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Inshore circulation of the Agulhas Current off Natal

by E. H. Schumann¹

ABSTRACT

The variability of the inshore circulation of the Agulhas Current on the Natal continental shelf region is investigated using historical ship-based data, and more recent measurements made on moorings deployed at various points along the coast. The existence is confirmed of a recirculation flow inshore of the Agulhas Current on the wider shelf region, although emphasis is laid on the inherent variability. It is apparent that the different flow regimes along the coast are primarily due to topographic effects; in particular, a narrowing shelf serves to reduce the variability being transmitted downstream.

1. Introduction

Off Natal (Fig. 1) the Agulhas Current emerges as the dominating dynamic feature affecting the flow along the whole coastal region. It is one of the world's major western boundary currents (Duncan, 1970; Veronis, 1973), with the poleward flow already well established off Cape St. Lucia.

Pearce (1977) has analyzed features of the Current utilizing measurements made off Richards Bay, Durban and Port Edward. In the north the maximum speed of the Current was found to be, on average, just offshore of the shelf break. However, on the terrace-like bathymetry off Durban a variable Current regime occurred, with the mean position of the core about 40 to 50 km offshore. Further south off Port Edward a more stable region existed, with the Current core within 10 or 15 km of the coast. Gill and Schumann (1979) have shown that this onshore movement is a consequence of the inherent vorticity structure within the Current.

A discussion of the features of the shelf circulation has been given by Pearce *et al.* (1978). In particular, moored current measurements within 6 km of the coast showed a variable regime off Richards Bay, a generally northward flow off Durban, and a southward flow off Port Edward. These results led to the postulation of a semi-permanent cyclonic gyre off Durban. More recently, a *Landsat* image presented by Malan and Schumann (1979) showed the existence of a gyre with a diameter of some 30 km situated east of Durban.

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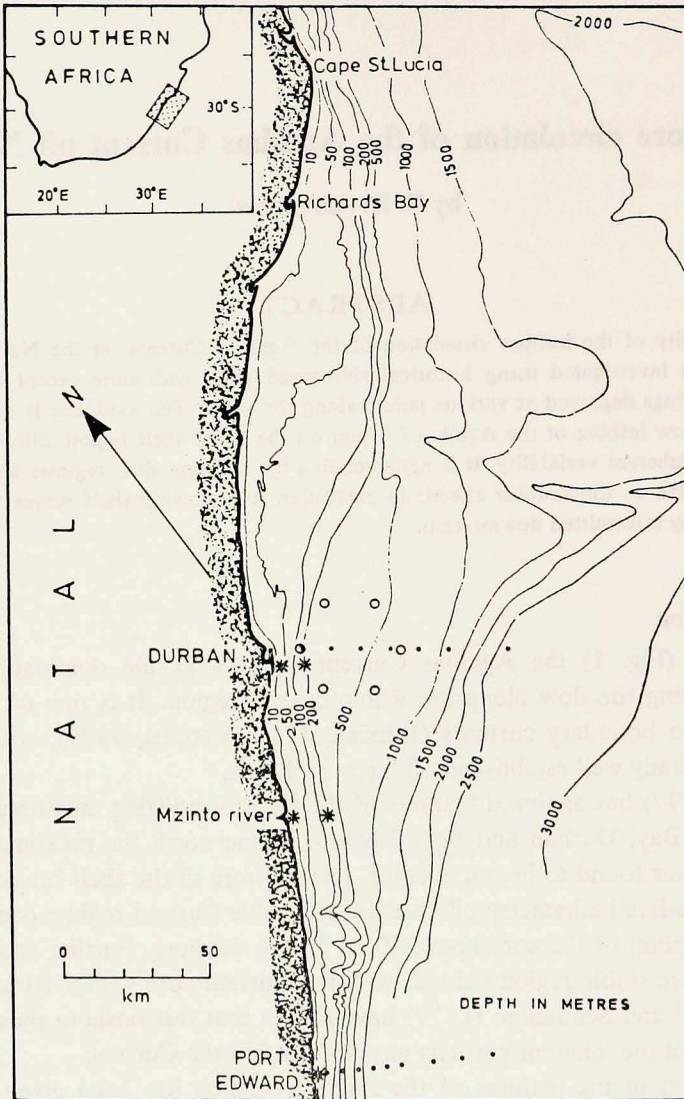


Figure 1. The coastal bathymetry off Natal after Goodlad (1978), with the inset map showing the location of the area. The orientation of the map is at 38° to true north, judged to be the average direction of the coastline and bathymetry in this area. Also shown are the station positions on the lines measured off Durban and Port Edward (\bullet), with the stations on the hexagon grid off Durban (\circ), and the approximate positions of moorings discussed in the text ($*$). Greater detail of the situation off Durban and Port Edward is given in Figure 7.

Schumann (1981) analyzed data from moorings deployed in about 30 m depth at four points along the Natal coast, and came to the conclusion that distinct coastal regimes existed depending on the local bathymetry and on the influence of the Agulhas Current. In particular it was found that off Richards Bay the longshore wind component was the dominating influence on the local currents, with minimal intrusion of external signals. This isolation was postulated to be a result of a varying shelf width and Agulhas Current structure precluding the propagation of subtidal signals such as shelf waves northward beyond the Durban area. In contrast, further south the direct effect of the local wind was substantially reduced.

The object of this paper is to present further evidence on the nature of the circulation on the shelf inshore of the Agulhas Current. In particular, the recirculation flow off Durban will be investigated.

2. Data

The data used in this analysis have been selected from a variety of projects carried out off the Natal coast. Thus in 1969 measurements were carried out on a hexagon-shaped grid of ship stations over a period of twelve days, while further measurements were carried out over a number of years on lines of stations off Port Edward and Durban (listed in greater detail by Pearce, 1977). The station positions in all these investigations are shown in Figure 1.

The measurement techniques used on board the *R/V Meiring Naudé* to determine values of temperature, salinity and current at various depths have been discussed by Stavropoulos (1971), Pearce (1977) and Gründlingh (1977). In essence, these variables are measured by means of a hydrosonde lowered to the required depth while the ship is drifting. In order to obtain absolute values of current, the relative current determined by the hydrosonde is vectorially added to the ship's drift. The precision of this method is considered to be within about 10 cm/s, depending on conditions. In particular, in regions of strong vertical current shear measurements at greater depths tend to be unacceptably affected by movement of the hydrosonde itself, and in such circumstances are rejected.

On the hexagon cruise the maximum depth to which measurements were made was 100 m, with each station on the grid being occupied approximately twice daily. On the other cruises the maximum depth was 500 m, with one line of offshore stations being completed per day. However, current measurements in the analysis here will be considered only in the upper 100 m.

More recently, Aanderaa current meters with temperature sensors have been deployed on the continental shelf at depths of up to 230 m. Data points were taken at 15-minute intervals; subsequent three-hourly values were also obtained after the application of a Cosine-Lanczos filter with a fairly sharp roll-off and a half-power point of 0.13 cycles/hour. The results of two such mooring programs will be

Table 1. Deployment details for the two sets of moorings discussed in the text. (See also Figs. 1 and 7).

Location	Water depth (m)	Meter depth (m)	Record length (days)	Period
Durban AA1	29	26	47	June to August 1977
Durban AD1	245	70	12	
Mzinto	195	45	51	
		155	51	
Port Edward AE1	25	22	50	
Durban AD1	230	55	36	March to April 1978
		110	21	
		180	36	
Durban AD1	41	16	37	
		37	37	
Mzinto	41	38	37	

presented here. The details are given in Table 1, while Figure 1 and Figure 7 show the approximate positions along the coast. The record lengths of data obtained vary as a result of problems with meters and mooring recovery.

There is a close relationship between variations in sea-surface temperature and the position of the Agulhas Current. Pearce (1977) found that the inshore boundary could generally be identified by a sharp rise in temperature—as high as $1^{\circ}\text{C}/\text{km}$ —associated with an increase in current speed. Remote sensing of this temperature front can therefore be utilized to detect the Current; measurements using a Barnes Radiation Thermometer, model PRT 14-313, in an aircraft flying at an altitude of 150 m are also reported here.

3. Ship-based measurements

Results from the hexagon cruise in June, 1969, are shown in Figure 2. The parameters depicted are sea-surface temperature (as in Pearce (1977), this was measured at a depth of 2 m, where the water intake on the ship is situated) and currents. These latter values were averaged over the upper 50 m from measuring points at 10, 30 and 50 m.

Pearce (1977) defined the core of the Agulhas Current as that region with a flow exceeding 1 m/s ; on this basis it is apparent that the core never came within the measuring regime over the twelve-day period. It was only toward the end of the cruise that a markedly stronger southwestward flow appeared at the outermost station. On about 16 June, stronger currents were also registered at station HB3, with the indication that these ran obliquely across the measurement hexagon. The

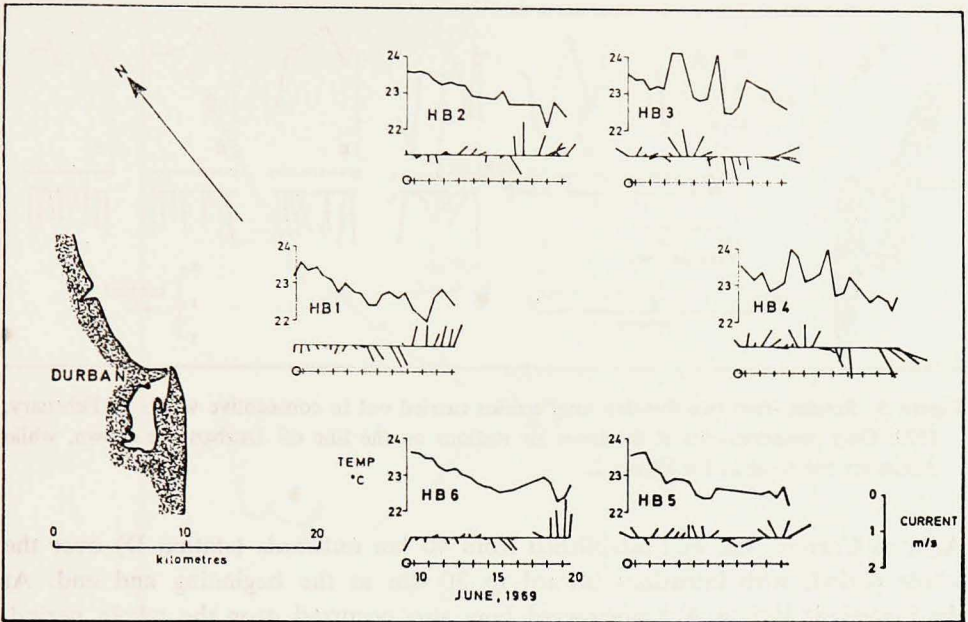


Figure 2. Surface temperature measurements and currents averaged over the upper 50 m at each of the stations on the hexagon cruise of June, 1969. The spatial position of the stations relative to Durban is given by the circle at the start of the time scale.

possibility is that these were associated with a meander in the main stream of the Current; this, however, did not reach station HB5.

The temperature also does not give any indication of the presence of a Current boundary, with a slow decrease registered at all the stations over the measuring period.

Assuming that the Agulhas Current lay offshore of the station positions, over the first six days or so the northeastward recirculation flow is evident at the three outermost stations. However, inshore of this again there was a weak southwestward flow, possibly due to an anti-cyclonic cell. This whole structure would then have moved shoreward over the last few days of the measurement period.

Of particular note is the approximately four-day period fluctuation in the flow evident at HB3 and HB4 and to a lesser extent also at some of the other stations. Temperature peaks also occur, and it may be that these were associated with warmer water from the Agulhas Current being pulsed through in the recirculation flow.

A different situation occurred over the 12 days in February 1973 shown in Figure 3 (actually the results of two consecutive cruises over two weeks). The

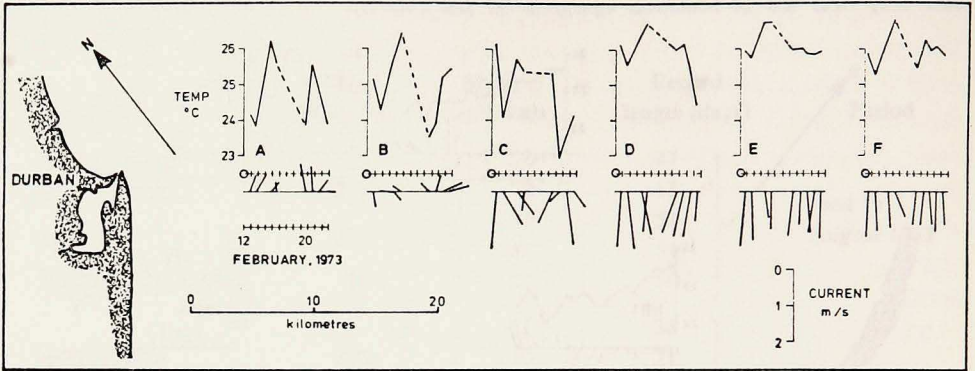


Figure 3. Results from two five-day long cruises carried out in consecutive weeks in February, 1973. Only measurements at the inner six stations on the line off Durban are shown, while details are the same as for Figure 2.

Agulhas Current was well established from 40 km outwards (station D) over the whole period, with intrusions inward to 30 km at the beginning and end. At the innermost station A a northward flow also occurred over the whole period, with a more variable situation at the intermediate station B.

The temperature records support these conclusions, with a value at the outer three stations (D, E and F) consistently higher than at the three stations inshore. The variability is also associated with the variations in current flow: thus the shoreward movement of the main Current corresponds with the increases in north-eastward flow at station A and with the substantial increases in temperature registered there. The low temperature recorded at station C, on the other hand, accompanies the low current speeds and the movement offshore of the Current boundary.

4. Moored-meter results

Progressive vector diagrams from the moorings deployed in 1977 are shown in Figure 4. It is apparent that fairly consistent conditions occurred over much of the measuring period, i.e., a northeastward flow near the coast at Durban, an onshore flow at Mzinto, with a southwestward flow close inshore at Port Edward.

The flow off Mzinto is particularly revealing, for with the known concentration of the Agulhas Current further south this probably represents the best evidence to date of the fairly permanent nature of the recirculation of the inshore waters of the Agulhas Current. The temperature records are not shown, with perhaps the most important point being that the temperatures measured at the upper meter at Mzinto, and those measured at the inner mooring off Durban generally remained within about 0.5°C of each other over the whole 51 day recording interval.

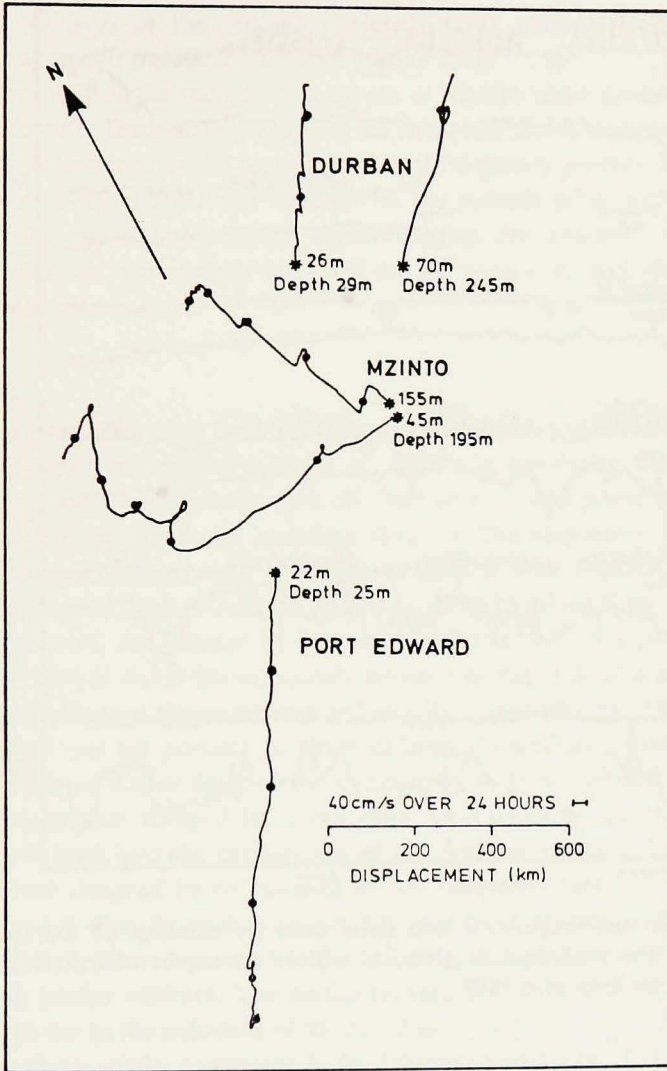


Figure 4. Progressive vector diagrams from moorings off Durban (AA1 and AD1), the Mzinto River mouth and Port Edward (AE1) during June to August, 1977. The water depth as well as the depths of individual meters are given, while an asterisk is shown at the start of each record, with a • every 10 days.

Time series from the 1978 moorings are presented in Figure 5, and the following features should be noted:

- a) The essentially barotropic nature of the current reversals off Durban from a predominantly northeastward flow to a southwestward flow.

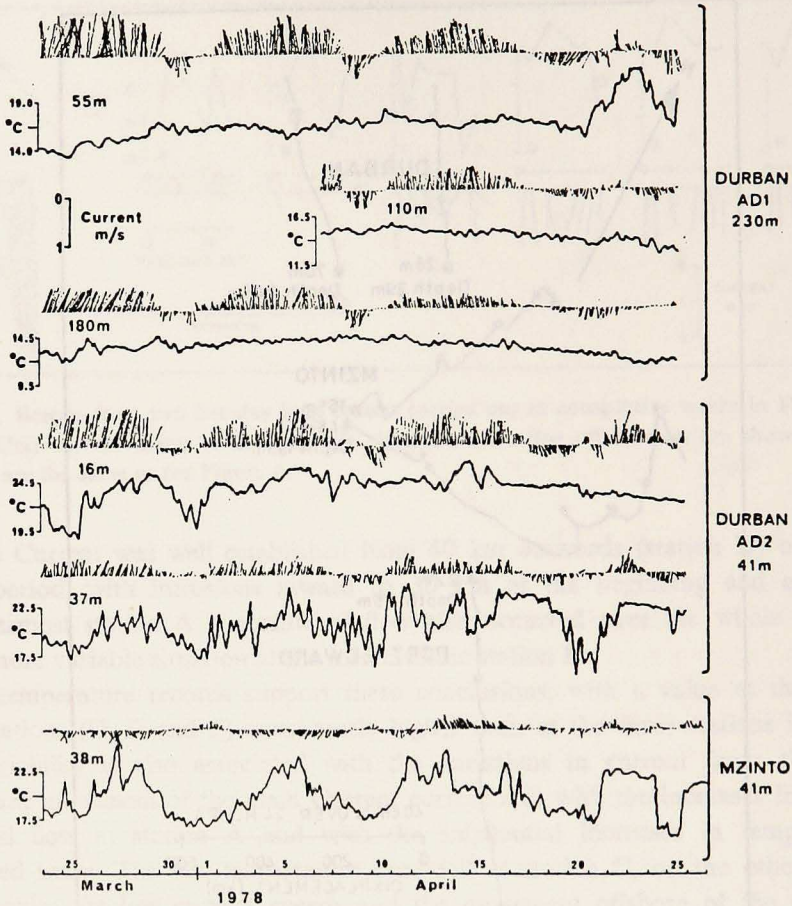


Figure 5. Current and temperature time series from the moorings off Durban and Mzinto during 1978. The total depth is given, as well as the depths of individual meters. The orientation of the figure is at 38°T .

- b) The close correlation between temperature variations at Mzinto and the current reversals off Durban. Thus with a northeastward flow the temperature reached a maximum of about 22.5°C , while a southwestward flow accompanied a drop of around 5°C . This was also reflected to a lesser extent by the temperatures measured on the lower meter at AD2; note that at the same depths these two temperature series also agree approximately in the actual values registered. It is apparent that the meters at AD1 were situated below the thermocline, with little correlation with the currents. It was only at the end of the record that the thermocline dropped to a depth great enough to intersect the upper meter and to cause an abrupt increase in temperature.

- c) Over the 33 days of the records depicted, these currents and temperature variations appeared to follow a distinct 10-day cycle.
- d) For the first half of the record the currents at Mzinto show an inverse correlation with those at Durban, while during the latter half this is reversed.
- e) There are fluctuations at the semidiurnal tidal frequency present in most of the records, this being particularly apparent in the records taken close to the seabed at AD2 and Mzinto. While acknowledging the possible importance of these fluctuations, the analysis here will not be concerned with these relatively high frequencies.

5. Discussion

The results presented here have confirmed concepts of the circulation patterns off Natal presented previously (Pearce *et al.*, 1978). In particular, the recirculation flow forming an apparent cyclonic gyre off Durban has been given strong support from the results of current meter moorings (Fig. 4). The ship-based measurements showing increases in temperature at the inner stations with apparent increases in the gyre strength also tend to confirm that it is partly Agulhas Current water that is being recirculated. An attempt to further consolidate this idea utilizing salinity measurements proved inconclusive, mainly because of the lack of a strong correlation between the Current characteristics and salinity values (Pearce, 1977).

It is therefore not yet possible to draw definite streamlines showing the origin and eventual fate of waters forming the cyclonic gyre. It is probable that some of the water may remain trapped for some time, circulating on the shelf and then being entrained back into the mainstream of the Agulhas Current. Figure 6 shows the tracks of two drogued buoys released at two different times and followed by a ship for about 1.5 days on each occasion. Of particular interest is the buoy track moving northward, since it seemed to be following the 200 m isobath and, in so doing, moving further offshore. The partial turnaround at the end of the track may then have been due to the influence of the Agulhas Current.

One of the main results to emerge is the inherent variability of the situation on the shelf off Durban. This is shown further in Figure 7, where current vectors measured over a period of about three and a half years are depicted (see Pearce, 1977, for cruise details). The trend from a generally northeastward flow at the innermost station to a southwestward flow at about 60 km offshore is evident, although even at this latter site very slack current conditions were encountered at times.

In contrast the situation at Port Edward is shown to be much more consistent, with a dominating strong southwestward flow evident at all the stations. Figure 1 shows a much more regular bathymetry in this region, and it is clear that the Agulhas Current has moved onshore with the narrowing shelf (Gill and Schumann,

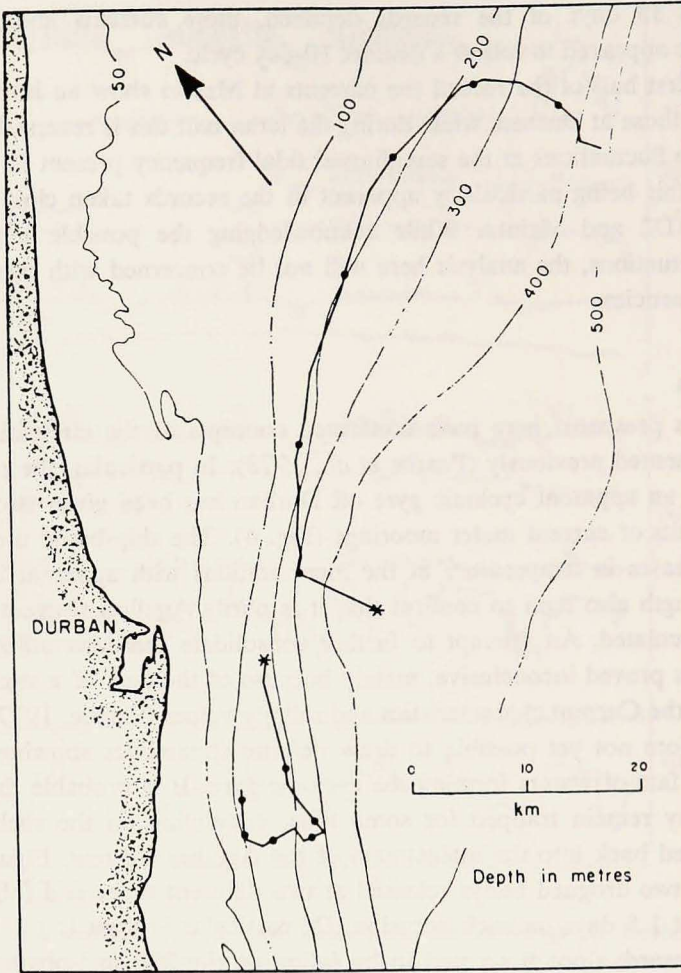


Figure 6. Drift tracks of a free-drifting, drogued buoy released on two different occasions. The starting point is indicated in each case by an asterisk, while a • is shown every six hours along the drift tracks (with acknowledgment to R. A. Carter).

1979). The reduction in the variability of the position of the Current boundary leads to the speculation that the changing bathymetry has had a stabilizing effect on the Current, although more would need to be known about the ocean interior flow before definite conclusions can be made. It is also known that additional waters enter the Agulhas Current from the east during its flow southwestward (Gründlingh, 1980).

The origin of the variable flow on the wider shelf region off Durban has not been established. Considerable insight may, however, be obtained from the ART measurements shown in Figure 8. The Agulhas Current boundary is clearly evident from

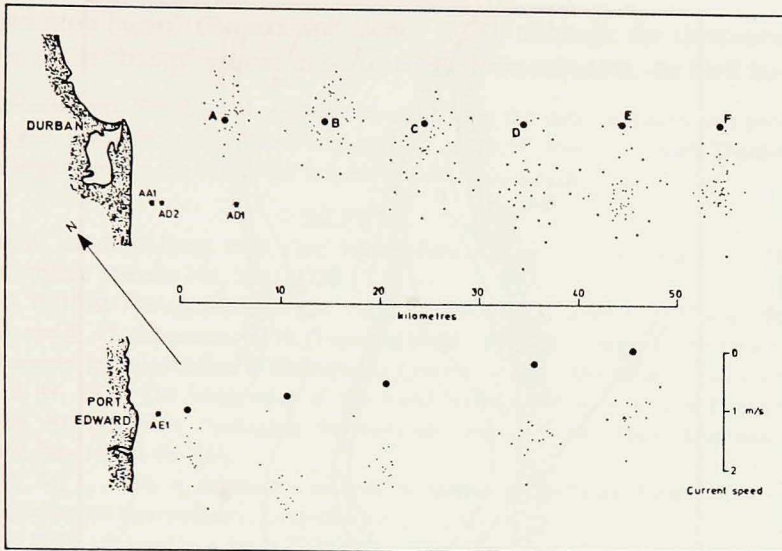


Figure 7. Current measurements made on the lines of stations off Durban and Port Edward. Each dot represents the head of a current vector averaged over the upper 100 m with respect to the associated station position (from measurements at 10, 20, 30, 50, 75 and 100 m). Also shown are the positions of moorings discussed in the text.

the strong horizontal temperature gradient, and of particular interest is the **apparent** onset of the meander south of Cape St. Lucia.

Gründlingh (1974) also used ART measurements in a limited area here to investigate the occurrence of meanders, and suggested that these were correlated with local wind and atmospheric variations. It is of interest to note that Schumann (1981) found a significant 9-day period in the wind-dominated currents in the shallower water off Richards Bay.

Lee and Brooks (1979) found a similar situation on the wide Georgia shelf. A large portion of the shelf is isolated from disturbances at the shelfbreak, i.e., from the effects of the Gulf Stream. Nonetheless, the suggestion is made that Gulf Stream meanders may at times be generated by the offshore Ekman flux associated with northward wind episodes.

Figure 8 shows a dramatic growth in the meander off Durban with a strong onshore tendency off Mzinto and indications of a recirculation flow. Further south off Port Edward the Current flow has apparently re-established itself.

The meander shown is very similar in appearance to the "warm filament/cold tongue" features reported in the Gulf Stream off Florida (Lee, 1975; Legeckis, 1975). However, the Gulf Stream meanders were observed to propagate downstream, whereas no such propagation is evident in seven pairs of ART measure-

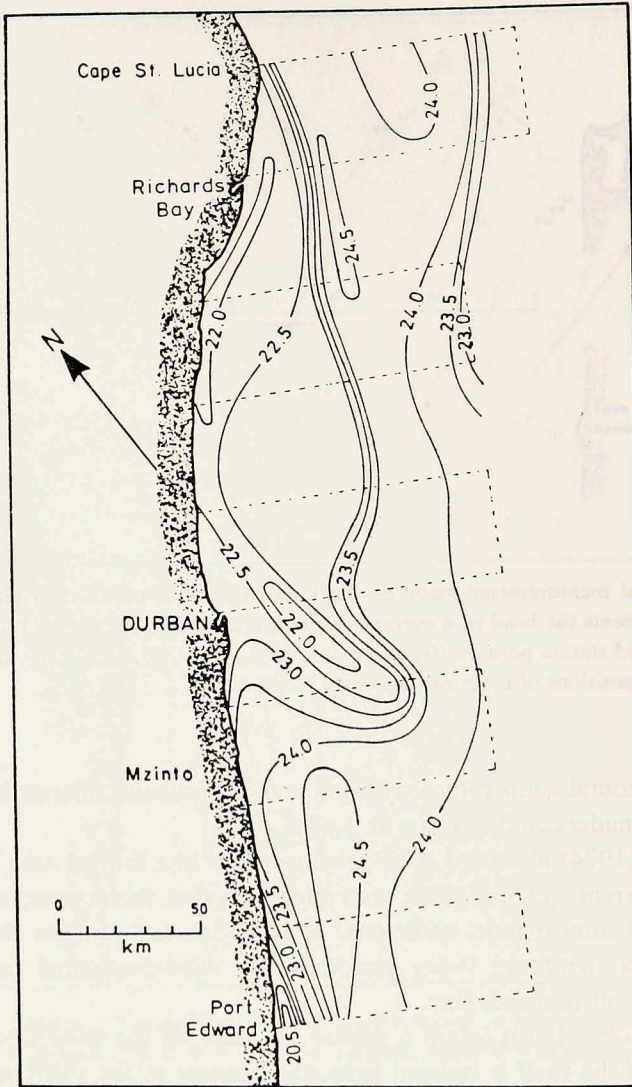


Figure 8. Sea surface temperatures from an airborne radiation thermometer (ART) flight on 30 November, 1967 (from Snyman, 1969). Temperatures are given in degrees Celsius, while the aircraft flight pattern is also shown.

ments taken in each case on two successive days over the Agulhas Current (Snyman, 1969). Indeed, the mean sea surface temperature figure in Pearce (1977) utilizing all 14 ART flights shows a distinct kink in the isotherms off Durban. It is therefore apparent that the meander shown in Figure 8 bears a specific relationship to its position over the bottom topography. In this respect it is more akin to the effect of

the "Charleston bump" (Brooks and Bane, 1978), although the downstream consequences of the "bump" appear to be accentuated meanders on the Gulf Stream.

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