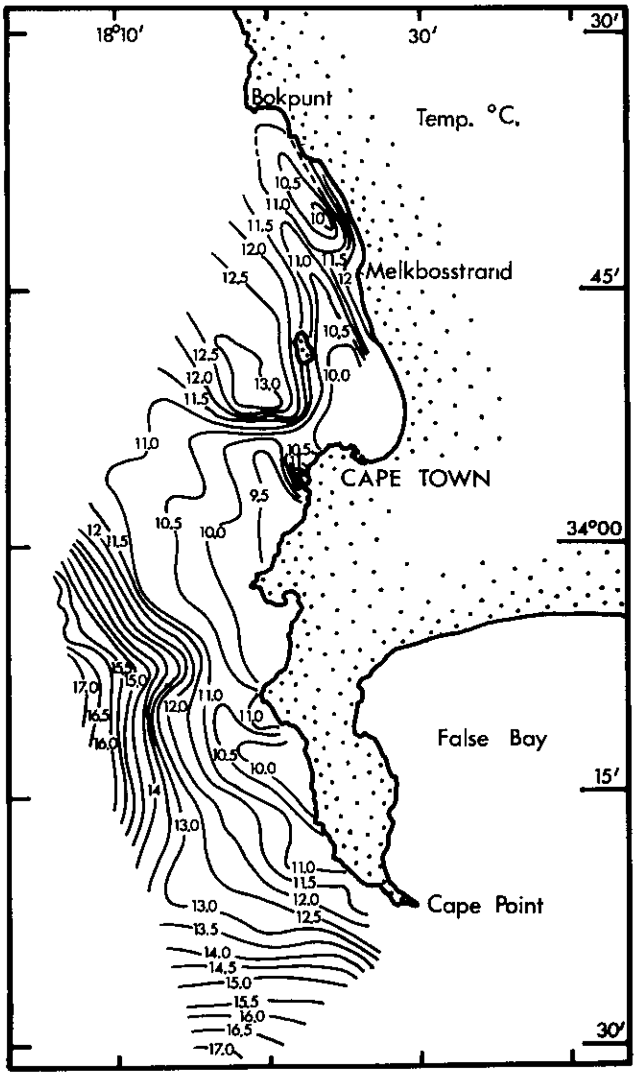


Figure 62 Surface isotherms (°C) constructed from airborne radiation thermometer readings indicating cold up=welled water orginating along the Peninsula and flowing out west of Robben Island; and another cold tongue north of Table Bay, with warmer water between them (data from Sea Fisheries Branch, drawing from Gunn 1977a).

Closer to the coast the currents have been measured by Atkins at Camps Bay (1965a) and Green Point (1965b) near Cape Town. His method was to track floats from the shore. Figure 63 shows some of the float trajectories for Camps Bay. There was apparently little correlation with the wind - probably on account of the influence of coastal discontinuities. The figure illustrates the complexities of current patterns in Cape embayments.

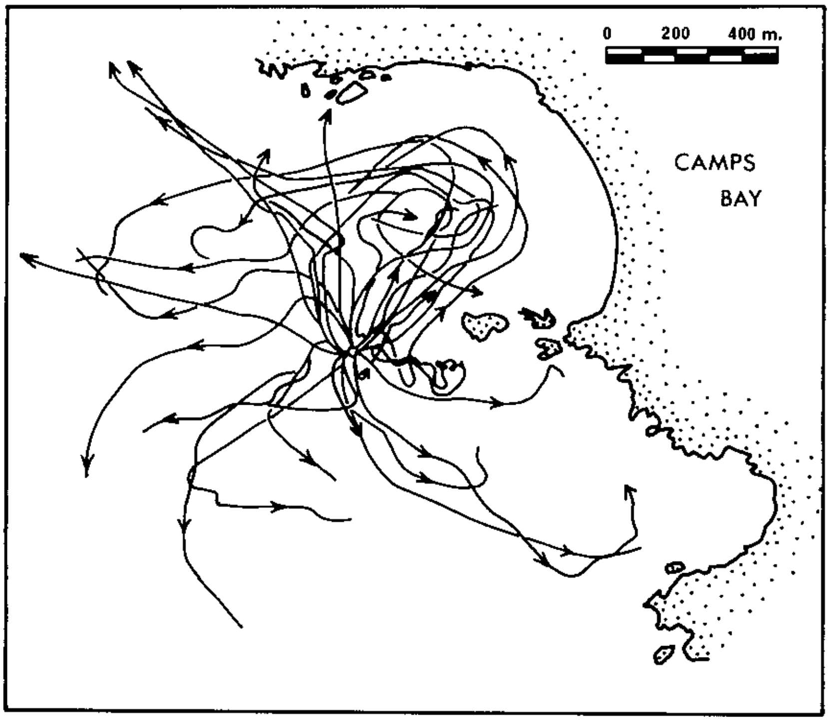


Figure 63 Trajectories of floats at Camps Bay in the winter months (after Atkins 1965a).

Similar intensive studies have also been made at Green Point which is situated a few kilometres to the west of Cape Town. The procedure was to track floats (drogued at 2 m depth) which were released up to about 3,5 km from the shore. Observations were made on nearly 1 000 floats. The results, reported by Atkins (1965b) include the following points:

(a) Green Point is in the wind shadow of Table Mountain and does not experience the same high frequency of southeasterly winds that occur commonly in this region in the summer months. Nevertheless during the months October to March currents (one mile offshore) directed between 60° and 120° true, have by far the highest frequency of occurence (70%). However, northerly and easterly winds occur and do generate onshore currents.

(b) In the winter there is more variety of direction, mostly between north and west (36%) and between west and south (54%) (for floats released one mile offshore).

(c) While the prediction of currents during strong southeasterly winds is possible, the prediction of slow onshore currents due to northerly and easterly winds is difficult.

Table Bay

An intensive study of the currents in Table Bay has been reported by Van Ieperen (1971). Currents were measured by tracking free floats with drogues, from a ship. The drogues were set at 1,8 m depth. Floats with deeper drogues (13-50 m depending on the water depth) were also tracked at deep water stations. Complete coverage of 16 stations was achieved in 36 hours. Measurements were made on 33 occasions (approximately every month) during the period July 1966 to May 1969. In addition 'surface' currents were measured on a line of four stations between Bloubergstrand and Robben Island (14 times) and on a line of seven stations between Green Point and Robben Island (5 times). From these data estimates were made of the residence time of the water in the bay. Finally, a moored current buoy system was set up at a point 800 m offshore, 2,4 km south of Bloubergstrand. The drogue was set at 2 m.

The main conclusions were:

(a) that the direction of the currents correlated well with those of the prevailing wind (see Figure 64). On the other hand velocities did not correlate;

(b) residence times were about 1-4 days;

(c) current velocities were generally weak - of the order of 20 cm s^{-1} - and were weakest in the winter;

(d) deep currents (10-25 m) were weaker than the surface currents. Their directions were similar to the surface currents, being strongly correlated for northerly currents but less so for directions 60^o-180^o;

(e) at the moored current buoy site, near Bloubergstrand, the dominant current direction was northwesterly (81% in summer and 69% in winter);

(f) the predominant flow of Table Bay water is northward (except in the lee of Robben Island where slack current conditions were most frequent). See Figure 65 for current roses.

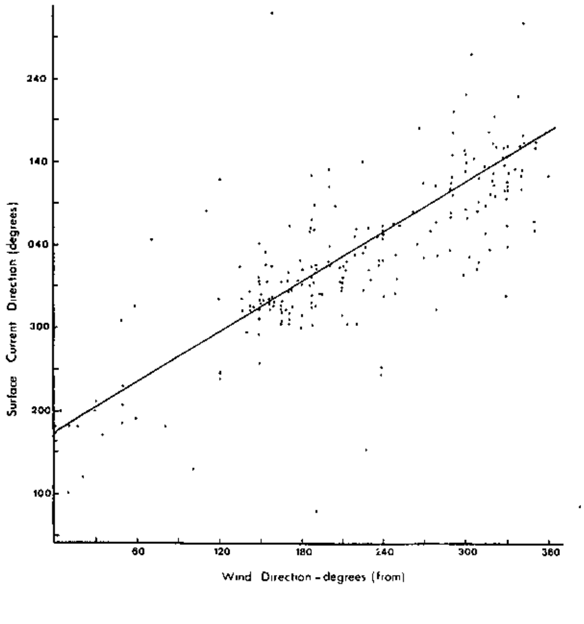


Figure 64. Comparison of surface current and wind directions in Table Bay (Van Ieperen 1971).

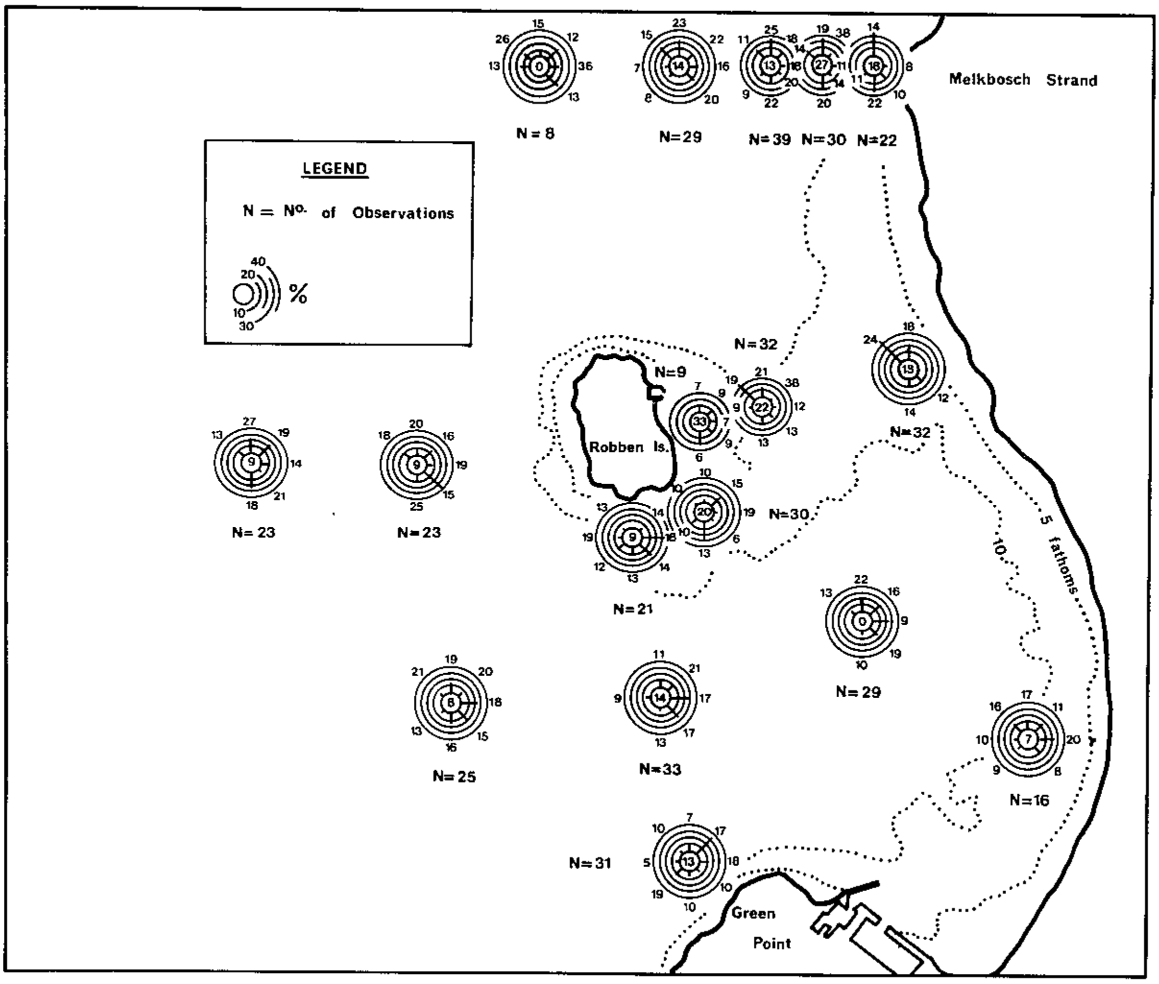
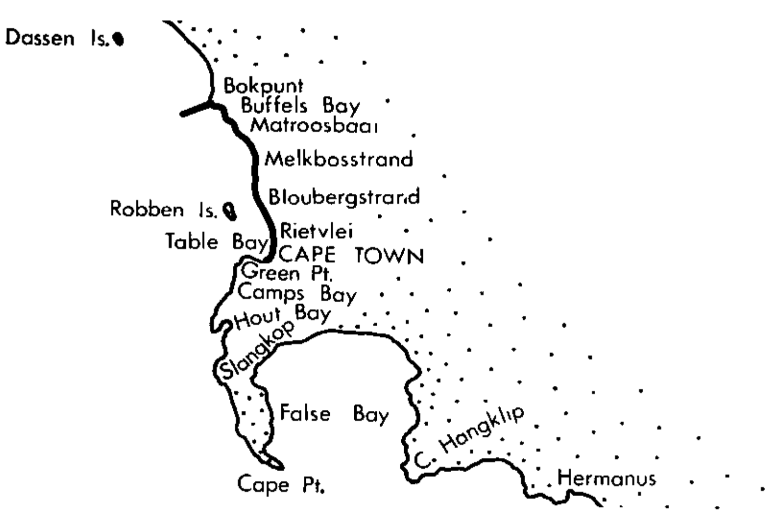


Figure 65. Surface current roses for Table Bay. Numbers around roses are average velocities in cm s^{-1} (after Van Ieperen 1971).

4.3 TABLE BAY TO BOK POINT



Apart from the studies made by Bang and Andrews (1974) referred to above, there is little information about the offshore currents in this region. Closer inshore however, within a few kilometres of the coast, there have been intensive investigations by the University of Cape Town and the coastal currents are fairly well known. These investigations include water movement studies made for the Electricity Supply Commission in connection with a proposed nuclear power station at Duynefontein (not used in these notes) as well as those sponsored by the Atomic Energy Board (Bain & Harris 1975-1977) and the National Programme for Environmental Sciences (Gunn 1977a, 1977b).

The general conclusion is that (apart from wave-driven currents in the nearshore region) currents flow in response to a steady wind - a conclusion in line with van Ieperen's studies in Table Bay referred to in the previous section. Figure 66 shows the current trajectories of floats and accompanying southeasterly winds in the embayment just north of Melkbosstrand and currents in the same bay under the influence of contrary (northwesterly) winds.

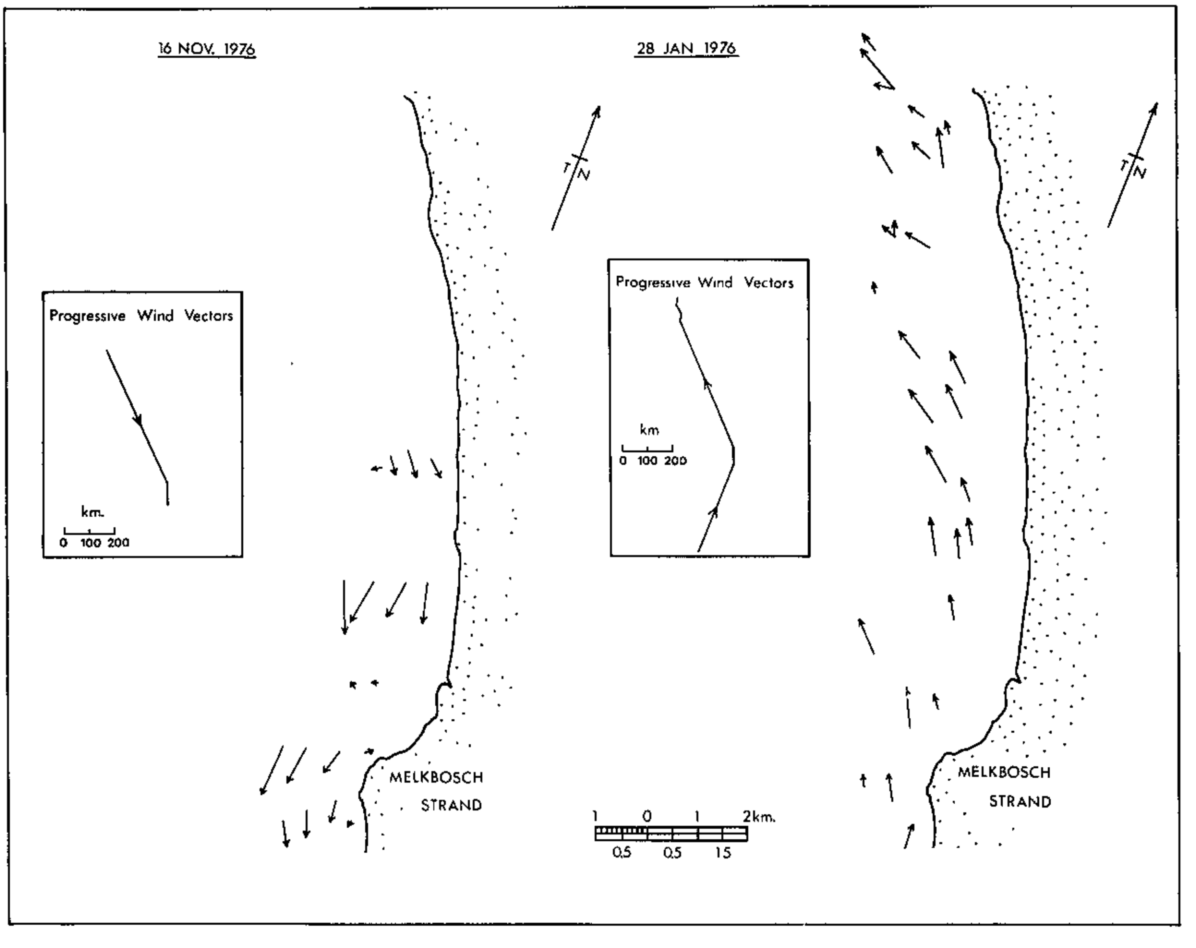


Figure 66. Float trajectories of one hour's duration off Melkbosstrand, with progressive wind vectors (north-going and south-going inset) (after Bain & Harris 1975-1977).

Some conception of the wind regimes for this region is given by the directional frequency roses in Figure 67.

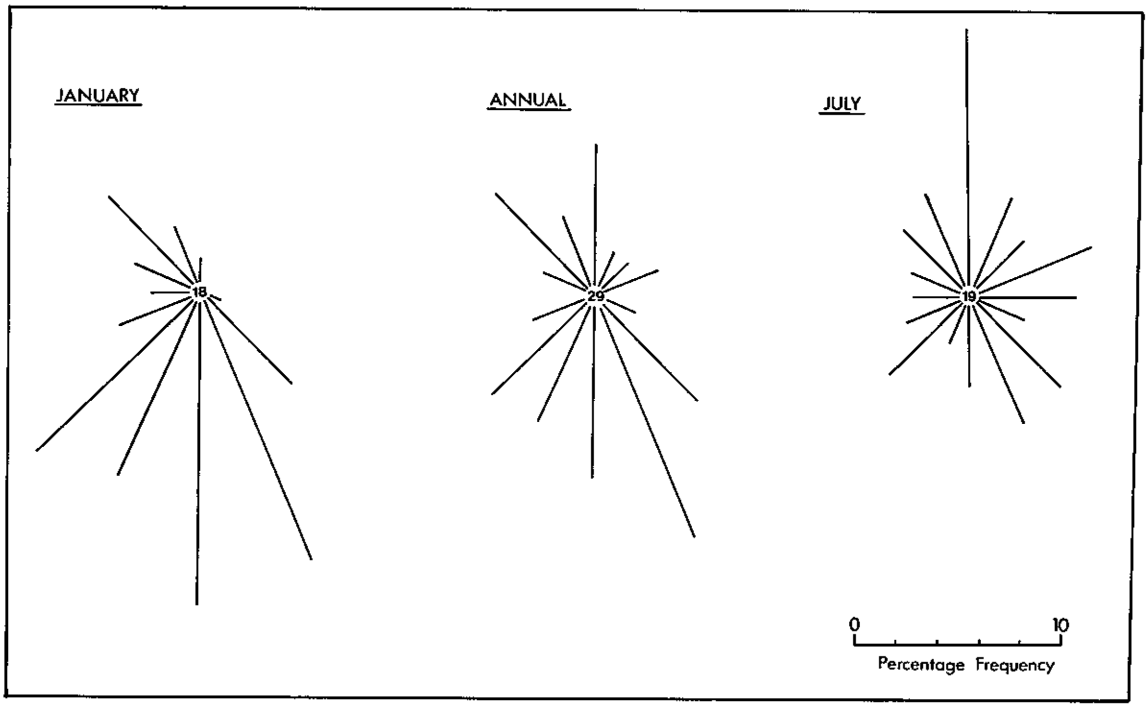


Figure 67. Directional frequency roses for winds near Melkbosstrand. (data from University of Cape Town 1977 with permission).

Several points have emerged from studies in this region.

(a) Current velocities were seldom greater than 20-30 cm s^{-1};

(b) under the influence of northwesterly winds there is a tendency for onshore movements;

(c) in this part of the coast occasions of no wind or light airs occur relatively frequently, especially in the winter months when the percentage frequency may be 30-40%. Concurrent slack currents are likely to be experienced.

While it may be true that the currents near the shore in this region are primarily wind driven, complications must arise because of the following processes:

(a) There will be a tendency for the Ekman effect to operate and for currents to deflect to the left of the wind. Theoretically this will not be significant in shallow water;

(b) Winds are not steady and when the wind drops the inertia effect will theoretically cause currents to deflect to the left and they may execute inertia circles;

(c) In some Cape embayments such as that in which the above measurements were made, the sea floor near the coast shelves very slowly. The slope is less than 1 in 100. The surf can be relatively wide (500 m) and rip currents may penetrate seawards for a considerable distance (say 3 km). In these instances the nearshore circulation is superimposed.

As stated already the current data for this region have been collected within a few kilometres of the coast. Further offshore there may well be complications, a hint of which (during southeasterly winds) is contained in Figure 55 and Figure 62. The current flowing up the Cape Peninsula appears to separate from the shore in the vicinity of Hout Bay (where the coastline direction changes) and forms a kind of jet passing to the west of Robben Island. Between Robben Island and the mainland another jet stream moves up the coast. Both systems probably entrain water and this process might cause a counterflow between them. During a southeasterly blow, both jet systems advect cold water and there is initially a warmer region between these which might represent the counterflow consequential on entrainment. In Bang's (Bang & Andrews 1974) direct current measurements along a line out from Cape Town this counterflow was found to have a velocity of 20 cm s^{-1} at 45-55 km off-shore. A schematic idea of such a system is drawn in Figure 68.

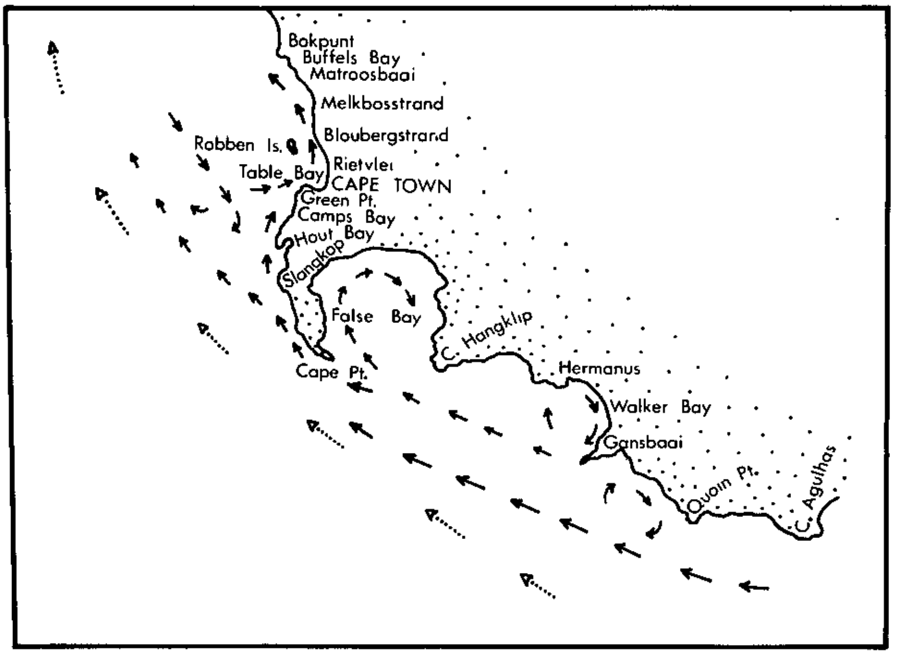


Figure 68 Schematic surface currents chart for southerly winds (tenta= tive), ·····▷ Agulhas water, ⟶ wind driven circulation.

Wave-driven Currents

Reference to wave-driven nearshore circulation has already been made. These circulations, while being of significance on open coasts because of their scale, assume a different but equally important role in embayments. There have been two studies of the circulation in embayments by the University of Cape Town - sponsored by the National Programme for Environmental Sciences and reported by Gunn (1977a and b). They were carried out on a small embayment, Matroos Bay (1,5 km wide) and a medium size one, Buffels Bay (4 km wide).

Matroos Bay

The results from Matroos Bay suggest that in bays of this size (and waves approaching normally) there will be two kinds of circulation depending on wave height (and possibly period):

(a) With high waves, the wave crest obliquity causes an inflow at the sides and a central rip current returning the water seawards;

(b) with low waves, the non-uniformity of the wave heights around the bay, caused by refraction at the sides (higher waves at the centre), cause an inflow towards the centre of the beach and an outflow, by way of rip currents, along the sides.

These two types of circulation are illustrated by examples in Figure 69.

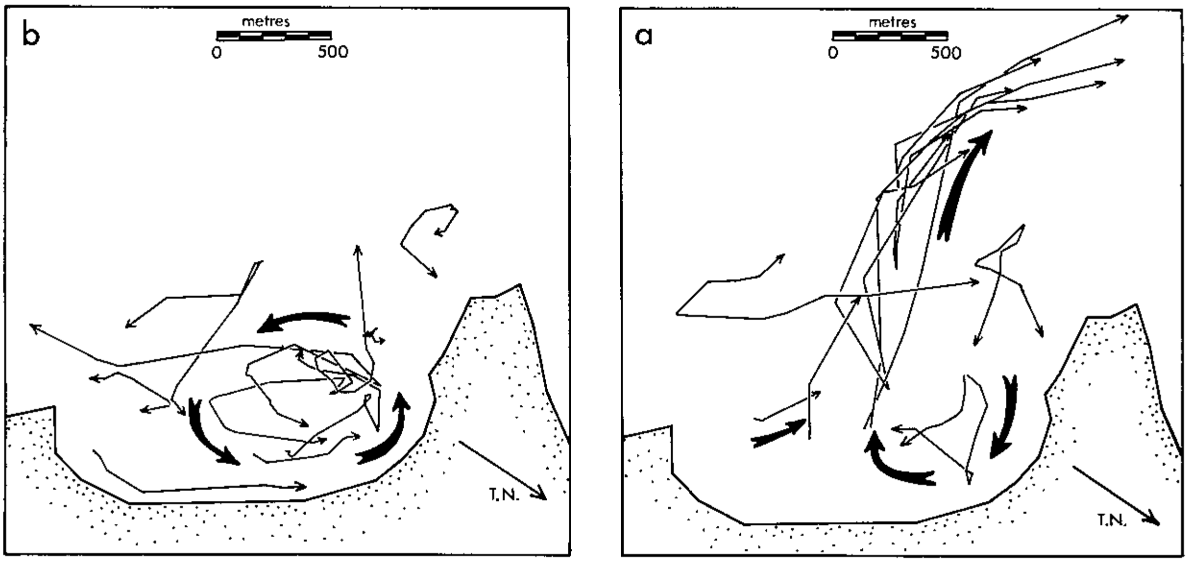


Figure 69. Circulation in Matroos Bay (a) high waves (b) low waves (after Gunn 1977b).

Buffels Bay

Both wind and wave influence were found to drive circulations of this larger bay.

(a) Southerly winds of moderate strength (possibly greater than 10 m s^{-1}) caused a flow from the southern to the northern headland.
No data for moderate northerly winds are available;

(b) under light wind conditions the circulation tended to be mainly wave-driven, with some characteristics of the wind-driven component still present at times.

Circulation types occurring under light winds include a southerly drift, a clockwise circulation with high waves (1,4-2 m), and an anticlockwise circulation with low waves (0,4-1,2 m). These four circulations are illustrated in Figure 70. There were also other mixed types of circulation.

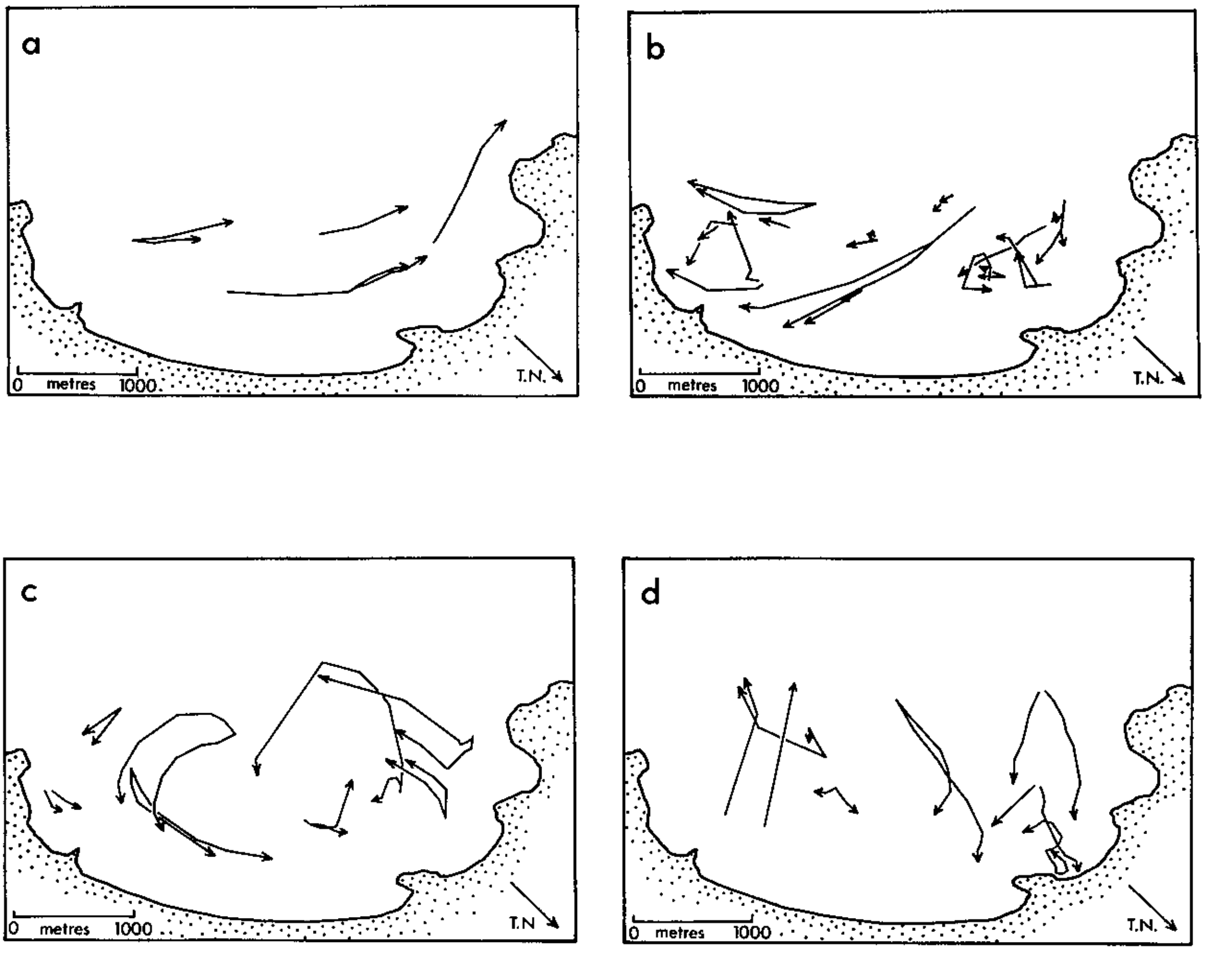


Figure 70. Circulations in Buffels Bay (after Gunn 1977a)
(a) with southerly winds
(b) light winds - southerly drift
(c) anticlockwise circulation - low waves
(d) clockwise circulation - high waves.

On the open coast the nearshore circulation can exert an influence on coastal currents to a maximum distance of very roughly 3 km. Some impression of the size and extent of rip currents which can be generated by high waves in this region may be had from Figure 71.

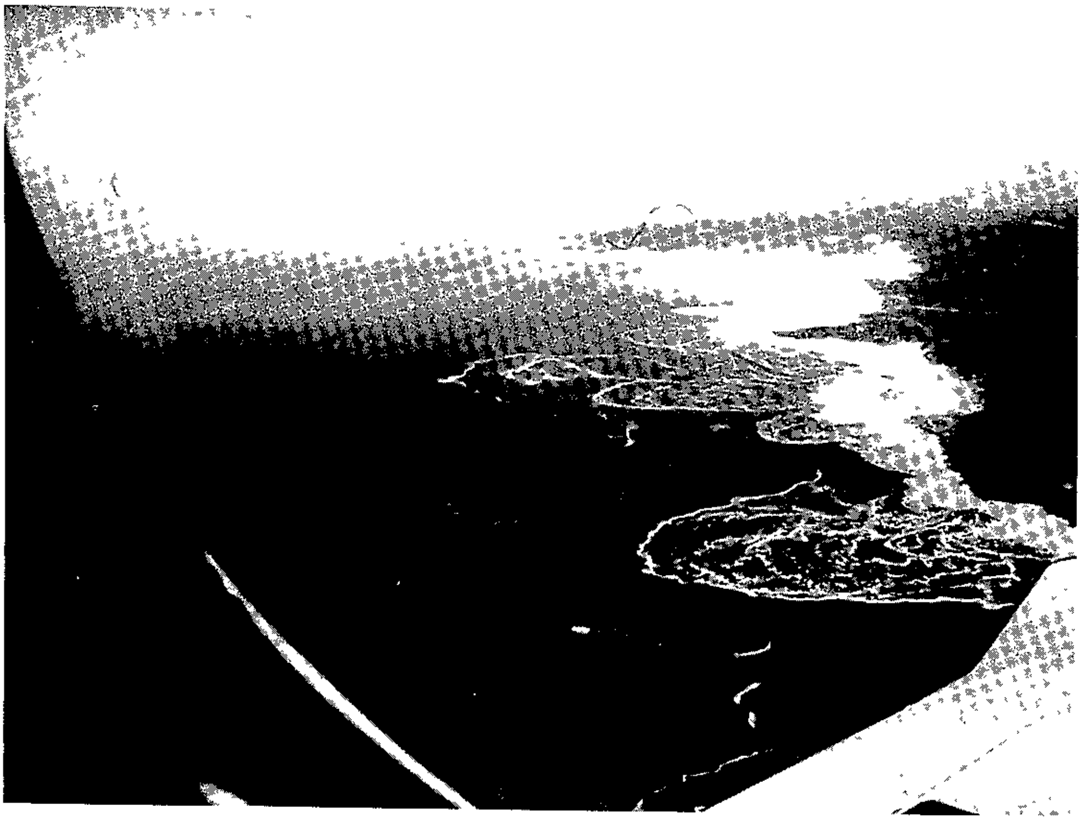
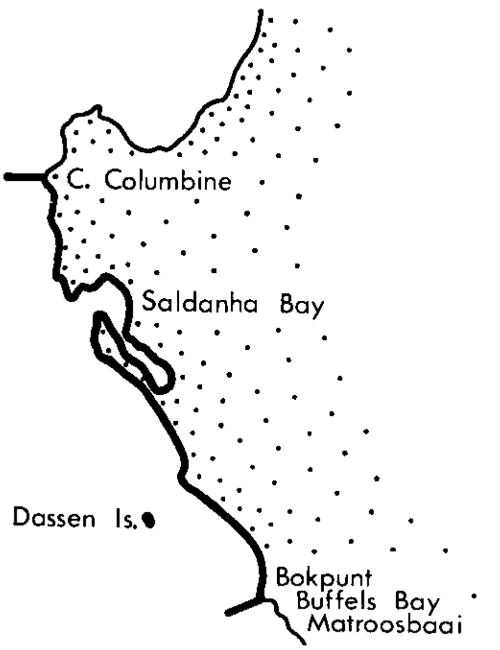


Figure 71. Rip currents outlined by foam, off the coast in the Matroos Bay region (photograph by C A R Bain).

4.4 BOK POINT TO CAPE COLUMBINE



The only known measurements of coastal currents in this region are those made by NRIO (1976) between Saldanha Bay and Cape Columbine. Stations were occupied along three lines from 5 km out to the 100 fathom line, during nine days in August/September 1974, eight days in June 1975 and nine days in November 1975. Measurements of current direction and velocity were made.

The general conclusions are as follows (taken from the report, NRIO (1976):

(a) 'The direction of water movement in the area is mostly equatorward and its speed is generally low, but local velocities in excess of 1 m s^{-1} are found at times (most velocities were less than 30 cm s^{-1}';

(b) 'the subsurface currents tend to agree both in velocity and direction, with the surface currents';

(c) 'the inshore currents tend to be weaker than the offshore currents';

(d) 'the currents are mainly wind-driven and are not only set up by the local wind but may also be caused by wind fields further away'.

Figure 72 shows the current vectors on 21, 22 and 24 June 1975. The winds were respectively NNE (10 m s^{-1}), NNW/S, S(5 m s^{-1}), and represent the passage of a front. The sensitive response to the wind is noteworthy.

The sample in this study was not large (25 days), but until more intensive studies are made, it seems reasonable to assume that the currents respond readily to the wind. There will be exceptions. Wind data for Cape Columbine are given in the next section.

Saldanha Bay

Currents in Saldanha Bay were reported by Shannon and Stander (1977) during a symposium on the bay. They used drogued floats, dyes, and drift cards to investigate the near-surface currents. Their preliminary conclusions include the following.

The currents in the bay are both tidal, and wind-driven (in the upper 5 m). Current velocities were typically 10-20 cm s^{-1}. In the mouth the tidal currents at ebb and flow were 14 cm s^{-1}. A schematic representation of the current circulation is shown in Figure 73. No doubt it will be modified by the prevailing wind.

In the Langebaan lagoon the currents were mainly tidal reaching 1 m s^{-1} during spring tide. The wind is a modifying factor.

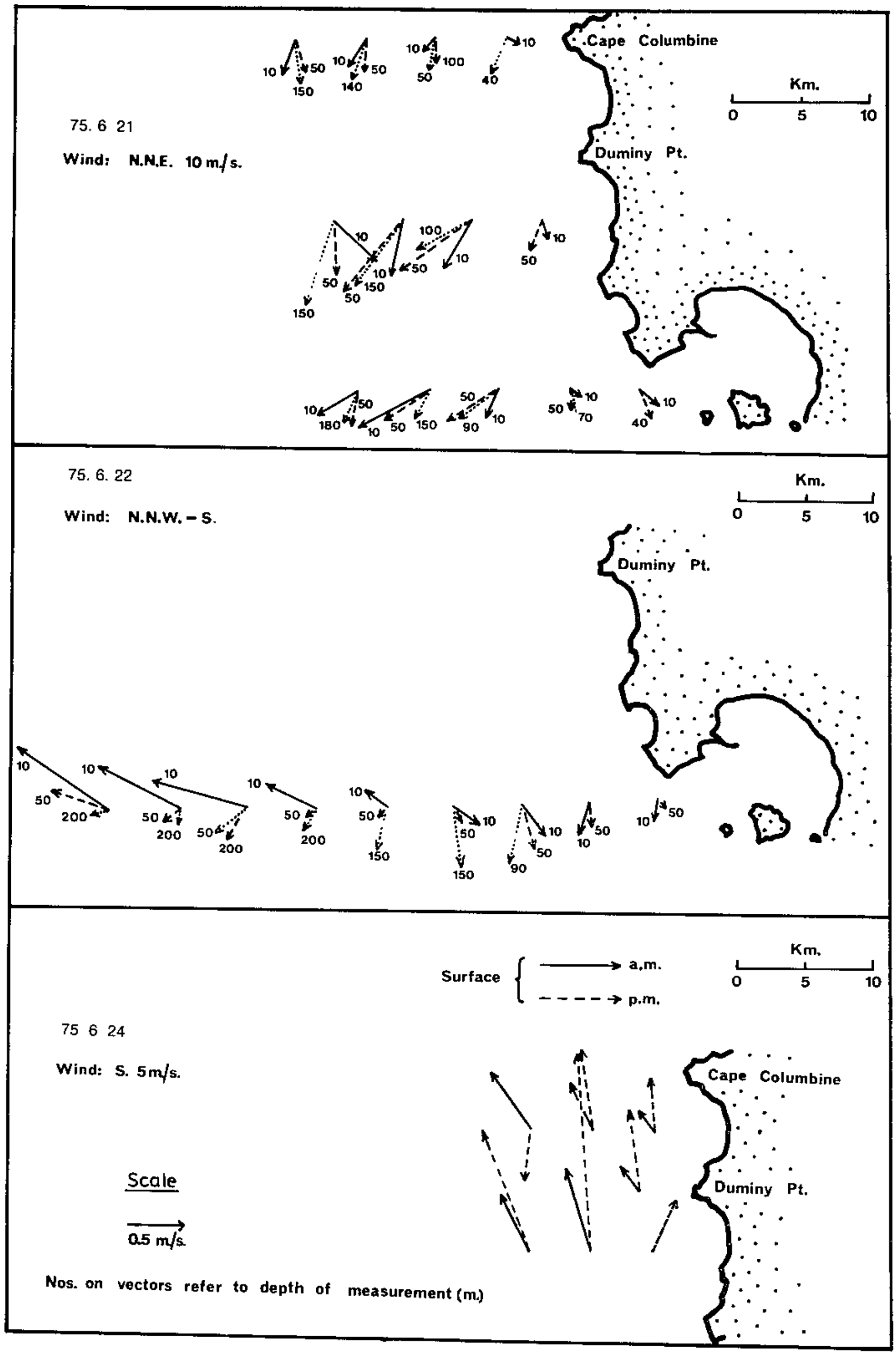


Figure 72. Measured currents off Saldanha - Cape Columbine region, during the passage of a 'front' (after NRIO 1976 with permission).

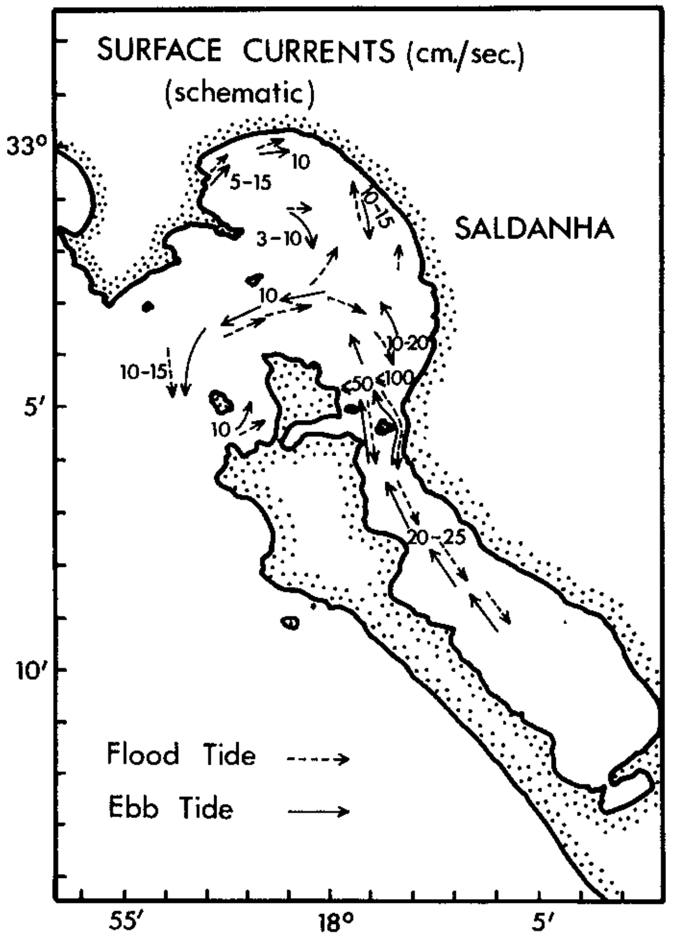


Figure 73. Schematic representation of surface currents in Saldanha Bay (Shannon & Stander 1977 with permission).

4.5 SUMMARY SECTOR IV CAPE AGULHAS TO CAPE COLUMBINE

Several factors have important influences on the coastal currents in this sector.

(a) The sector lies within latitudes which are sensitive to well known seasonal migrations of the large scale atmospheric pressure systems. In the summer months a high pressure system from the subtropical Atlantic 'high' lies to the south of the Cape and generates the southeasterly winds which blow around the coast. While this is periodically displaced by fronts arriving by way of the subpolar westerlies, the clockwise system dominates. In the winter months the high pressure retreats equatorward and then westerly (or southwesterly) winds accompanying fronts move equatorward and increase their influence. Insofar as winds are responsible for the sector's currents therefore, a seasonal approach seems essential;

(b) the prevailing winds tend to be parallel to the coast and consequently induce up- and down-welling;

(c) the shelf region is wide at Cape Agulhas, rapidly narrows towards Cape Point and then parallels the coast to Cape Columbine;

(d) a branch of the Agulhas Current (or Agulhas Current water) moves approximately northwest along the shelf break. Its actual behaviour is not yet clear. There is evidence that it moves in this way in the summer months apparently under the influence of southeasterly winds. Its winter regime is also not well understood;

(e) the coastline is broken, embayments are common.

The Regime of the Summer Months

The general current generating system which obtains in the summer months - approximately September to March - has two main components.

(a) Southeasterly winds apply wind stress and induce the upwelling of cold water which tends to deflect offshore;

(b) the upwelled water forms a front with the Agulhas Current water which lies offshore. This front appears to exist between Cape Point and Cape Columbine but its southeastern limit is not known. On the front a concentrated current moves to the northwest.

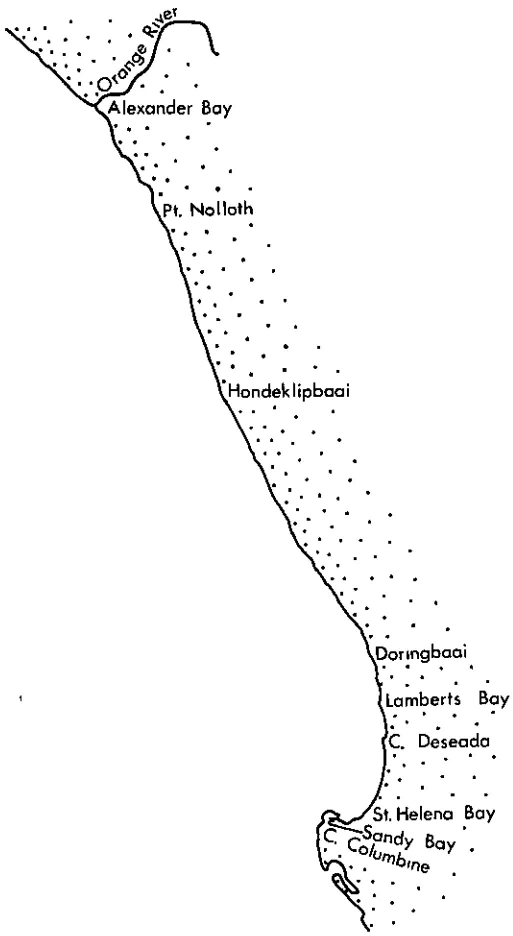
It is the current system between the coast and the front which is of particular interest. It seems to be dependent on wind stress, coastal configuration and the requirements of continuity. Such information as we have at present suggests a system of currents schematically represented in Figure 68. This is a representation of the system under the influence of the southeasterly winds. Experience has shown that the coastal waters are very sensitive to changes in the wind regime, although there may be additional considerations involving the restoration of the density distribution consequent on the release of the water from the wind stress.

The common experience is then that away from coastal discontinuities the coastal currents over the greater part of the sector may be predicted by considering the wind stress. Each coastal discontinuity will impose its own pattern on the local currents and it is possible, though not established, that a special area lies between the offshore front current and the region subject to upwelling along the coast in the region north of Robben Island.

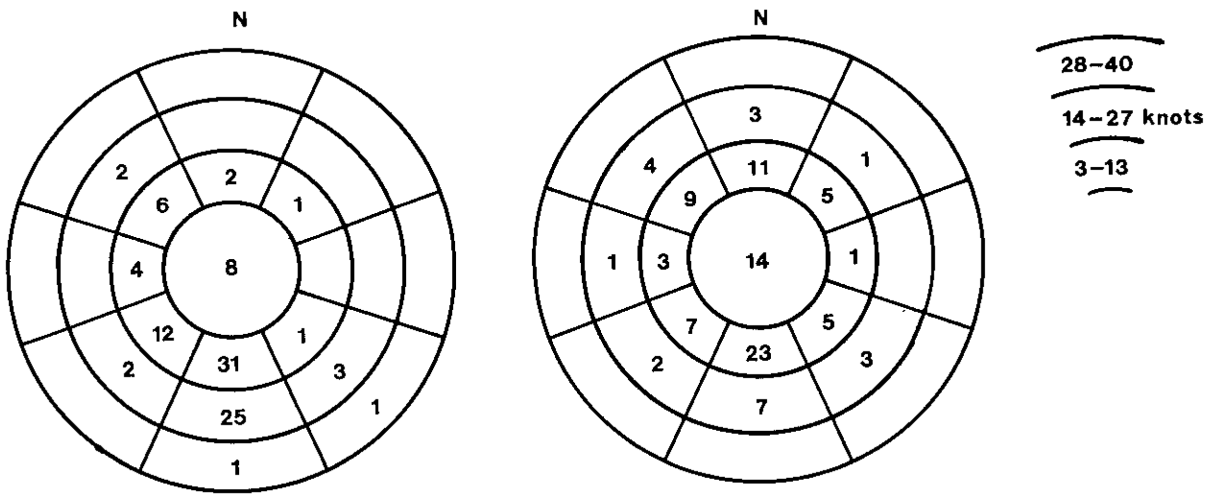
As may be expected the current velocities are not high compared with those in sectors in which the Agulhas Current has a more direct influence. Velocities over 50 cm s^{-1} are not common.

Wave-driven currents are an important influence in the smaller embayments. On the open coast (under high wave conditions) rip currents can penetrate seawards perhaps as far as 3 km. The cells of circulation of nearshore currents can therefore be much larger than those of the Natal coast for example. The reasons may be that this part of the coast is often gently sloping and experiences higher waves.

SECTOR V CAPE COLUMBINE TO THE ORANGE RIVER



For this sector as well there is very little information about the currents. However, some hint of what the current regime is likely to be may perhaps be deduced from the wind data. The distribution of winds at Cape Columbine is given in the two roses in Figure 74 for winter and summer.



SEPTEMBER TO FEBRUARY **MARCH TO AUGUST**

Figure 74. Percentage frequency of wind directions and velocities at Cape Columbine 15h00 (data from Royal Navy and South African Air Force 1942).

During the summer months 76% of the winds blow from between the SE - SW sectors and 11% from the NE - NW sectors. In winter the percentages are 47% and 33% respectively. If one assumes that the percentage frequency represents percentage of time, and calculates the products of the frequency and velocity for each class of wind, the result is the miles of wind blown. The values for the two opposing sectors are:

Table 34. Winds, Cape Columbine to Orange River.

Direction	Summer		Winter	
SE - SW	1 034 miles	(91%)	424 miles	(59%)
NE - NW	96 miles	(9%)	296 miles	(41%)

Wind roses for Port Nolloth near the northern boundary of the sector are shown in Figure 75. Southerly winds are the more frequent there at all seasons. Periods of calm or light winds are more frequent than at Cape Columbine.

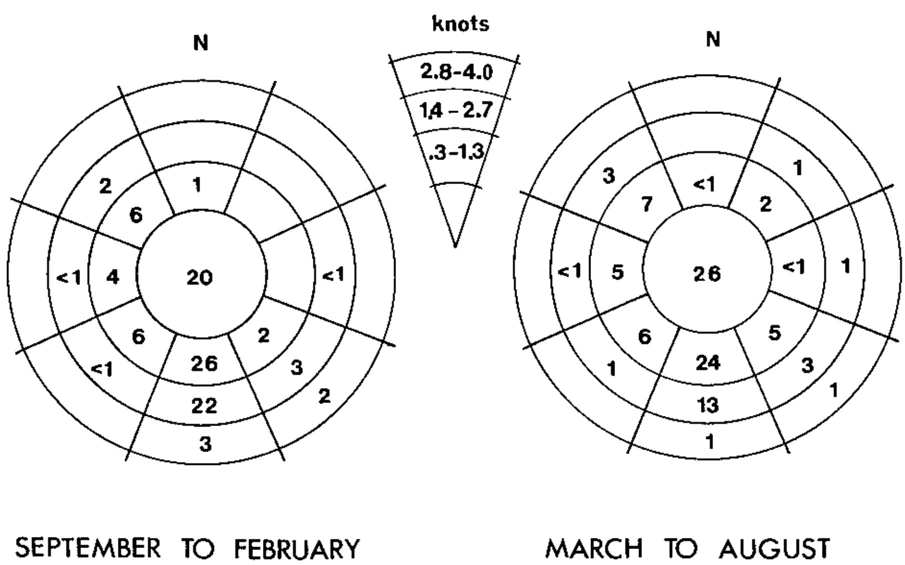


Figure 75. Wind roses for Port Nolloth 15h00 (data from Royal Navy and South African Air Force 1942).

From the wind data it is anticipated that the summer currents will be largely north-going. This is supported by the behaviour of a satellite tracked drifter, which was released off Cape Town in March and followed the trajectory shown in Figure 76 (Harris and Shannon 1978). The wind prevailing at the time is shown in the form of progressive wind vectors (using the square of velocity). The drifter's trajectory was about 15° to the left of the wind. Its mean velocity between the positions at day 70 and day 100 was about 0,25 m s^{-1} (approximately 0,5 knots).

Further support is to be had from a drift card study by Duncan and Nel (1969). The authors note, however, that near the coast, in the large bight just north of Cape Columbine, there is sometimes a counter current. This would be understandable in terms of an entrainment vortex formed by the main Benguela Current separating from the coastline.

In the winter months the position is less clear. The frequencies of north-going and south-going winds at Cape Columbine are more evenly balanced. Duncan and Nel have shown that during the months June to August their drift cards moved south. However, at Alexander Bay the winter winds show a slight north-going resultant (Weather Bureau 1960).

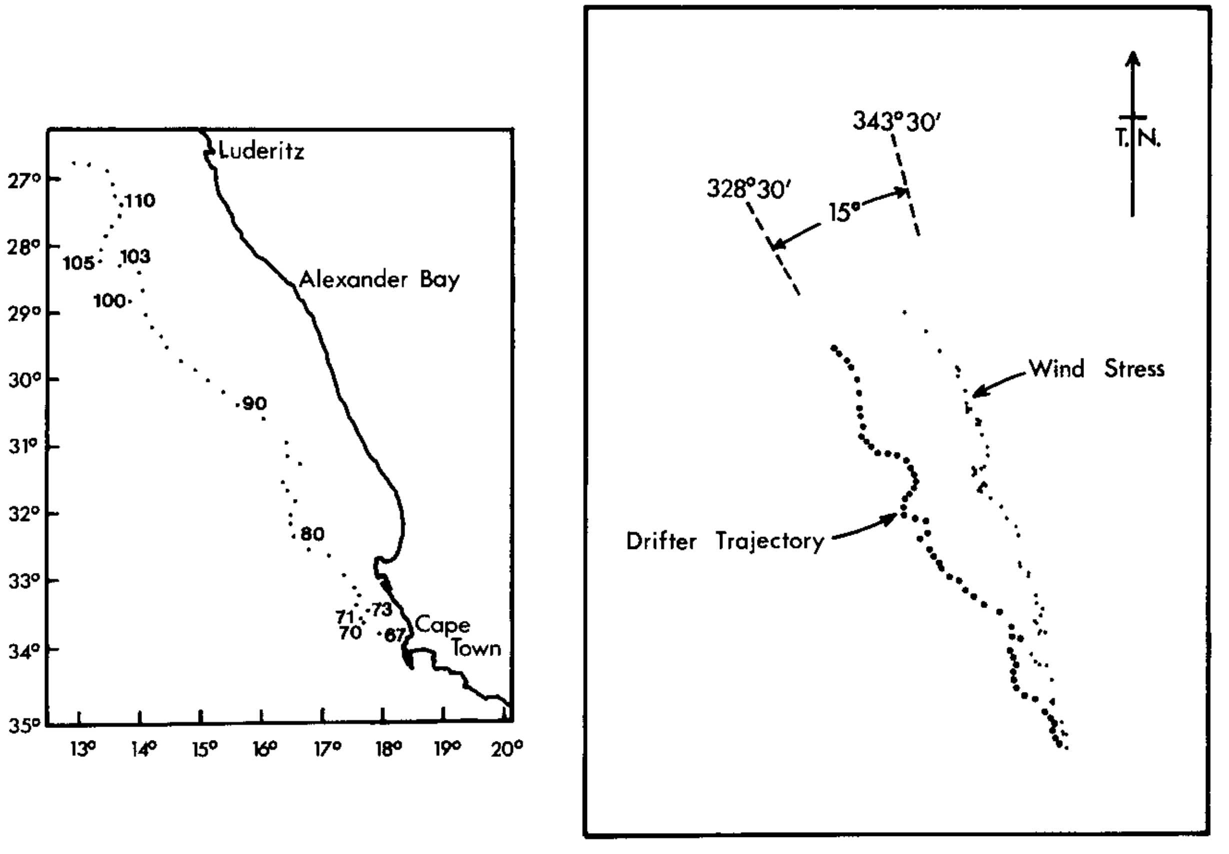


Figure 76. Satellite tracked drifter trajectory (left). Numbers next to fixes are the days of the year. Comparison of trajectory with a progressive wind 'stress' vector diagram (right)(after Harris & Shannon 1978)

Ships' drift data in the Benguela System have been compiled by the U S Navy Oceanographic Office (Boisvert 1967). Unfortunately the areas to which they refer are not entirely suitable for the present study. The most relevant one is presented in Figure 77 labelled 'Area 1', but it included the coastal section dealt with in the previous sector. It nevertheless confirms that the mean velocity is 0,5 - 0,7 knots. It shows little difference in the winter and summer percentage frequency of direction, the most frequent being northwesterly (315°). The relatively high proportion of west-going currents recorded in both seasons is notable and may be due in part to the inclusion of the Cape Agulhas - Cape Columbine section.

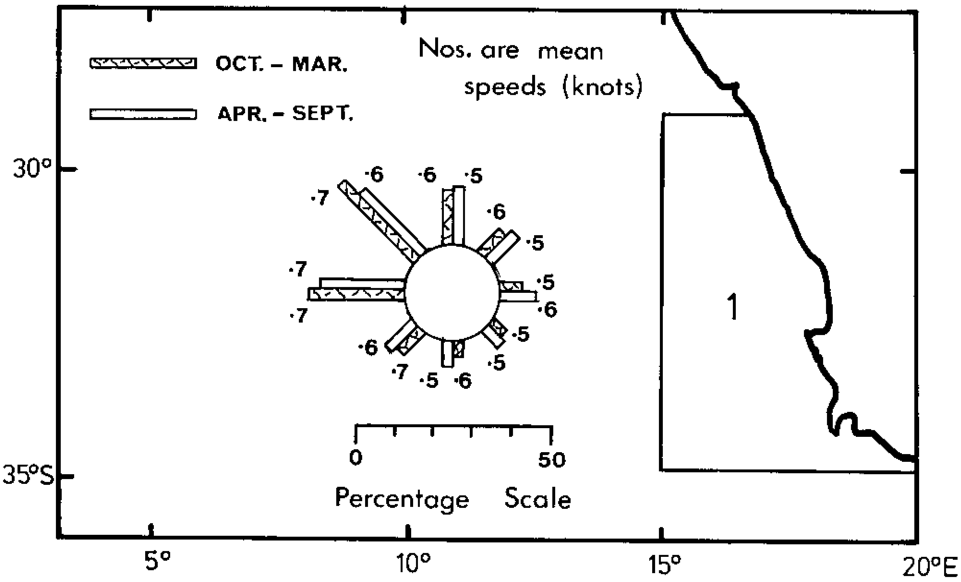


Figure 77. Current rose from ships' drifts for indicated area (after Boisvert 1967)

Direct current measurements have been made in Chamais Bay to the north of the Orange River (Marine Diamond Corp 1966). The results showed no clear patterns of currents and do not throw any light on currents in this sector.

St Helena Bay

Currents near the harbour at St Helena Bay (Sandy Bay) have been measured by the Fisheries Development Corp (1977). Observations on drogued floats were made on nine occasions, during January, March and July 1972. Currents outside the harbour, but within about 1 km of the shore, tended to be in sympathy with the winds having regard to the constraint imposed by the coastline which has a mean direction of northwest-southeast. During light winds and relatively calm conditions, the dominant directions of the surface currents were west to east. Velocities under the conditions encountered were about 0,04 to 0,2 m s^{-1}.

It should be noted that the area studied is shallow (under 15 m).

Lamberts Bay

Lamberts Bay is a small indentation in a coastline oriented approximately north-south. Studies of the currents in and near it were made by the Fisheries Development Corporation (Moore 1970), from 1969 to the middle of 1971, using drogued floats. The findings, to quote the report, were:

> 'In general it appears that the whole current system in the Lamberts Bay area is governed by the wind direction. Generally drogues show a very rapid reversal of currents with changing conditions, a new pattern being set up within an hour of a wind

> change. This occurs even up to 6 m depth although the deeper floats are generally slower initially, than the shallower ones, in their reactions'.

Current patterns generated by winds between west and south-southwest were found to be similar; so were those for winds between northwest and northeast. The former group of winds caused north-going currents, while the latter produced south-going currents which were deflected westward in the offing of the harbour - perhaps because of the coastal discontinuity.

5.1 SUMMARY OF SECTOR V CAPE COLUMBINE TO THE ORANGE RIVER

There is unfortunately very little information to summarize. In the summer months when the southerly winds dominate it seems fairly certain, as shown by the satellite drifter, that the flow will be predominantly northwards. The observations made by the Fisheries Development Corporation suggest that this may also be the case closer to the coast.

Although in the winter months the wind from the northern and southern sectors are more evenly balanced, the miles of wind blown show an 18% net 'blow' northwards at Cape Columbine. What is not clear, is how sensitive the system is to a reversal of wind direction - which will accompany the passage of 'fronts'. Possibly the tracks of satellite tracked drifters, released in the winter months, would throw some light on this.

CONCLUDING REMARKS

Forcing Mechanisms and their Time and Space Scales

The evidence reviewed above suggests that amongst the most potent mechanisms forcing water movements in South African water are:

(a) The Agulhas Current. Its direct effects are felt primarily on the coast between Pta do Ouro and Cape St Lucia, and between North Sands Bluff and somewhere in the region of East London. These effects are intermittent because of the meanderings or wave-like character of this current, whose time scales are not well known but may be of the order of weeks. Its space scales are perhaps about 300 km (at the southern end). Its indirect effects include the generation of vortices, because of entrainment or horizontal volocity shear, notably in the Natal Bight between Cape St Lucia and Green Point, and possibly between East London and Port Elizabeth. Indirect effects also include the generation of density currents, probably between Port Elizabeth and Mossel Bay, and about 20 n miles off the Cape Peninsula;

(b) Atmospheric effects. Direct wind stress is clearly an important factor wherever the Agulhas Current's influence is weak or absent. It must be considerable close to the coast in the Natal Bight and between Mossel Bay and the Orange River.

The indirect effects include the changes in atmospheric pressure which accompany the passage of fronts and it has been suggested that these pressure changes correlate with current directions off the Natal coast. Another indirect effect, associated with Ekman transport, causes upwelling with resultant barotropic currents between Cape Agulhas and the Orange River.

The time scales for wind effects are intimately associated with the periodicity of the passage of 'fronts' which is of the order of days. Imposed on the scale are the seasonal changes;

(c) Surface gravity waves. The nearshore circulation, its type and intensity depends upon the characteristics of the incident waves, especially the wave height and direction. Along the uniform coastline of Natal the longshore currents, which oblique waves generate, are important features but their extent seaward is limited to about the surf zone. On the Cape coast the influence of waves is particularly marked in the coastal embayments. On this coast the high waves, incident normally, may generate rip currents extending 2 or 3 km seawards.

The crude time scales of the waves are of the same order as those of the winds. The actual circulation can pulse with periods of the order of 5 minutes in response to beats between wave trains of different periods. Space scales for symmetrical circulations are about 0,5 km for the larger cells; and for the longshore currents, the distance between coastal discontinuities.

Sampling

The sampling of coastal currents is a formidable task both on account of the time and space scales and the practical difficulties. Furthermore it is sometimes exacerbated by anomalous conditions which may prevail. Examples of these are to be found off Durban where the reversing current, usually of say six days period, flowed in one direction for nearly a month on one occasion. Again, in November 1976, there were practically no winds from the southeast off the Cape coast - apparently because of the persistence of an atmospheric wave number one mode around Antarctica.

Nevertheless, the problem has to be tackled and there is some comfort to be had from the fact that the crude methods used so far have led to significant advances in our knowledge.

Possibly some guidance can be had from the following past experience:

(a) The important reversing nature of the Natal currents first came to light from drift card studies. It was later confirmed by continuous daily observation of moored current buoys (in daylight hours). These buoy systems are a very useful cheap method for building up directional frequency statistics;

(b) the broad conception of the current system off the Natal coast was built initially on ships' drift data. In regions where the current directions are reversing and the frequencies in either direction evenly balanced, a very large number of observations is required. A minimum might be 100, and 200 desirable. A disadvantage is that only the average current in the region between fixes is obtained. This space scale is often too large. Furthermore a single ship's rate of sampling a particular piece of coastal water is too slow for the data to yield any sort of time series, which for example might be used to establish the meanders in the Agulhas Current. Such a time series would require the data from a good number of ships.

Recommendations

If the prediction of coastal currents is ever to be a practical proposition there are two important pieces of fundamental information which must be acquired:

(a) What triggers off the meanders of the Agulhas Current? Is the reason to be sought in the conservation of vorticity? Theoretical work has shown this to be a promising approach, and that the trajectories are sensitive to volume flux. Do joining tributaries contribute relative vorticity? How is divergence to be dealt with?

(b) How are we to translate wind velocity into current velocity, especially during the growth and decay of winds? This is an old problem but the waters off the Cape coast, which are little influenced by tidal currents or larger oceanic currents, would seem to be an unusually suitable laboratory in which to do some intensive investigation.

Concurrently with the above the following matters should be dealt with:

(a) The maritime winds should be reviewed comprehensively;

(b) the systematic collection of ships' drift data should be initiated. Now that Decca navigation is available the quality of this type of observation should be higher. Emphasis should be placed on the south coast, which, because of onshore currents, is vulnerable to pollution, and which is very poorly understood. The west coast also needs attention;

(c) a data bank of satellite images from infra-red and visible radiation should be archived over a period of two years, concurrently with the ships' drift data. The component of the Nimbus-7 programme concerned with the interpretation of the pattern of radiation from suspended matter in terms of coastal currents, should be expanded. Ultimately the remotely sensed data must go a long way to meeting the difficulties inherent in the time dependency and the space scales of currents in Southern African waters;

(d) satellite tracked drifters should be released in the Benguela System in the winter months.

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APPENDIX

NOTES ON CURRENT-MEASURING METHODS

The current characteristics reported in these notes were measured in a variety of ways. The main purpose of this Appendix is to comment briefly on the methods used and to draw attention to references in which a more detailed description has been given.

Ships' drifts

Coasting vessels fix the ship's position at intervals by obtaining fixes on prominent coastal features such as lighthouses. Knowing the distance and time between two successive fixes the ship's velocity made good 'over the land' can be calculated. This velocity includes both the ship's speed through the water, known from the engine revolutions, and that of any ocean current (and the effect of windage on the ship). The difference between the ship's speed and the velocity made good is taken to be prevailing current - the windage, unless corrected for, is a source of error. The method is a cheap way of building up current statistics. The currents deduced are of course those which affect the ship on its passage between the two fixes.

One set of ships' drift measurements used in these notes comes from the log books of Captain Bray (1959-1964) who plied between Cape Town and Durban between 1955 and 1964. He reported the currents only as they affected the ship - adversely or favourably - so that they are the vectors approximately parallel to the shore-line.

Velocities were measured to 0,25 knot. It was Captain Bray's practice to make the 'up' passage (Cape Town to Durban) close to the coast (along the east coast - within 1-2 nautical miles, say 2-4 km) and to shape a course further offshore (5-20 miles) on the 'down' passage. On the south and southwest coasts there was less difference in the courses chosen.

The data used for calculating the percentage frequencies of current directions close to the coast (i.e. 2-4 km on the east coast) were those collected between 1959-1964. Those used in plotting the current velocities with distance offshore were for 1955-1961.

The other ship's drift data used were those reported by Tripp (1967) who has published his findings in an atlas. His data were not limited to currents parallel to the ship's course. In handling his data however, Tripp removed the local effect of the wind on the water by subtracting 3% of the wind speed. The assumption here is that a steady wind generates a current with a velocity equal to 3% of its speed. It is not possible to comment on the validity of this assumption. The idea in making the deduction was to establish the basic current, if any.

Tripp divided his data into four seasons. The sample was a little small for this degree of subdivision. Accordingly the data has been reconstituted for the whole year - and sometimes a half year. Velocities reported are the weighted mean of Tripp's seasonal means.

While it is necessary to treat ships' drift with caution it is noted that as mentioned earlier in this report, experience has shown that in Natal waters the patterns of current circulation deduced from them are probably valid.

Moored current buoys

The system of moored current buoys is illustrated in Figure A.1. Two floats are tethered in series to a moored buoy. The remote float has a drogue. Between the floats there is a weight which tends to draw the floats together. Any current will act to draw the drogued float and open the distance between the floats, and this distance can be compared with the standard distance between the moored buoy and the undrogued float. The system can be calibrated to relate the distance between the floats to the current velocity.

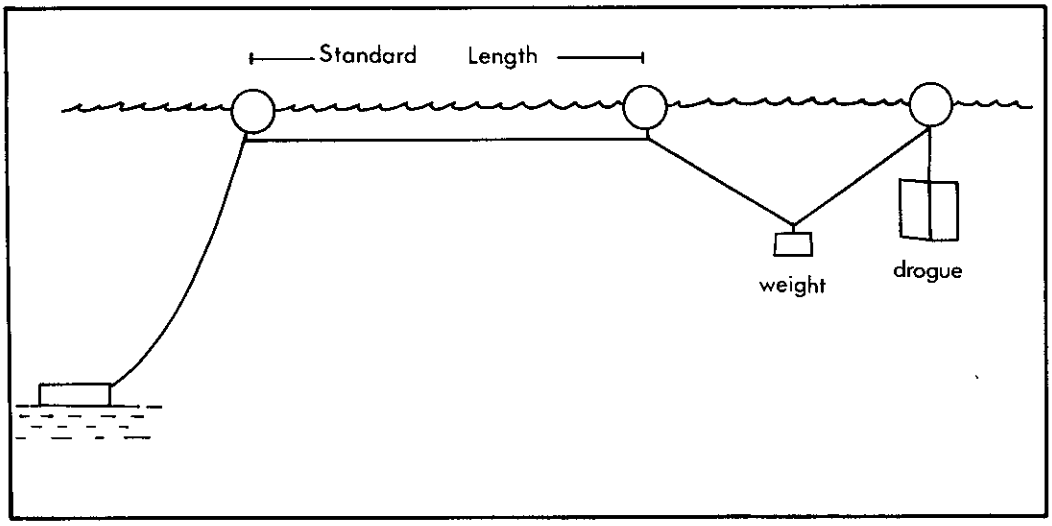

Figure A.1 Moored current buoy system.

In practice the distance between the floats can be estimated from the shore by using binoculars with a graticule. At a distance offshore of 1 km it is estimated that velocities could be deduced with an accuracy of 25%. The direction of the current can only be crudely estimated (say about 15°).

The disadvantages of the method are:

(a) ordinarily measurements can only be made in daylight;

(b) it can only be used in water depths suitable for mooring;

(c) offshore distances are limited by the need to make visual observations.

Further details are available in Harris and van der Linden's paper (CSIR 1964).

Tracked floats

Current trajectories can be determined by making successive fixes of free floats. The construction of the kind in common use is shown in Figure A.2.

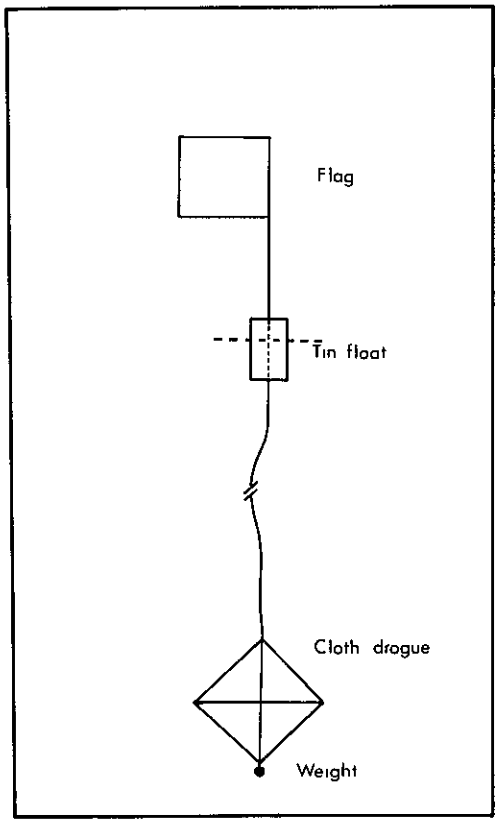

Figure A.2 Sketch of float & drogue

Tracking methods include:

(a) Theodelite measurements from two stations on a measured base. This was the method used by Gunn (1977a, 1977b) and Atkins (1965a, 1965b);

(b) Range finder. Off Durban the floats were tracked by this method (Anderson 1965);

(c) Radar. Suitably modified, with the addition of a radar reflector, floats can be readily tracked by radar in the absence of radar 'clutter' caused by reflection off waves. Since the reflector usually adds considerably to the windage of the floats this method is only practical under calm conditions. It can be used after dark;

(d) By observation from an aircraft. Atkins (1970), in part of his False Bay study, used a modified float system which could be released and observed from an aircraft. The device consists of two parts dropped from the aircraft in a single package. The first part is a self-anchoring small float with a bag of fluorescein dye (green) which acts as a point of reference. The second is a small float plus drogue which has a bag of rhodamine B dye (red). After a certain period of time (40 minutes) the distance to which the second float has drifted from the moored float is determined (by measuring angles from the aircraft at a known height). The method is crude but quite effective in experiments which require quasi-synoptic data over an area of say 50 km square. Bain (Bain & Harris 1975-1977) used a variant of this method in his current measurements reported in sector IV.

The tracked float method is still one of the most useful methods for measuring local currents. It has obvious limitations, the most serious of which is the windage on the exposed part of the float and flag. Gunn (1977b) has investigated the windage in wind-tunnel tests and suggests that the error in velocity due to windage is 0,4% of the wind speed.

Further information on tracked floats is available from Welsh (1967), Atkins (1970), Stavropoulos (1964), and Gunn (1977a, 1977b).

Current meters

The obvious method of measuring currents, by means of a current meter lowered from a ship, is in practice very difficult because of the ship's motion even when moored. To overcome this difficulty Anderson and Stavropoulos (CSIR 1964) devised a method by which:

(a) The current was measured while the ship drifted freely;

(b) the ship's drift was accurately determined by two precise navigational aids at the shore (of the Hydrodist or Tellurometer type);

(c) the current was calculated by the vector addition of the measured reading and the ship's drift.

This method allows currents to be measured out to a distance of about line of sight from the navigational aids. Measurements down the water column are also possible.

The current meter used had a rated precision of 0,05 m s^{-1} with linearity in practice up to 0,8 m s^{-1}. The navigational aid measured distances to about 2 m.

The method is perhaps the most precise of all the methods. Spatial coverage is limited by the speed of the ship (say 8 knots) in getting from station to station.

Pearce (1977) used the method during his studies off Richards Bay and Anderson (1965) off Durban.

Further information is to be found in the paper by Anderson and Stravopoulos (CSIR 1964).

Drift cards

The drift card is a small plastic envelope marked with an address to which the finder can return it. Batches of cards are released at sea and their subsequent recovery after stranding gives some rough indication of the net direction travelled. One type floats flat in the surface and is very susceptable to the wind action. An improved type is weighted so it floats vertically.

Their shortcoming is obiviously the fact that the history between launch and recovery is unknown. Furthermore recovery from remote coasts is unlikely. Recovery is therefore weighted in favour of frequented coastlines.

Further information is available in Duncan's paper (1965).

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* Out of print.