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The Delagoa Bight eddy

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Abstract—The results of two recent research cruises show that the cyclonic Delagoa Bight eddy observed on satellite imagery fills most of the continental shelf and terrace landward of the Mozambique Current at all depths, but is particularly dominant below 100 m depth. It consists of well-mixed Equatorial Surface and Sub-Tropical Water underlain by an upwelled dome of Antarctic Intermediate Water. A detailed analysis of all available historic hydrographic data from the last 25 years demonstrates the prevalent nature of the eddy. Sediment patterns on the shelf support the concept of a quasi-permanent topographically trapped eddy.

INTRODUCTION

ALTHOUGH recently called into doubt (SAETRE and JORGE DA SILVA, 1984; SAETRE, 1985), the western boundary current system of the South West Indian Ocean has long been thought of as a Mozambique Current–Agulhas Current continuum (PEACH, 1926; MICHAELIS, 1923). Flowing in a south-southwesterly direction, this current generally follows isobaths of the continental slope while remaining close inshore (GRÜNDLINGH, 1983). Large indentations in the coastline cause an abrupt downstream broadening of the continental shelf and terrace in at least two locations south of 20°S in the Delagoa Bight (26°S), and adjacent to Richards Bay (29°S). The Richards Bay area is known for strong inshore current reversals (GRÜNDLINGH, 1974) which have been assumed to be related to lee eddies driven by the adjacent Agulhas Current (MALAN and SCHUMANN, 1979). These eddies have been suggested (LUTJEHARMS, 1981; LUTJEHARMS and ROBERTS, 1988) as the source of large downstream meanders in the Agulhas Current (GRÜNDLINGH, 1979). Eddies of this nature may be topographically induced (SMITH *et al.*, 1984) or be trapped by a southward-flowing barotropic coastal current (BOWMAN, 1985).

The possibility of a similar lee eddy in the Delagoa Bight has been implied by analyses of ships' drift (MICHAELIS, 1923; PEACH, 1926), by hydrographic data (HARRIS, 1972; LUTJEHARMS, 1976; SAETRE and JORGE DA SILVA, 1984), satellite imagery (LUTJEHARMS, 1981) and by the results of studies on the sediment distribution on the continental shelf (MARTIN, 1981a,b). Recent detailed hydrographic measurements (JORGE DA SILVA, 1983; NEHRING, 1984) in the Delagoa Bight, combined with the availability of about 10 years of thermal infra-red satellite imagery for the area, makes it possible to study the nature and occurrence frequency of this feature more comprehensively.

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HYDROGRAPHIC DATA

Two sets of recent hydrographic data in the Delagoa Bight area offer instructive data on the physical structure of the water column in the area. The first is a line of closely spaced stations undertaken from the R.V. *Alexander von Humboldt* during March 1980 (NEHRING, 1984) (Fig. 1). The second set of data was collected on a cruise on board the R.V. *Ernst Haeckel*, specifically designated to study the circulation of the Delagoa Bight in January 1982 (JORGE DA SILVA, 1983) (Fig. 3).

The hydrographic section from the R.V. *Alexander von Humboldt* across the Delagoa Bight and into the Mozambique Channel (Fig. 2) clearly shows the extent of the southward drift of the general Mozambique Current flow by the general downward slope

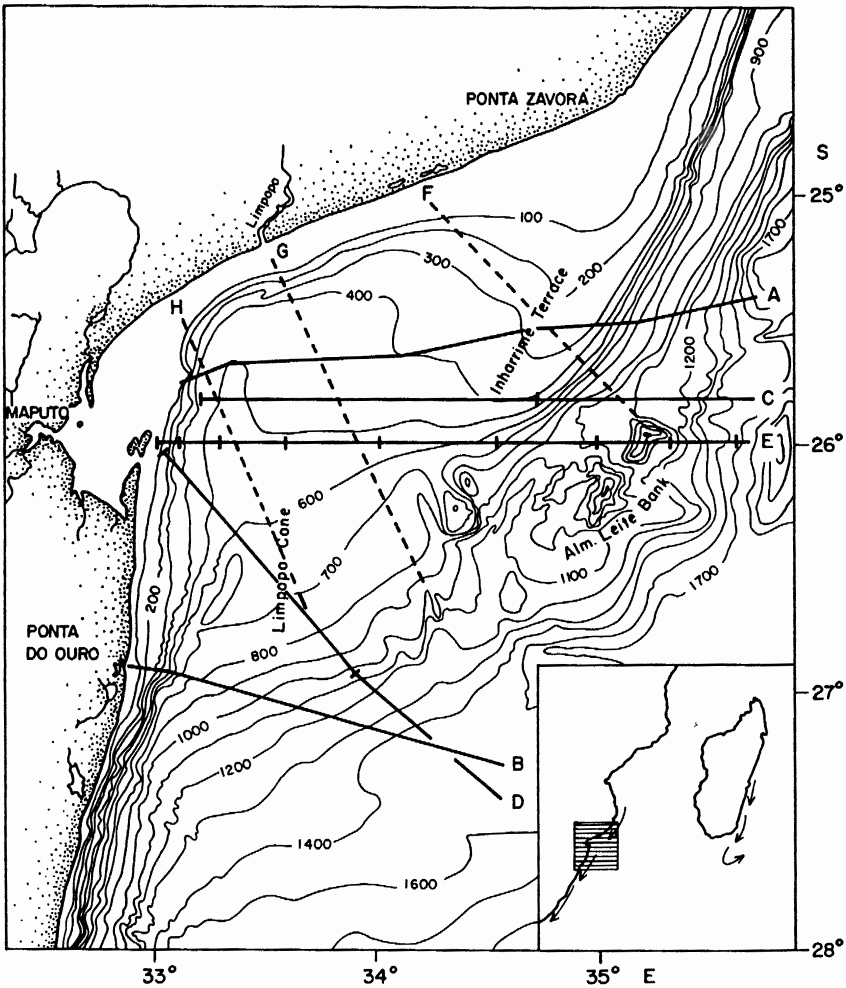

Fig. 1. The bottom topography of Delagoa Bight (in metres) after MARTIN (1981a,b), with its general location relative to the African continent shown in the inset. Lines A and B show locations of seismic reflection profiles portrayed in Fig. 8. Hydrographic station lines with station positions are C (Fig. 8), D (Fig. 8), E (Fig. 2) and the dotted lines F, G and H represnt tracks of the dedicated cruise the results of which are given in Figs 3 and 4.

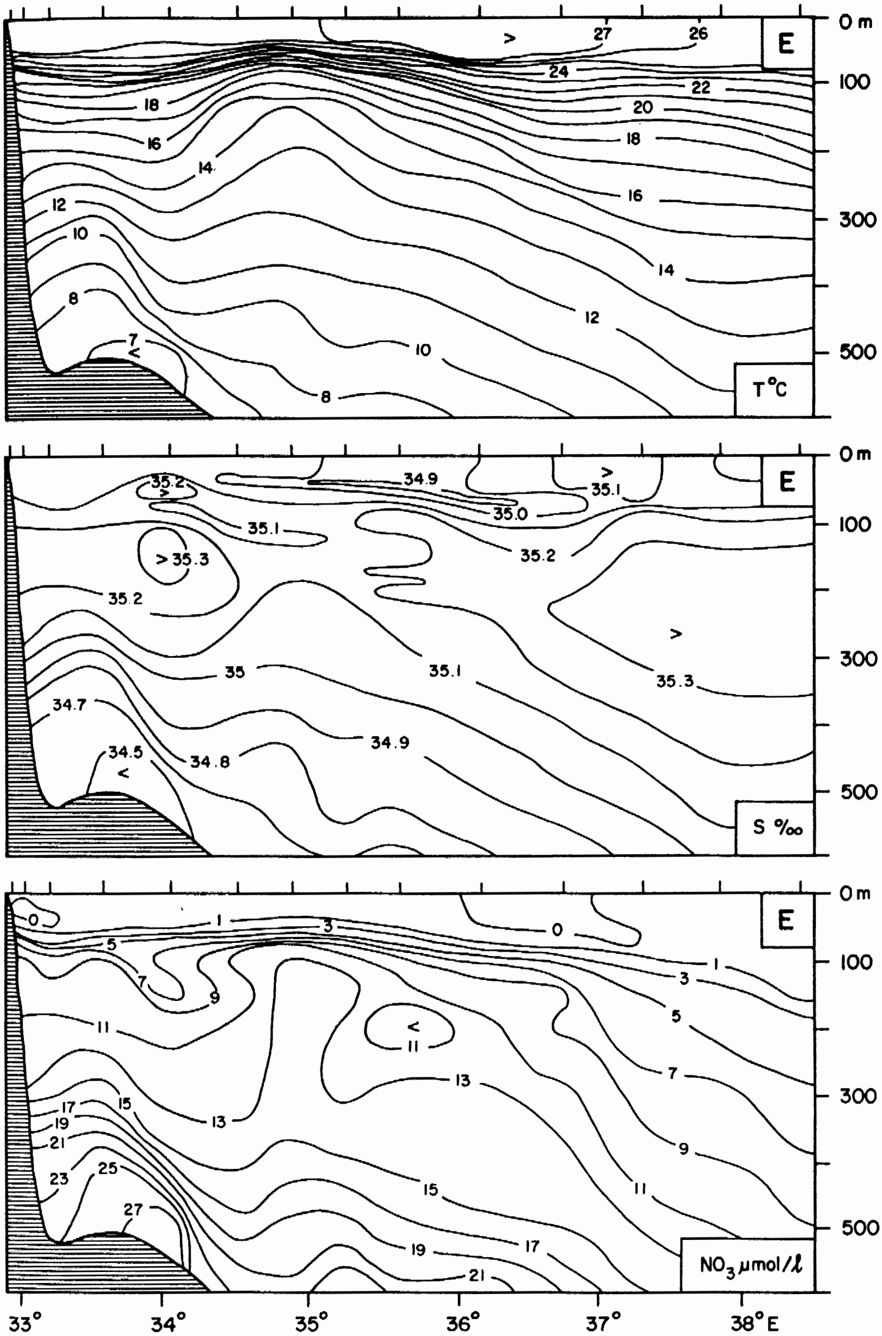

Fig. 2. Hydrographic section across Delagoa Bight in March 1980 (after NEHRING, 1984). Station disposition for this line (E) is given in Fig. 1. The upper panel represents temperatures measured in °C, the middle panel salinities as per mille and the lower panel nitrate as μmol l^{-1}.

in an easterly direction of all parameters, implying a similar slope in the isopycnals. Two breaks in this general trend are noticeable, one centred at about 35°E, the other between 33° and 34°E. The former is located in the vicinity of the Almirante Leite Bank (Fig. 1) and may therefore be a topographically induced eddy to the seaward side of the Mozambique Current proper. The second feature is on the continental terrace itself. It shows a marked intensification of the isotherm and isohaline slopes at the terrace break (34°E, Fig. 2) below 200 m. This may be the shallow, landward expression of the Mozambique Current proper, carrying high salinity ($>35.2 \times 10^{-3}$), low nutrient water southward. The current is generally assumed to have a considerably deeper extent. Its axis, however, may be tilted so that the deeper part of the Mozambique Current lies further offshore (GILL and SCHUMANN, 1979). It is important to note that no obvious thermal or haline signature intersects the sea surface, such as in the case of the Agulhas Current (PEARCE, 1977). The current would therefore be indistinguishable by infra-red satellite sensing on such an occasion as would the eddy located astride the greater part of the continental shelf. The signature of this eddy is particularly marked below 250 m. Deeper than 400 m the water mass of the eddy is characterized by temperatures below 8°C, salinities below 34.6×10^{-3} and nitrate loads of >24 μmol l^{-1} (Fig. 2). These characteristics define Antarctic Intermediate Water situated at around 1000 m depth further offshore (WYRTKI, 1971; LUTJEHARMS, 1971), implying a significant degree of upwelling of intermediate depth water onto the shelf. Downward slopes in the isotherms and isohalines abutting the coast show a northward countercurrent forming the landward side of the eddy. Here again no surface gradients demarcate the extent of this coastal feature.

The full Delagoa Bight area was further surveyed extensively during a cruise of the R.V. *Ernst Haeckel* between 4 and 7 January 1982. Water samples were collected at 15 standard depths at each station (Fig. 3) to a maximum depth of 600 m. Unprotected thermometers were used to 125 m and salinities determined on board using an inductive salinometer. Surface temperature distributions show higher values along the 300 m isobath and a notable horizontal thermal gradient at the shelf edge. Surface salinities were patchy, with fresher water north of Maputo which might have been due to river run-off into the bay. At 200 m depth these distributions were markedly different (Fig. 3). A clear centre of low temperatures and salinities was situated at about 26°S over the level part of the shelf (Fig. 1). The temperature distribution at this depth was closely related to the sigma-*t* value (SAETRE and JORGE DA SILVA, 1984). This distribution therefore indicates a strong and well-defined cyclonic eddy. The temperature and salinity distributions at 400 m essentially show the same feature, more laterally constricted by the surrounding shelf topography and with the eddy centre somewhat closer inshore (Fig. 3). The eddy fills the whole continental shelf area at all depths.

Three selected sections which bisect various parts of the Delagoa Bight, obtained during this cruise, clearly show various water masses (Fig. 4); this is particularly true for the combined temperature–salinity (T–S) scatter diagram for these stations given in Fig. 5. At the northernmost section F (Fig. 4) the general west–east slope in the properties shows the southward Mozambique flow. The core of the current lay at the shelf edge and was typified at the sea surface by a band of water with temperatures >27°C. Salinities on the whole were $<35.4 \times 10^{-3}$ except at the outermost stations 6 and 7 (Figs 3 and 4), where higher salinities were measured. A thin layer of fresher water lay at the sea surface. A salinity maximum at mid-depths of 100–200 m was found at all stations but was more intense at the outer stations 6 and 7 (Fig. 5). At this section across the northern

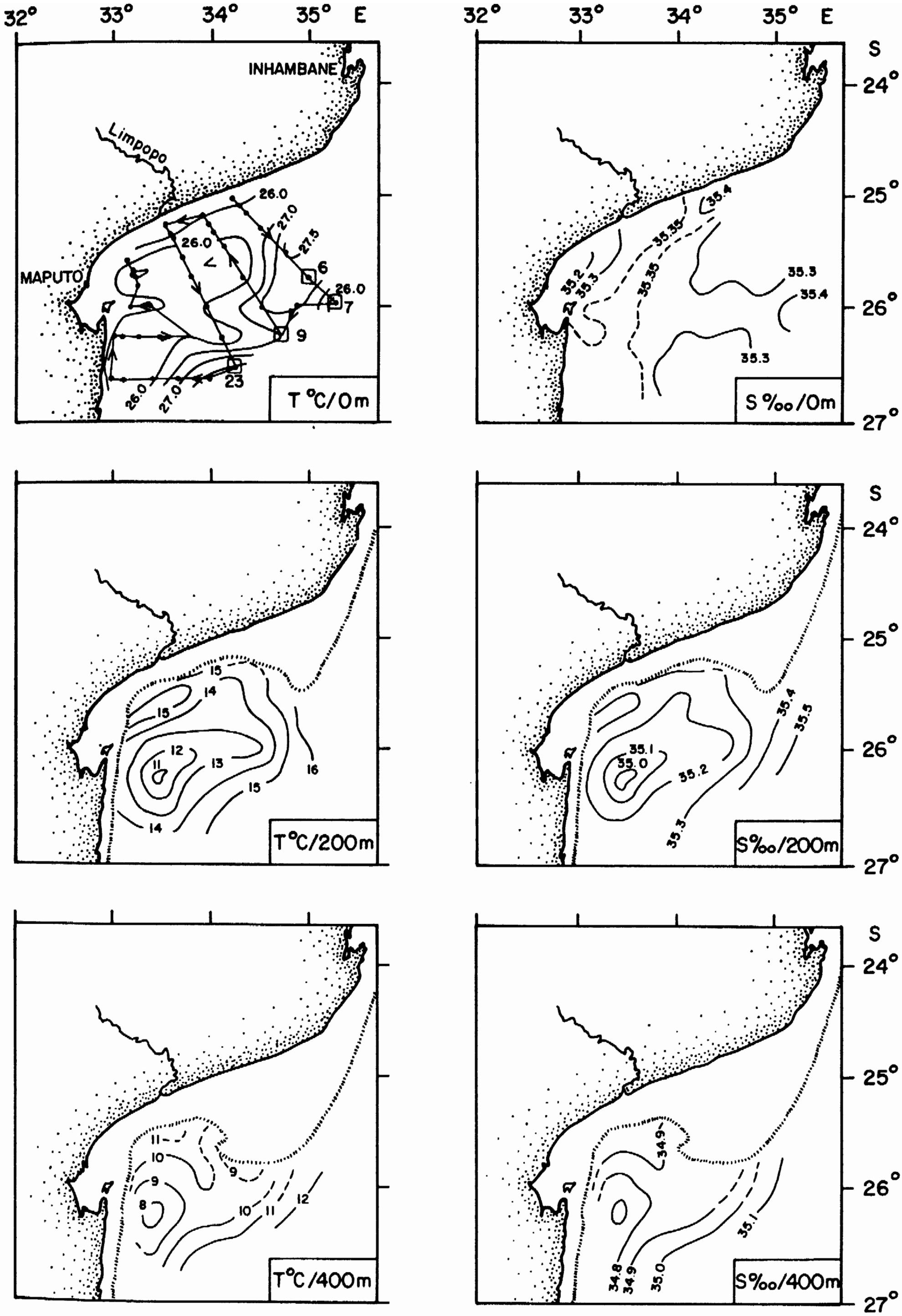

Fig. 3. Results of the *Ernst Haeckel* cruise in Delagoa Bight during January 1982. Cruise lines are shown in the left top-most panel. Stations for which individual temperature–salinity relationship are shown in Fig. 5 have been numbered. The left-hand column shows the temperature distrubution at the sea surface, at 200 m and at 400 m, while the right-hand column shows the salinity distribution at corresponding depths. Dotted lines show intersections of each respective depth with the continental shelf.

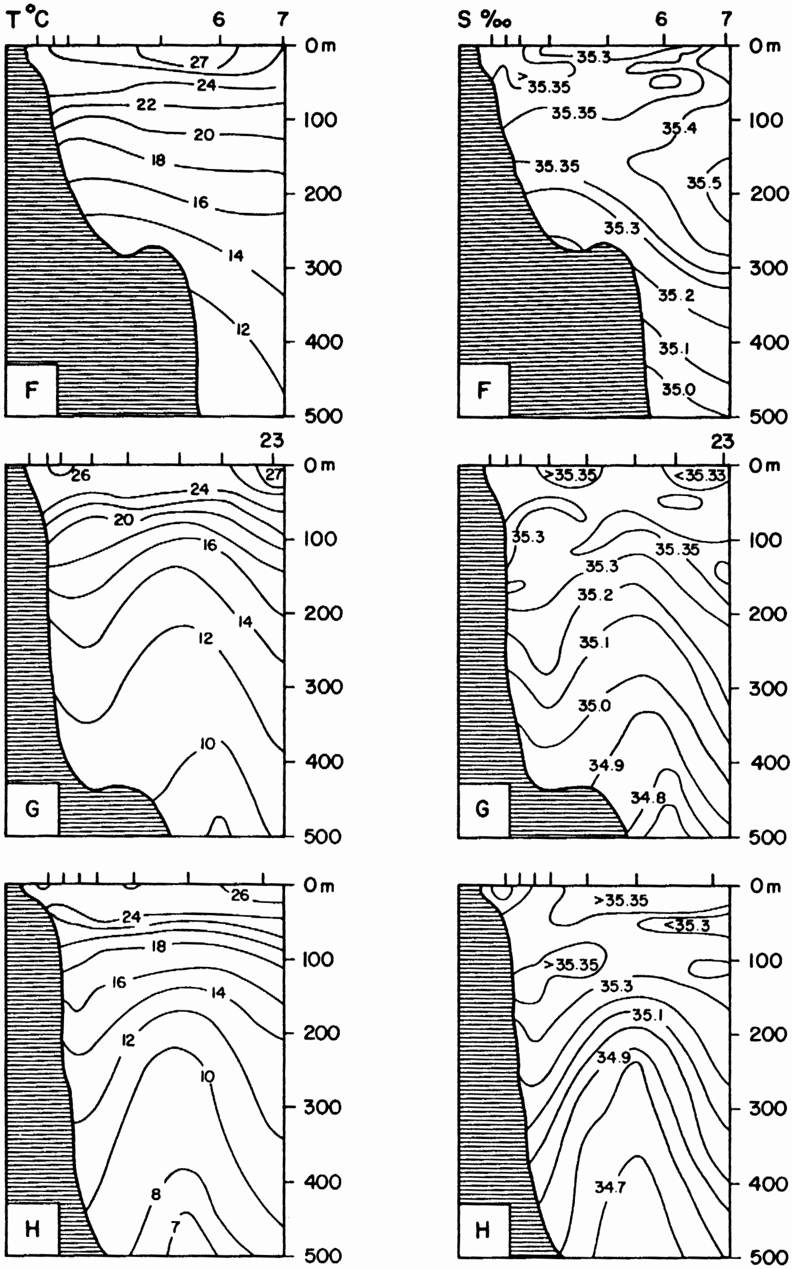

Fig. 4. Hydrographic sections across selected parts of the Delagoa Bight circulation during January 1982 (cruise lines shown in Fig. 1). The left-hand column shows the temperature distribution while the right-hand column represents the salinities.

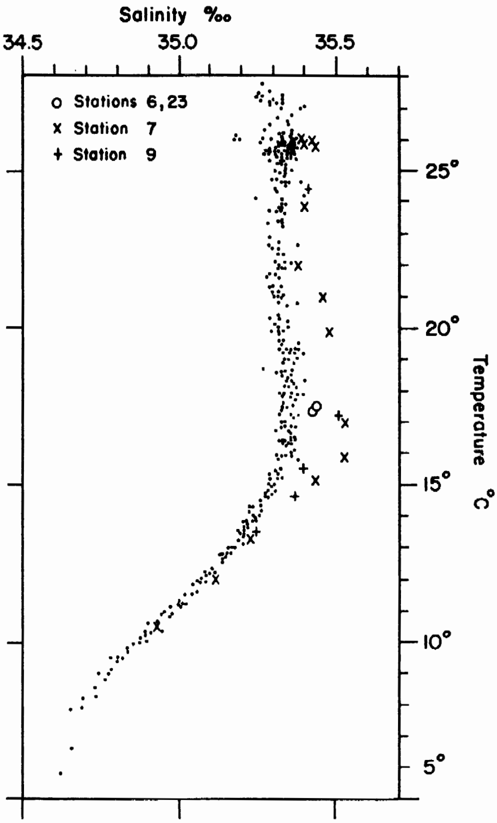

Fig. 5. Temperature–salinity scatter diagram for all stations undertaken as part of a dedicated cruise in Delagoa Bight. The temperature–salinity relationships of certain individual stations are shown. The locations of these stations are shown in Figs 3 and 4.

part of the Inharrime Terrace there was no evidence of an eddy. The second section G lay across the centre of the Delagoa Bight and clearly showed the eddy-like thermohaline structure below 100 m. Temperatures at the sea surface were indicative of the warmer cores of the Mozambique Current and the coastal countercurrent. A mid-depth salinity maximum was evident with salinities $>35.40 \times 10^{-3}$ measured only at the outermost station 23. The T–S relationships of the central dome of the eddy below 400 m showed the clear characteristics of Antarctic Intermediate Water. The same holds true for section H which bisected the core of the eddy and where the Antarctic Intermediate Water was conspicuous at even shallower depths.

The general T–S relationships for the area (Fig. 5) show the normal structure recognized for the Mozambique Channel (Saetre and Jorge Da Silva, 1984). The indistinct remains of a salinity minimum at about 23°C denotes the remains of characteristic Equatorial Surface Water, while the salinity maximum at 16°S corresponds to Sub-Tropical Water. Antarctic Intermediate Water is found at temperatures <7°C. Between the latter two lies the Central Water. Strong evidence of Sub-Tropical Water was found only at the outermost stations of each line (Figs 1 and 3), such as Stas 6, 7, 9 and 23 (Fig. 5). Since water masses on the shelf and in the eddy are vertically more thoroughly mixed, the area's water masses may be relatively stagnant. The diminishment of the Sub-Tropical Water salinity maximum is also evident on the northern Natal continental shelf (PEARCE, 1978) and off Durban (PEARCE, 1977), suggesting similar mixing of this water on the shelf in these areas, but not to the same extent as the Delagoa Bight. A more advanced degree of mixing between water masses at different depths may be due to their substantially longer contiguous residence time in the Delagoa Bight. A more advanced degree of mixing between water masses at different depth may be due to their substantially longer contiguous residence time in the Delagoa Bight eddy compared to the water masses further offshore. Antarctic Intermediate Water was found only at those stations situated in the core of the eddy.

SATELLITE IMAGERY

The thermal contrast between the sea surface temperature of Equatorial Surface Water and the cooler water of the Delagoa Bight past which it is being carried by the Mozambique Current is such as to lend itself to investigation by thermal infra-red data from satellites. Satellite imagery for a period from 1976 to 1985 for the geographic area was searched. These data included measurements from the Very High Resolution Radiometer carried on board the NOAA 4 and 5 orbiting satellites and the Advanced Very High Resolution Radiometer carried on board NOAA 6 to 9 and on TIROS N. These images have been contrast enhanced in the appropriate oceanic radiance range but not geometrically or atmospherically corrected. Subsatellite resolution is about 1 km.

A number of characteristic thermal features are observed relatively frequently. On some occasions (Fig. 6, left) a well-defined warm western boundary current more or less follows the 1000 m isobath. The greater part of the Delagoa Bight is covered by a large cyclonic vortex, the warm water of which seems to be derived from the Mozambique Current, flowing northward along the coast and curving back to form a warm annulus with a diameter estimated at 180 km. On the other occasions thermal features are more complex (Fig. 6, right-hand panel) with smaller eddies, warm water filaments and characteristic shear-edge features similar to those found on the edge of the southern Agulhas Current (LUTJEHARMS, 1981) and the Gulf Stream (LEE *et al.*, 1981; CHEW, 1981) in evidence. In all cases the implied circulation is cyclonic.

A number of interpreted line drawings of such circulation features observed in the area (Fig. 7) show that cyclonic eddies with a range of diameters may occur. In those cases in which more than one shear-edge feature is present, an increase in downstream dimensions of the features is observed (11 September 1982; 17 June 1983) similar to the increase noted in the southern Agulhas Current (LUTJEHARMS, 1981). Large features seem to have as a general axis a point near 26°S, 34°E (7 April 1984) although there are numerous examples to the contrary. When it flows near the coast, the Mozambique current frequently goes to the east or exhibits a large eastward meander south of 25°S, thus effectively bypassing the Delagoa Bight (GRÜNDLINGH and PEARCE, 1984). In these cases shear-edge features with a range of diameters are observed; none, however, with the horizontal extent of the vortices shown in Fig. 7 and none within the confines of the Delagoa Bight. A more complex set of vortices may on these occasions be formed downstream over the Mozambique Ridge (GRÜNDLINGH, 1984, 1985). An additional feature observed on many occasions is a plume of warmer water flowing northward and northeastward along the borders of the bay (Fig. 7). This feature does not seem to be in any way related to the edge dynamics of the Mozambique Current.

Fig. 6. Two characteristic thermal infra-red satellite images for the Delagoa Bight area. The one on the left is from the NOAA 7 satellite for 22 May 1982 while the one on the right also is from NOAA 7 but for 24 August 1984.

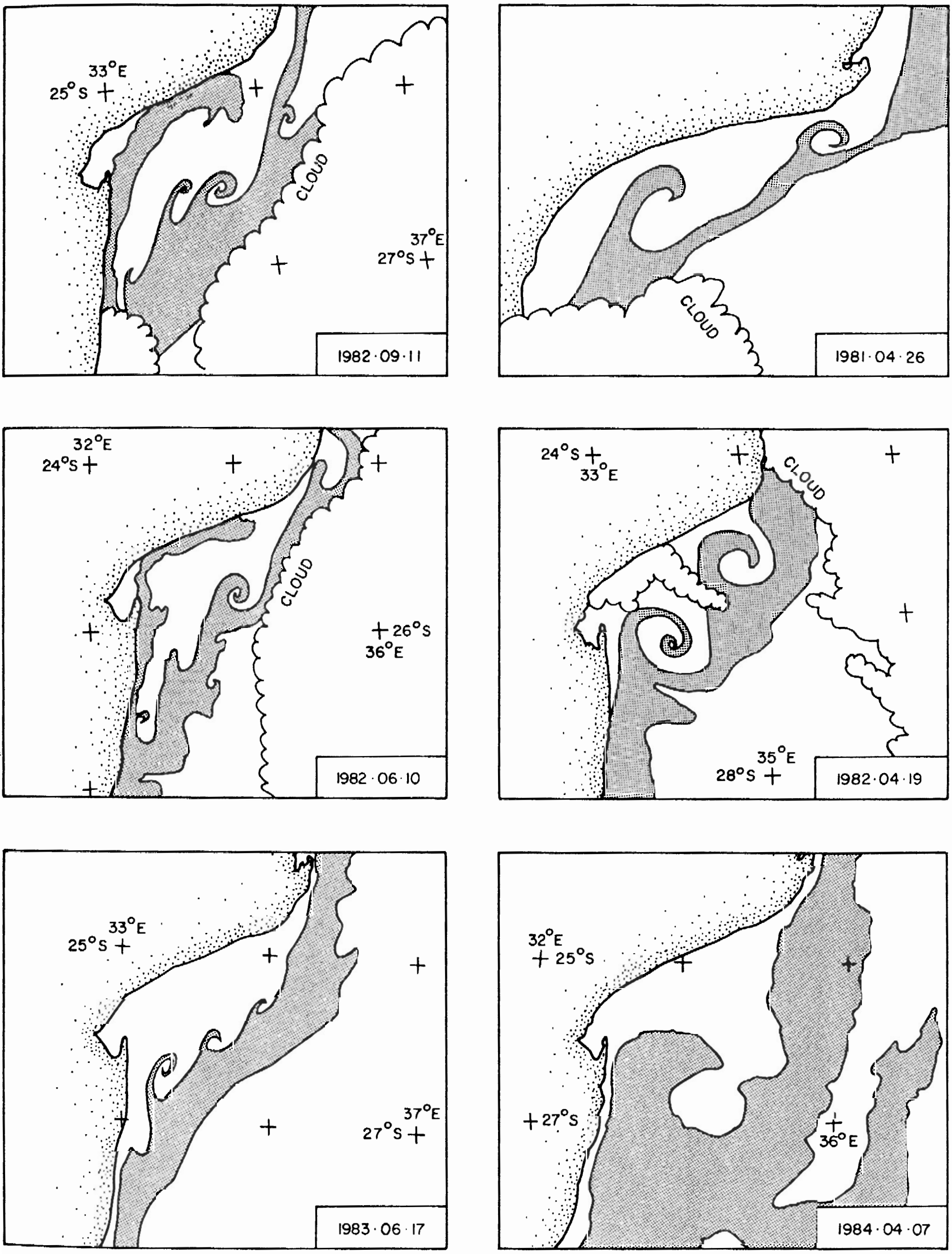

Fig. 7. Interpreted line drawings for a number of characteristic thermal configurations observed in Delagoa Bight by satellite remote sensing. They are from the satellites NOAA 7 (11 September 1982), NOAA 6 (26 April 1981), NOAA 7 (10 June 1982), NOAA 7 (19 April 1982), NOAA 7 (17 June 1983) and NOAA 7 (7 April 1984).

Table 1. Occurrence frequency of mesoscale features in Delagoa Bight according to satellite imagery

Satellite	Images of area	Cloud-free images	Countercurrent	Shear feature	Distinct eddy
NOAA 4	0	–	–	–	–
NOAA 5	69	14	6	0	0
TIROS N	10	3	2	0	0
NOAA 6	39	12	9	2	0
NOAA 7	184	95	37	15	12
Total	302	124	54	17	12
Percentage total of cloud-free images			44	14	10

A statistical analysis of all the available images (Table 1) quantifies the occurrence frequency of some of the features mentioned. Cloud obstruction of the sea surface effectively eliminates about two-thirds of the available images for use in the analysis. Of the remainder, 44% exhibit a warm countercurrent along the coast while only 14% have noticeable shear-edge features and 10% large distinct eddies (such as in Fig. 6) adjacent to the Mozambique Current. Although eddies are present a substantial part of the time, the warm countercurrent is clearly the most significant feature of the circulation in the Delagoa Bight based on surface thermal features.

SEDIMENT DISTRIBUTION

Since sedimentation patterns on the shelf may present time-integrated portrayals of the prevalent circulation regimes [see, e.g. FLEMMING (1978) for similar relationships in the Agulhas Current], a review of what is known on the physiography and the sediment patterns of the Delagoa Bight may be valuable for a further understanding of the flow structure in the area.

The average disposition of the circulation elements in the Delagoa Bight seems to follow the bottom topography (Fig. 1). The shallow part of the continental shelf, less than 100 m depth, is narrow with the exception of the area south of Ponta Zavora. The central part of the continental terrace is flat, lying between 400 and 700 m for the greater part. The two main physiographic features of the area are the Limpopo Cone and the Inharrime Terrace. These two sedimentary piles merge to the east (MARTIN, 1981a). The continental shelf break is quite sharp along the seaward edge of the Inharrime Terrace and south of Ponta do Ouro. Between these points it is more diffuse. About 80 volcanic seamounts and asymmetric mounds comprise the Almirante Leite Bank seaward of the shelf break.

In describing the sedimentation pattern of the area, MARTIN (1981a,b) has concluded that current influence is significant. Two seismic reflection profiles (A, B) have been compared to calculated current velocities on adjacent lines (C, D) based on historic hydrographic data (Fig. 8). Flow velocities were calculated by applying the Witte–Margules equation (LUTJEHARMS, 1971). Because station spacing was wide, the lateral detail of the current structure is considered to be only suggestive. Other available hydrographic sections differ, nonetheless, only in detail. MARTIN (1981a,b) has shown that

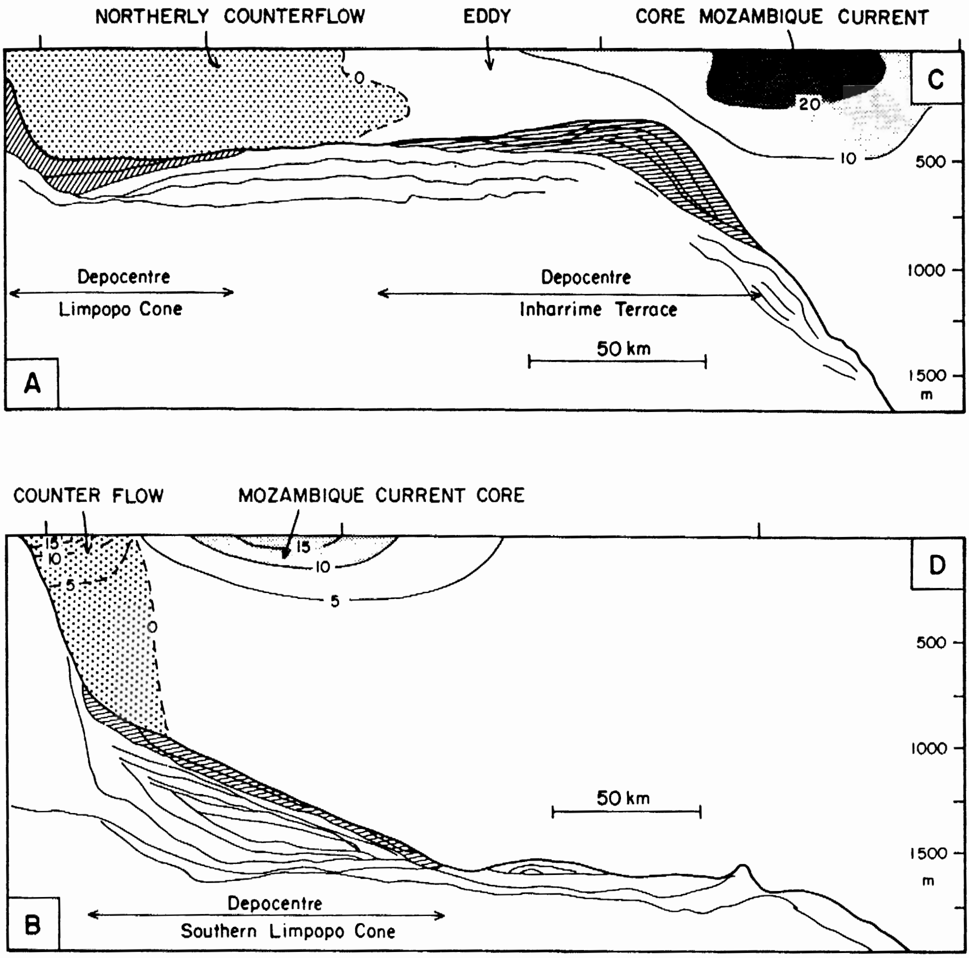

Fig. 8. Seismic reflection profiles across Delagoa Bight (lines A, B; locations in Fig. 1) with superimposed calculated current velocities for lines C and D (after MARTIN, 1981a). Current velocities in the bottom panel are based on stations worked from the R.V. *Almirante Lacerda* in September 1964 (HARRIS, 1972) while those in the upper panel are for the R.V. *Atlantis II* in November 1962. Broken lines denote northward currents. The subterraneous vertical scale is approximate, while the most important post horizon L depocentres are shaded.

the fast accumulation of the most recent sedimentation is restricted to the Limpopo sediment input, the Inharrime Terrace and off Ponto do Ouro (Fig. 8). Other parts of the Delagoa Bight show much slower sediment accumulation. The Mozambique Current, for instance, has scoured the continental slope free of post Pliocene–Recent sediment at section A. The input of sediment by the Limpopo River is similarly restricted zonally by the coastal countercurrent, while the biogenically rich surface sediments of the Inharrime Terrace are assumed to be due to enhanced biological productivity in the upwelling area at the edge of the Mozambique Current. The Inharime Terrace itself may be due to a previous debouchment position of the Limpopo River near Ponta Zavora (A. K. MARTIN, personal communication). Off Ponta do Ouro the countercurrent transports sand along the continental shelf (section B). Between the countercurrent and the Mozambique Current, a sediment deposition area is found (Martin, 1981a). The area further offshore (section B, Fig. 8) has also been scoured clean by the action of the Mozambique Current.

The distribution of sedimentary features of the bight are therefore in general agreement with the assumed average circulation composition according to hydrographic data and satellite imagery. This includes an intense western boundary current folowing the continental slope and a countercurrent following the 200 m isobath. The possible existence of a consistent mid-shelf eddy could be inferred from the geologically recent sediment accumulation in the centre of the bay. This sediment accumulation may be due to a process of settling of particles from sediment-carrying currents in an area of more quiescent flow such as the centre of an eddy.

DISCUSSION AND CONCLUSION

The consistent results regarding the location of the centre of the eddy over the continental shelf in the Delagoa Bight by the two sets of hydrographic data is further borne out by previous data sets (Table 2). Many of the historic hydrographic station lines considered here had widely spaced stations and were not specifically designed to investigate mesoscale features on the shelf. Nonetheless, an analysis of these results shows an eddy-like feature situated with remarkable consistency at more or less the same location. We must therefore conclude that this cyclonic eddy is found in the Delagoa Bight most, if not all, of the time. The relative geographical stability of its core in the centre of the flat area of the shelf leads one to suspect that it is a topographically constrained lee eddy driven energetically by the Mozambique Current and ventilated by fresh inputs of water, particularly of Sub-Tropical Water, only occasionally.

Gill and Schumann (1979) have calculated changes in the structure of an inertial current, such as the Mozambique Current, which can be induced by downstream changes in the topography of the continental shelf and slope along which the current flows. They show that a constriction in the width of the shelf, such as that which occurs south of the Delagoa Bight, can cause the development of a coastal countercurrent upstream of the constriction. A mechanism for the control of the Delagoa Bight eddy is therefore suggested by this model.

The distinctive characteristics of the eddy are most noticeable at depths greater than 100 m. Surface evidence of the eddy is probably intermittent when a filament of warm

Table 2. Approximate longitude of the Delagoa Bight eddy from previous research results at 26°S

Vessel	Period	Eddy centre	Reference
Commandant Robert Giraud	Oct. 1957	East of 33°30′E	Menaché (1963)
Africana II	Jun. 1961	33°40′E	Orren (1963)
Atlantis II	Nov. 1963	West of 34°30′E	Lutjeharms (1971)
Atlantis II	Jun. 1965	34°10′E	Jorge Da Silva *et al.* (1981)
Ariel	Aug. 1968	East of 33°30′E	Jorge Da Silva *et al.* (1981)
Dr Fridtjof Nansen	Sep. 1977	East of 33°30′E	Unpublished
Nikolay Reshetnyak	Dec. 1978	West of 34°30′E	Anonymous (1979)
Ernst Haeckel	Mar. 1979	33°45′E	Jorge Da Silva *et al.* (1981)
Nikolay Reshetnyak	May 1979	33°50′E	Anonymous (1981)
Ernst Haeckel	Aug. 1980	33°30′E	Brinca *et al.* (1982)
Dr Fridtjof Nansen	Oct. 1980	West of 33°55′E	Unpublished

Equatorial Surface Water, detached by the action of shear features on the landward edge of the Mozambique Current, is advected around the feature such as in Fig. 6 (left-hand). The coastal countercurrent forms the landward border of the Delagoa Bight eddy and is observed to advect warm water northward on many occasions. This is evident not only from the thermal infra-red satellite imagery but also from the hydrographic data. This can be observed in the surface temperatures (Fig. 3) as well as in section H (Fig. 4), for example. The dearth of thermal evidence for the existence of the eddy at the sea surface during ship crossings is consistent with it being observed only infrequently on satellite infra-red imagery.

Water masses in the Delagoa Bight eddy have T–S characteristics modified from that prevalent in the Mozambique Channel proper. In general, Sub-Tropical Water has been mixed out in the eddy and is no longer evident as a distinctive water type. The core of the eddy contains characteristic Antarctic Intermediate Water. This implies substantial upwelling from depths of at least 900 m to a position on the shelf of 400 m. Similar domes of water have been found in other western boundary currents such as the Agulhas Current off Durban (Pearce, 1977). the Florida Current and the Kuroshio (Worthington and Kawai, 1972). In most cases such domes have been assumed to drive coastal countercurrents or have been considered to be related to coastal eddies.

There is substantial evidence that the downstream counter-part of the Delagoa Bight eddy, namely the one adjacent to Richards Bay, occasionally may escape its shelf entrapment and drift southward on the inshore side of the Agulhas Current (Lutjeharms and Roberts, 1988). Some evidence for a similar intermittent process for the Delagoa Bight eddy is accumulating but is not yet sufficiently comprehensive to warrant detailed analysis.

The geographic distribution of geologically recent sediments on the continental shelf of the Delagoa Bight substantiates the persistence of both the Mozambique Current and the Delagoa Bight eddy.

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