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The hydrography and water masses of the Natal Bight, South Africa

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Abstract

The Natal Bight is an unusually wide coastal offset on South Africa's east coast along an otherwise uniformly narrow shelf. Interaction with the deep sea is limited by the strong Agulhas Current along the shelf edge. This semi-enclosed body of water has an unusual role in the local shelf ecosystem and also plays an important triggering role in major perturbations to the trajectory of the Agulhas Current. We present the results of the first dedicated research cruise that has encompassed the hydrography of the whole Bight. Water in the Bight consisted of South Indian Subtropical Surface Water and Indian Tropical Surface Water. There was only a negligible effect of river runoff. The topographically induced upwelling cell at the northern end of the Bight was characterised by lower temperatures, higher salinities, higher nutrients and higher chlorophyll *a* values. This upwelled water dominated the northern part of the Bight on this occasion and there is substantial evidence that the upwelling cell supplies the bottom water for the whole bight. There was little comparable water exchange along the rest of the shelf edge. This cell therefore also controls the supply of nutrients to the whole Bight. The abnormal divergence of the Agulhas Current from the shelf edge near Durban during the cruise suggests the initial stages of a Natal Pulse. Surface temperature distributions and nitrate values indicate a cyclonic motion in this incipient pulse. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Hydrography; Water masses; Natal Bight; Continental shelf slope; Current

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1. Introduction

One of the unusual characteristics of the northern Agulhas Current is the strong stability in its trajectory. This is brought about by the very narrow continental shelf and steep slope along this coastline that tend to stabilise the current (De Ruijter et al., 1999). The exception to this consistent shelf morphology is the Natal Bight. It lies in a substantial coastal offset between Cape St Lucia to the north and Durban to the south along the east coast of South Africa (Fig. 1). The Bight is about 160 km long and is about 50 km wide at its broadest, off the mouth of the Tugela River. The 200 m isobath constitutes the shelf break with a relatively steep slope seaward, but not as steep as either north or south of here. The high-velocity Agulhas Current follows this shelf break quite closely (Pearce, 1977; Schumann, 1988) thus enclosing the shelf waters of the Bight.

The Natal Bight plays a role in ocean dynamics out of all proportion to its size. It has been shown to be the inception region for the Natal Pulse (Lutjeharms and Roberts, 1988), a solitary meander on the Agulhas Current path that constitutes the major perturbation of this current. The Natal Pulse has a major influence on the disposition of the Agulhas retroflection, far downstream (Lutjeharms and van Ballegooyen, 1988; Van Leeuwen et al., 2000), where this major current turns back on itself and where Agulhas rings are shed that carry Indian Ocean water into the South Atlantic Ocean. Natal Pulses thus influence the exchange of water between the Indian and Atlantic Oceans. The dynamics of the Natal Pulse have been construed as consisting of a vortex shed from the Natal Bight (Lutjeharms and Connell, 1989). Current measurements in this region are consistent with such an interpretation (Schumann, 1981, 1982) but to date no hydrographic observations at the commencement of a Natal Pulse have been made. The triggering of a Natal Pulse seems to come about due to an instability in the core of the Agulhas Current (De Ruijter et al., 1999) when the intensity of this jet exceeds a certain threshold. Such instabilities are ruled out by the shelf morphology along the length of the northern Agulhas Current trajectory, with the exception of the Natal Bight. A more solid foundation to our knowledge of the circulation and hydrography of the Natal Bight is therefore of considerably wider interest than merely regional.

Current knowledge on the water masses and the circulation over the shelf of the Natal Bight is disjointed, is based on an eclectic collection of data and is thus mostly by inference. A considerable number of data have been collected off Richards Bay (Fig. 1) to the north (Pearce, 1978; Pearce et al., 1978; Gründlingh, 1974) and also off Durban (Pearce, 1977; Schumann, 1981, 1982; Anderson et al., 1988). These data have given rise to a few concepts of the circulation on the Bight that have been synthesised by Schumann (1988).

First and foremost, the shelf circulation is strongly influenced by the proximity of the swiftly flowing Agulhas Current. This current usually lies seaward of the 200 m isobath, but on occasion Agulhas water may penetrate landward to the 100 m isobath (Pearce, 1977). Water from the Agulhas Current is transferred onto the bank giving its water masses their tropical and subtropical characteristics (Schumann, 1988).

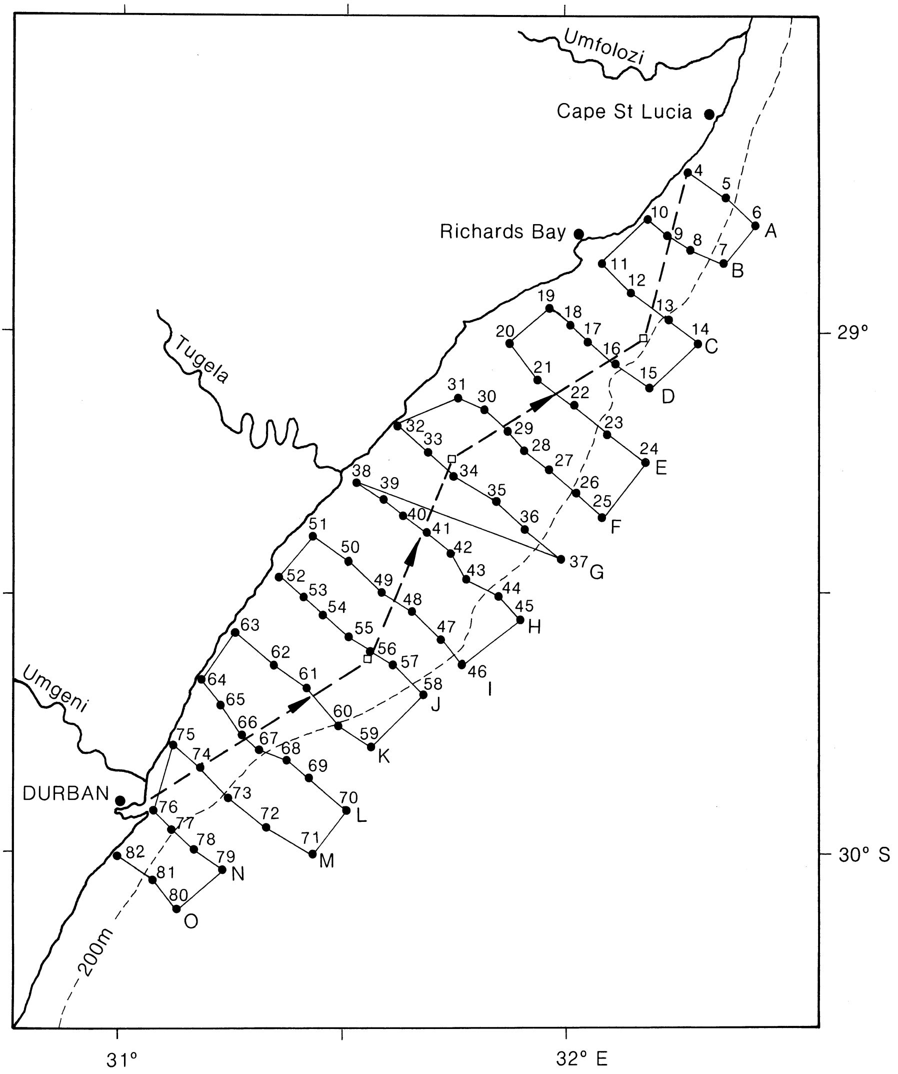

Fig. 1. The cruise track and location of hydrographic stations of the Natal Bight Cruise of 16–22 July 1989. Station lines are lettered. The interruption in the regular cruise pattern between Stations 37 and 38 was due to a severe storm. The edge of the continental shelf at 200 m depth is indicated by a broken line.

Tropical Surface Water is brought onto the shelf by shear edge plumes of the upper water of the Agulhas Current (Gründlingh and Pearce, 1990) while Subtropical Surface Water forms a salinity maximum at a depth of 200 m seaward of the Agulhas Current, but rises to a depth of 100 m or less on the inshore edge of the current (Pearce, 1977). Colder, deeper water may be brought onto the shelf by various upwelling processes.

A few distinct upwelling mechanisms have been suggested. First, bottom Ekman veering along the full length of the shelf slope has been invoked as a mechanism for bringing cold, nutrient-rich water onto the shelf at the edge of the Agulhas Current (Schumann, 1986). Secondly, a persistent topographically-induced upwelling cell off Richards Bay (Lutjeharms et al., 1989b) seems to contribute to a near-continuous flow of nutrients onto the bank (Carter and d'Aubrey, 1988) and creates a specific region of enriched biological production (Carter and Schleyer, 1988).

The water on the Bight has been considered to be generally well-mixed. Movement of the upper layers has been shown to be well-correlated with synoptic winds (Pearce et al., 1978), bringing about sudden current reversals, for example at Richards Bay (Gründlingh, 1974). Short term fluctuations in temperature and salinity due to various upwelling processes may mask or exceed any seasonal variation (Pearce, 1978).

The general circulation over the wider shelf itself is not understood well. From satellite remote sensing (Malan and Schumann, 1979) inferences have been made about a series of cyclonic, lee eddies over the Bight. Evidence for current reversals close to the coast (Schumann, 1981, 1982) as well as the distribution of bottom sediments (Flemming and Hay, 1988) are consistent with such an interpretation. The forcing of lee eddies in the Natal Bight by the passing current (Pearce et al., 1978) would be substantially similar to the driving of such an eddy in the Delagoa Bight to the north (Lutjeharms and Jorge da Silva, 1988).

Just upstream of Durban the shelf becomes abruptly narrower (Fig. 1). The Agulhas Current is known to overshoot this offset in the shelf edge and only to join the 200 m isobath again farther downstream (Schumann, 1987). In this region a small, trapped, lee eddy is often to be found (Pearce, 1977; Anderson et al., 1988). It therefore has become recognised as a quasi-permanent part of the circulation regime off Durban (e.g. Pearce et al., 1978).

From the above summary of what is currently known it is clear that knowledge on the circulation and the water masses of the Natal Bight as a whole remains disjointed at best, notwithstanding the recognised importance of this region, also for the proper understanding of the circulation over a much wider area. To address this lack of data, a dedicated cruise was designed and planned to cover, for the first time, the full extent of the Natal Bight with a network of quasi-synoptic hydrographic stations. We present here the results of this cruise, thus giving the first description of the hydrography and water masses of the Natal Bight as an entity.

2. Data and methods

The Natal Bight Cruise (16–22 July 1989) consisted of 15 short cruise lines (A to O) all more or less perpendicular to the coast and covering the continental shelf from north of Richards Bay to just south of Durban (Fig. 1). The seaward extent of each line depended on the width of the shelf there or the location of the landward edge of the Agulhas Current if the latter was further offshore. The Agulhas Current was found seaward of the shelf break on the four southernmost lines, particularly lines L and M (Fig. 1). The survey was executed from north to south. On the northward leg from Durban, towards Cape St Lucia, three stations were carried out mainly to test the equipment (Fig. 1). From here southward the cruise proceeded according to plan, with one interruption. On 18 July winds became so severe that shelter had to be sought close to the mouth of the Tugela River. The survey was resumed on 20 July. During this inactive period, drifting close to shore, signs of substantial river runoff were observed, i.e. tree trunks and other flotsam floating by and considerable discolouration of the water. On resumption of the observational programme (station 38, Fig. 1) the possibility was considered that the stratification over the shelf could have been materially altered by the storm. The extent of this alteration could best be determined objectively by repeating a station on the middle of the shelf that had also been sampled before the storm. Station 56 was a repeat of station 1 that had been occupied 5 days before (Fig. 1), on the way northward to start the full grid of stations. No significant differences in the depth of the mixed layer (50 m) nor of the values of any of the hydrographic variables were observed (Valentine et al., 1991). It is therefore concluded that the impact of the storm on the water column structure was negligible.

Eighty-two hydrographic stations were carried out that sampled 90% (80% in foul weather) of the water column at each station. A Neil Brown Mk III CTD (conductivity–temperature–depth) sensor, mounted inside a rosette sampler with 12 bottles of 2 l capacity, provided continuous measurements of temperature and salinity with depth. The methods used in calibrating the instruments and in validating the data have been described in detail in the resulting data report (Valentine et al., 1991). Water samples were taken at the standard depths of 5, 10, 20, 30, 40, 50, 75, 100, 125, 150, 175, and 200 m. Samples were used for the calibration of the CTD salinity measurements, for nutrient analyses and for chlorophyll *a* determinations. No samples were taken below a depth of 200 m, but CTD casts were taken to a maximum depth of 553 m (Valentine et al., 1991).

The micro nutrients silicate, nitrate, nitrite and phosphate were determined by a slightly modified version (Windt, personal communication) of the method described by Mostert (1983). A Technicon Auto Analyser system was used for these analyses. Chlorophyll *a* samples were frozen on board immediately after filtration and their concentrations determined in the home laboratory using standard methodology (SCOR/UNESCO, 1966).

Concurrent thermal infrared imagery for the region showed extensive cloudiness until the day after the cruise. These somewhat belated images came from the Advanced Very High Resolution Radiometer (AVHRR) on board the orbiting NOAA 10 satellite and have a nominal spatial resolution at nadir of about 1.5 km. Appropriate atmospheric corrections were made to these remotely sensed data and contrast enhancement was carried out for the thermal range to be expected in these waters.

3. Results and discussion

3.1. Water mass distributions

The distribution at 10 m depth of potential temperature, salinity and nitrate over the full Natal Bight is shown in Fig. 2. The trends and distributional patterns for the

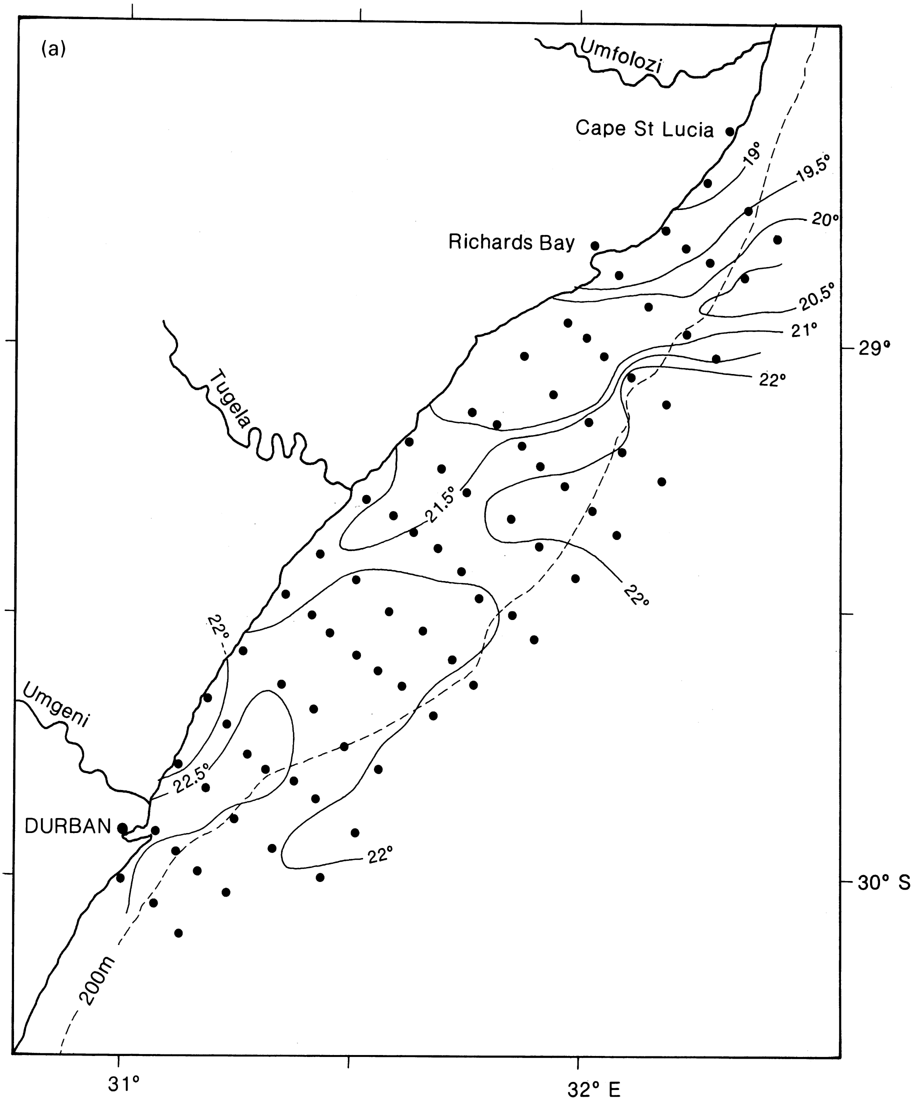

Fig. 2. The distribution of temperature (°C) (a), salinity (b) and nitrate (c, μmol/kg) at a depth of 10 m on the Natal Bight during July 1989. Only stations at which actual observations of that variable were made are shown. The broken line represents the 200 m isobath.

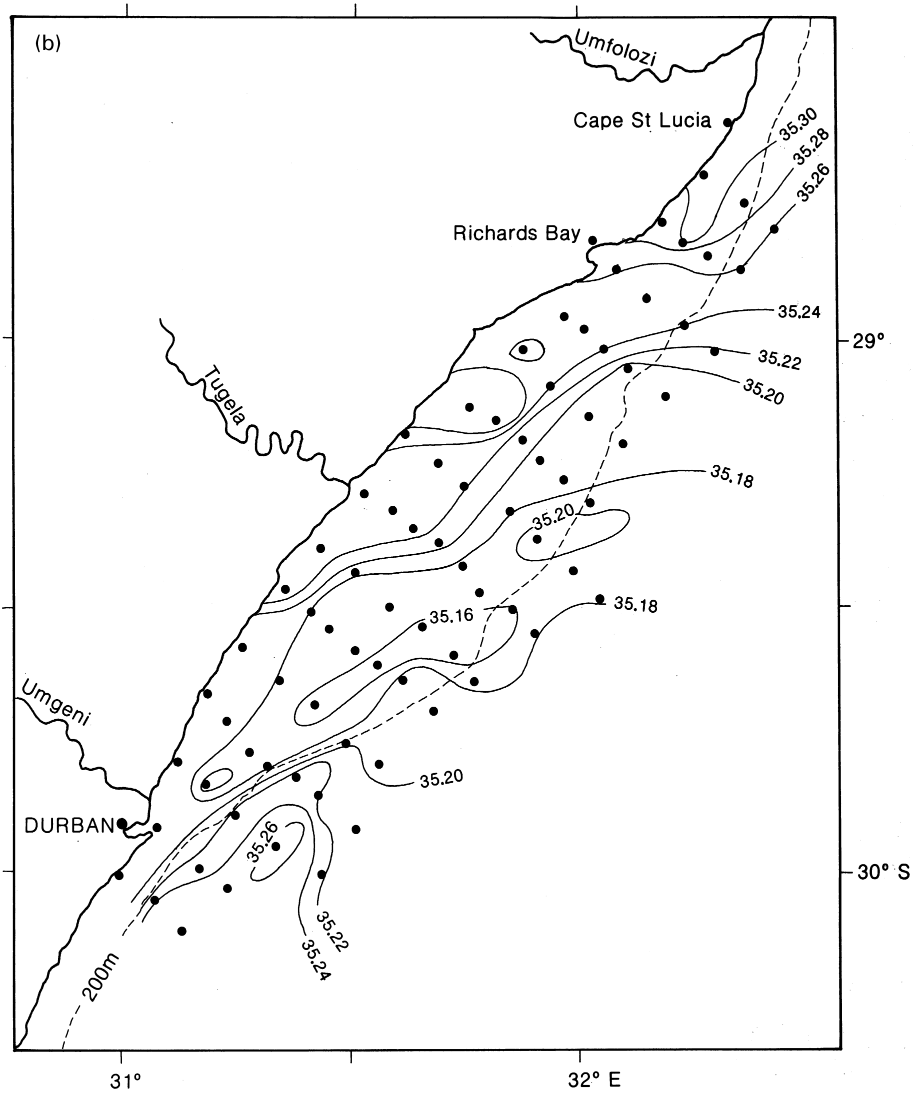

Fig. 2. (*Continued.*)

four nutrients measured were nearly identical at all depths. For this reason and since the nutrient chemistry of the Natal Bight is dealt with in greater detail elsewhere (Meyer et al., 1999) only the nitrate values are used here as representative of the nutrient distributions. The values of variables at 10 m depth, used in Fig. 1, are considered representative of the surface layer. A number of consistent and instructive patterns are evident.

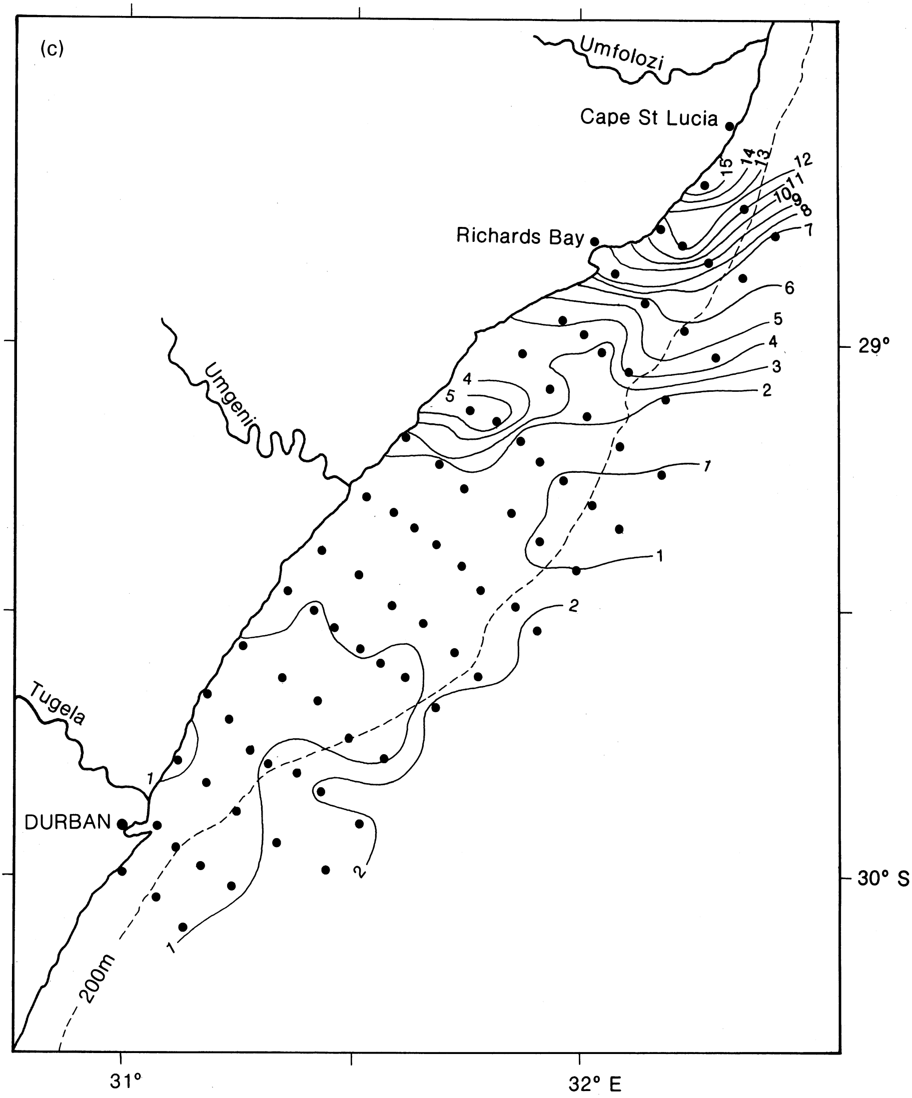

Fig. 2. (*Continued.*)

First, the surface layers may be considered to represent four provinces. The central part of the Bight was characterised by temperatures between 20 and 22°C. There is some indication of a surface front at about 21.5°C (Fig. 2) that dissects this distribution in a diagonal way from southwest to northeast. In the temperature distribution (Fig. 2a) this meridional gradient is only clear near the shelf break, but in the more conservative salinities this front is explicit across the full width of the shelf (Fig. 2b).

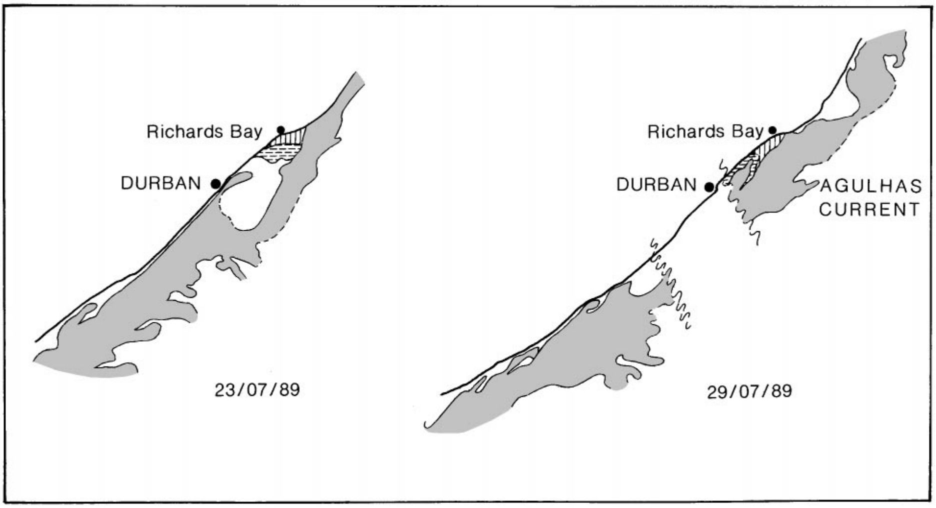

Fig. 3. Sea surface temperatures for the Natal shelf region inferred from thermal infrared readings on board the NOAA 10 satellite for the dates shown. Areas with vertical lines had the lowest, broken lines low and shaded areas the highest temperatures. On 29 July the region off Durban was obscured by cloud.

The third surface province was the colder, more saline and nutrient-rich upwelling cell north of Richards Bay. Visible in the distributions of temperature and salinity, it is extraordinarily clear in the distribution of nitrate (Fig. 2c). There was a steady decrease in nutrients from this cell southward, terminating more or less at the location of the cross-shelf front.

The uniform decrease in the nutrient values southward was interrupted only by a small cell of slightly enriched water of lower salinity along the coast, north of the Tugela (Figs. 2c and b). These slightly anomalous values were constant throughout the water column to the depth of 25 m measured (Valentine et al., 1991). The total water depth here is 40 m. It is likely that this represents runoff from the Tugela River that had moved along the coast in a northerly direction. Northward flows along this coastline are well-known (Malan and Schumann, 1979; Pearce et al., 1978) and the satellite image for 23 July (Fig. 3) in fact indicates a movement of warmer water alongshore in this direction.

The last hydrographic province is represented by the high salinity anomaly centred at station 72 east of Durban (Fig. 2b). It is not noticeable in the temperature or nutrient distributions, but the satellite image suggests that it may have come about as a result of the unusual disposition of the Agulhas Current at this time. These southern station lines were in fact extended seaward to find the landward edge of the current that was beyond its normal location above the 200 m isobath. This anomalous feature will be discussed at greater length below.

From these surface distributions a number of preliminary conclusions can be made. First, it is clear that on this occasion the upwelling cell at Cape St Lucia – already identified in previous studies (e.g. Carter and Schleyer, 1988; Lutjeharms et al., 1989a) – played a dominant role. The whole northern half of the shelf region had strong admixtures of upwelled water. The nature and the permanence of the cross-shelf front, that separated surface water derived from the upwelling cell from the water further south, is not known. Satellite thermal infrared information (Fig. 3) is consistent with the surface temperature distribution from the hydrographic information (Fig. 2a) but

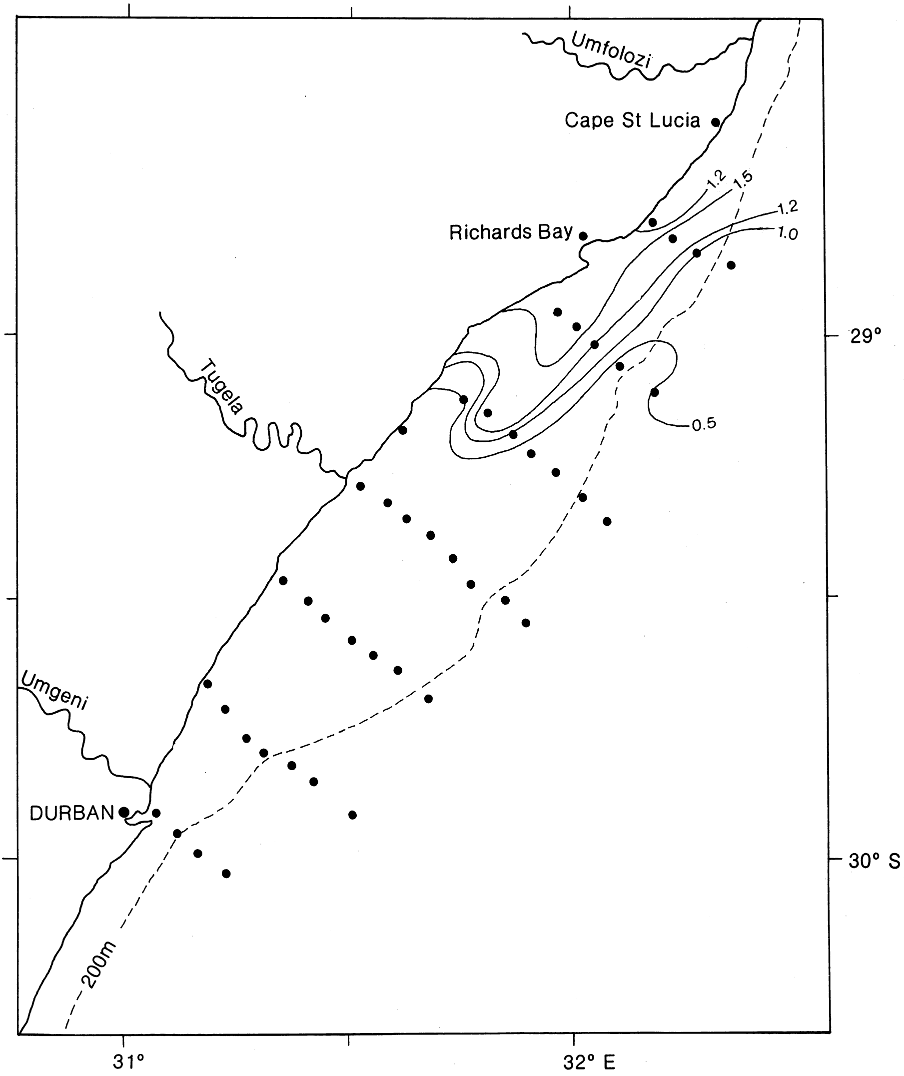

Fig. 4. The distribution of chlorophyll *a* over the Natal Bight in July 1989. Units are mg/m^3. The positions of only those stations where chlorophyll *a* readings were taken are indicated.

shows a rapid change with time. Surface temperatures collected seven days after the end of the cruise suggest (Fig. 3) that cold water from the upwelling cell had extended much farther south along the edge of the Agulhas Current. Such behaviour for upwelled water from this source is well-known (Lutjeharms et al., 1989b). One may therefore conclude that the upwelling cell is a key element of the Natal Bight hydrography, but that the subsequent distribution of the upwelled water over the Bight may be very variable. The impact of the nutrient-rich upwelled water on the biota of the shelf should be considerable.

Substantially elevated values for chlorophyll *a* were in fact observed over the northern Natal Bight (Fig. 4). This distribution is strongly correlated with that of the nutrients (Fig. 2c). Of particular interest is the southward gradients in chlorophyll *a* values. Closest to Cape St Lucia, where the values were highest, the chlorophyll *a* content was 1.2 mg/m^3. It increased to 1.5 mg/m^3 to the south and then decreased on moving even further southward as the nutrients got used up. This is the usual distribution in an active upwelling cell where the organisms closest to the source have not had the time to react fully to the new supply of nutrients and the most intense phytoplankton bloom is found at some distance from the centre of upwelling. One may therefore conclude that this upwelling cell was fully active at this time. From the distribution of chlorophyll *a* it is furthermore clear that this upwelling has a material impact on the primary productivity and therefore probably on the ecology of a substantial part of the Natal Bight as a whole.

It is important to establish exactly what water types were involved in these different regimes on the shelf at this time.

3.2. Water types and volumetry

The temperature/salinity characteristics representing all the observations during the Natal Bight Cruise are depicted in Fig. 5. They exhibit the characteristic relationships to be expected in the upper part of the Agulhas Current. The warm surface water shows a lower salinity compared to the water directly below it. This is Indian Tropical Surface Water that has a winter temperature of about 22°C here (Pearce, 1978). Indian Tropical Surface Water is found on the inshore side of the Agulhas Current (Gordon et al., 1987; Biastoch et al., 1999) and moves from the tropics, where it gains its relative freshness as a result of an excess of precipitation over evaporation, through the Mozambique Channel to join the Agulhas Current flow (Harris, 1972). Its salinity lies between 35.10 and approximately 35.25. The salinities at the sea surface of the Bight (Fig. 2b) show that the surface layers of the shelf were dominated by Indian Tropical Surface Water, with the exceptions of those parts dominated by water derived from the upwelling cell. This suggests that the influence of the Agulhas Current on the upper layers of the Natal Bight is mostly from its inshore side. This will probably be by way of surface plumes at the shear edge of the current (Gründlingh and Pearce, 1990) in the same way as at the Agulhas Bank, further south (Lutjeharms et al., 1989a). These features usually grow in lateral dimensions on moving downstream, so that there is a likelihood that the input of Indian Tropical Surface Water may be greater in the southern part of the Natal Bight.

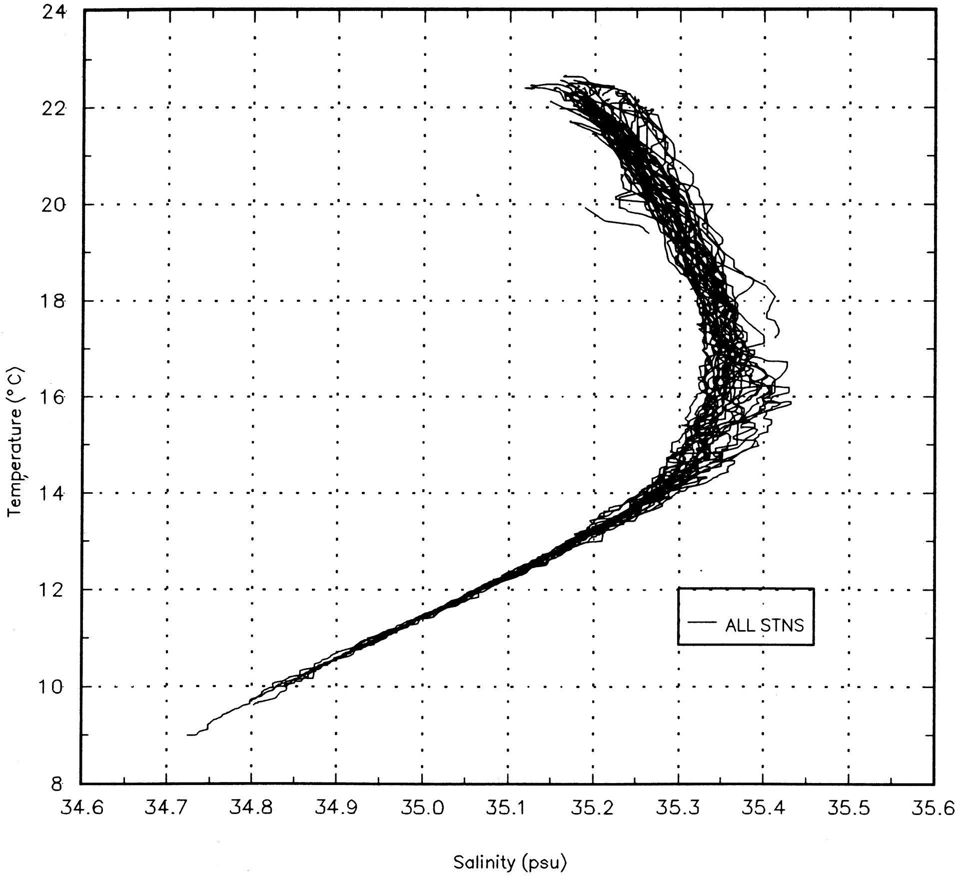

Fig. 5. A combination of traces for the temperature/salinity characteristics for all stations over the Natal Bight in July 1989.

Below the Indian Tropical Surface Water is the South Indian Subtropical Surface Water. This is shown by a salinity maximum at a depth of about 150 m in the Agulhas Current. It is clearly evident in most of the vertical sections of this cruise that have crossed the edge of the Agulhas Current (e.g. Fig. 6). This water mass has a temperature of about 16 °C. With few exceptions it was found only on the seaward perimeter of the Natal Bight at depths exceeding 100 m (Figs. 7–9). The one exception was the upwelling cell where South Indian Suptropical Surface Water was brought onto the shelf (Fig. 7a and b). As can be expected, the temperature/salinity characteristics of both these water masses that were in direct contact with the atmosphere exhibit considerable scatter. This is not the case for water at greater depth.

These temperature/salinity values of the upper water column of the Bight are consistent with those published previously for mid-summer (Schumann, 1988). There

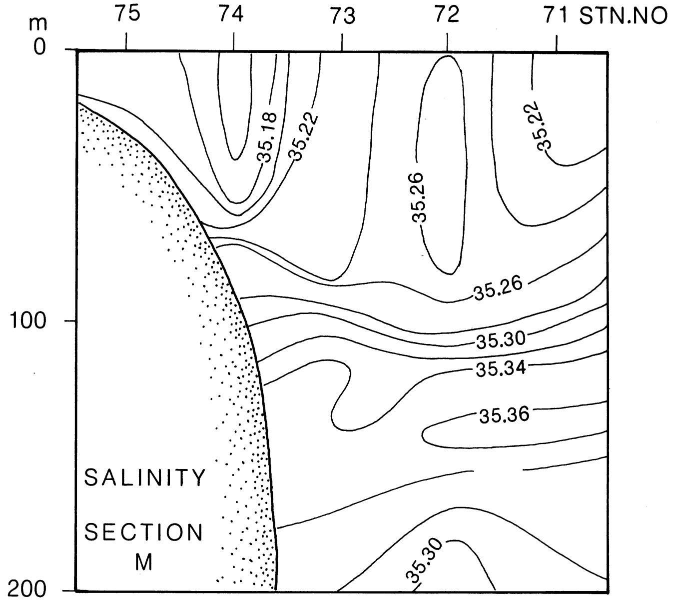

Fig. 6. The vertical distribution of salinity along station line M off Durban. The location of this line is given in Fig. 1.

therefore seem to be only small seasonal differences, since the data of the Natal Bight Cruise presented here were taken in mid-winter. An analysis by Pearce (1978) has shown substantial short-term variations in both temperature and salinity in the vicinity of Richards Bay, suggesting that the seasonal variability is overshadowed by the short-term variablity on the shelf.

The remaining, and deeper, water mass associated with the Natal Bight is the South Indian Central Water. It presents as a straight line on a temperature/salinity diagram (Fig. 5) and basically consists of a mixture between surface water and the Antarctic Intermediate Water below. At the edge of the continental shelf of the Natal Bight it has temperatures below 14°C and salinities lower than 35.3. The traces in Fig. 5a that include South Indian Central Water are from those stations at the farthest seaward end of each station line that included observations deeper than 200 m. The extent to which deeper water moves onto the shelf in the Natal Bight should depend on the exchange of water at the shelf edge as well as the efficiency with which water is moved vertically at the upwelling cell. It would seem that the upwelling cell is most important in this respect.

3.3. The St Lucia upwelling cell

The temperature/salinity characteristics of the water in the upper 200 m of the upwelling cell is given in Fig. 10. Comparing it to that of the shelf as a whole (Fig. 5), shows that this water is normal Indian Tropical Surface Water extending into the deeper South Indian Subtropical Surface Water. There is slight evidence of fresher water with a salinity below 35.20 at the sea surface. This was found only at Station 11 (Fig. 1) just off Richards Bay and was, most likely, due to river runoff. There is no evidence of South Indian Central Water being upwelled in this cell. This is in marked contrast to the upwelling in the Port Alfred upwelling cell on the Agulhas Bank

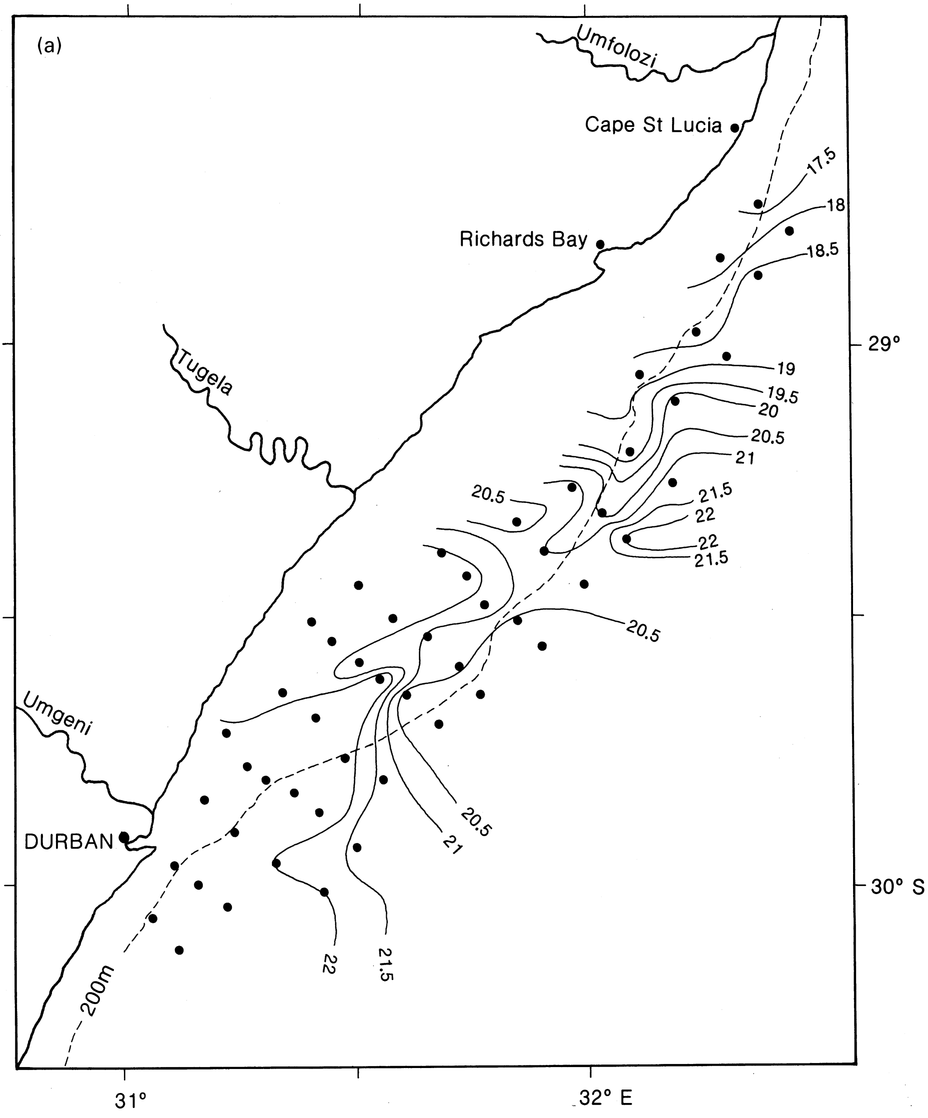

Fig. 7. The same as for Fig. 2, except at 50 m depth. The salinity values have been simplified by subtracting 35.00 and multiplying the remainder by 100.

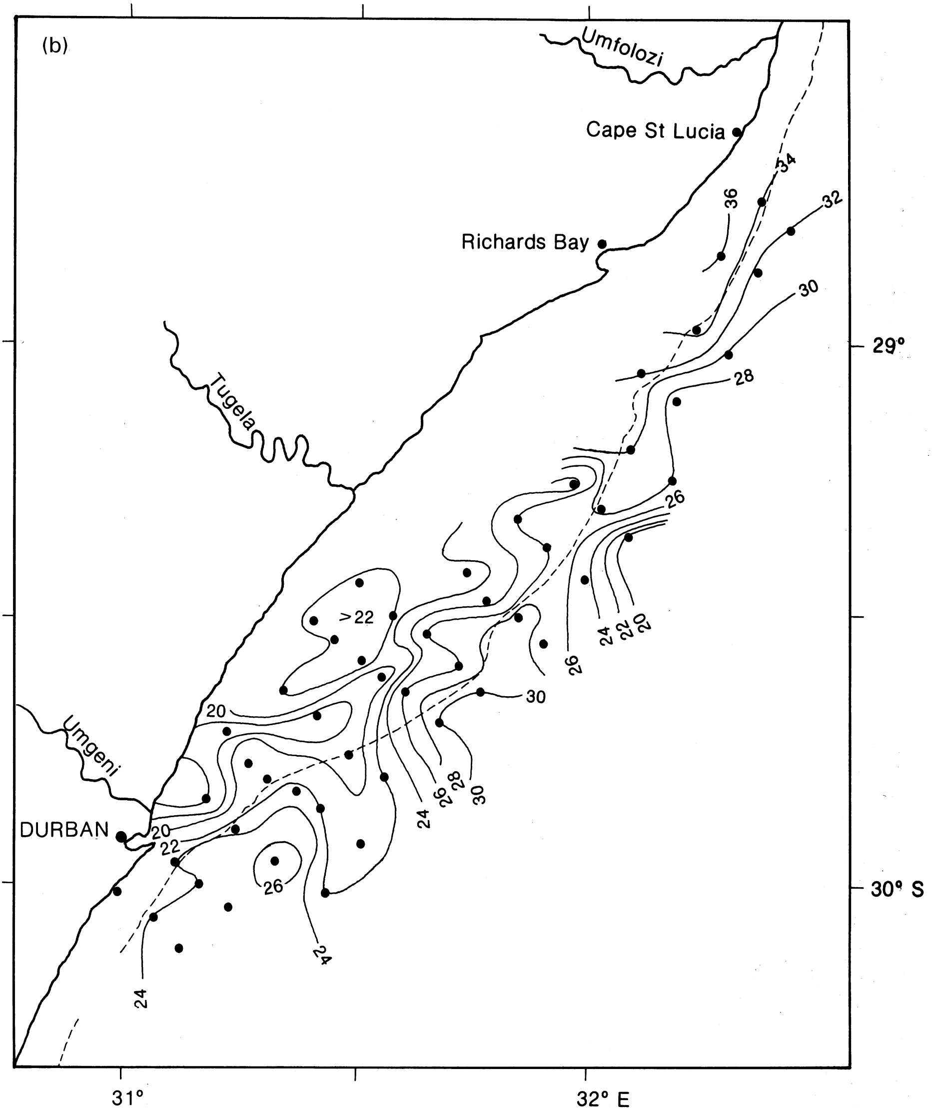

Fig. 7. (*Continued.*)

(Lutjeharms et al., 1999) which in all other respects is very strongly analogous to the St Lucia upwelling cell. Both lie at the upstream end of a broadening continental shelf and both are topographically driven by the passing Agulhas Current. The reasons for the noted difference are probably twofold. First, the shelf at Port Alfred is considerably deeper than at St Lucia, allowing access to deeper waters. Secondly, the speed of the Agulhas Current may be higher further downstream thus enhancing the

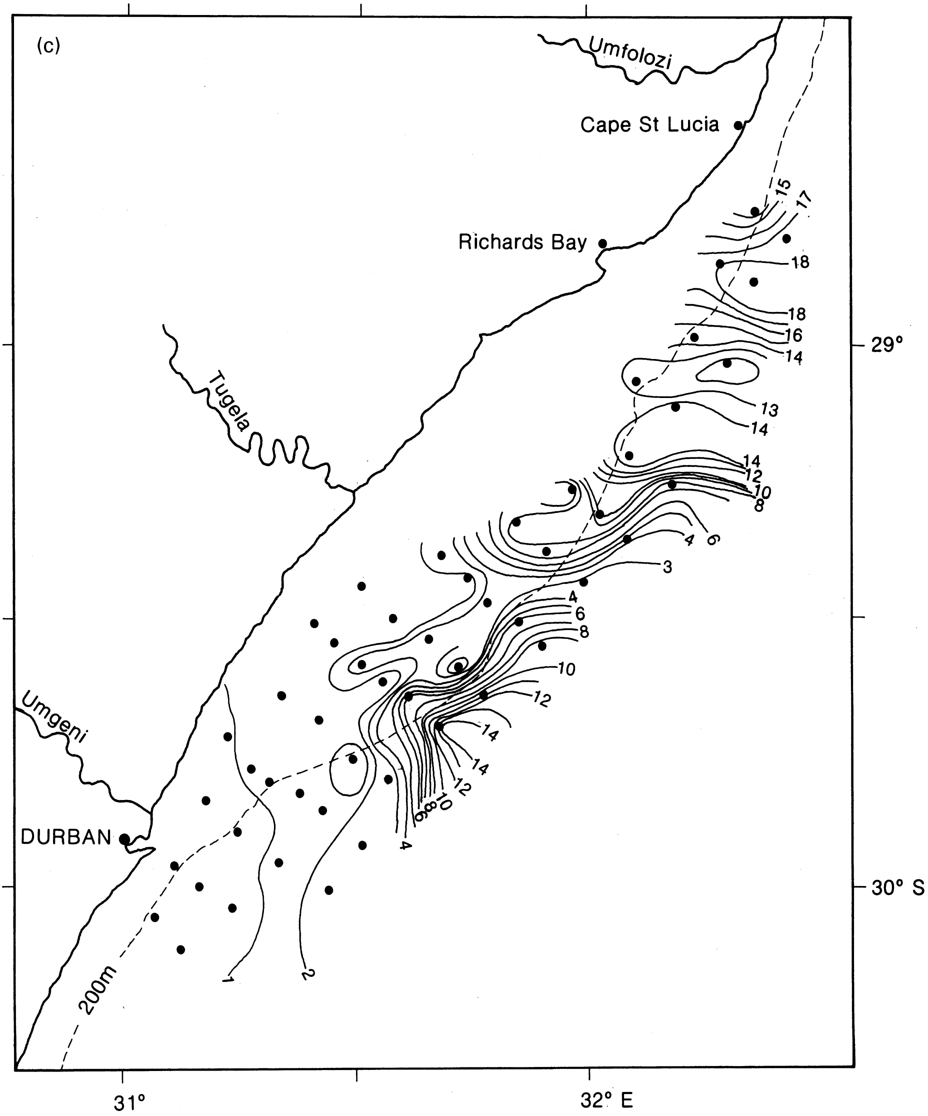

Fig. 7. (*Continued.*)

upwelling effect (Gill and Schumann, 1979). The vertical extent of the different water masses in the St Lucia upwelling cell is clear from the hydrographic variables at the appropriate station lines.

Comparing the temperature section through the upwelling cell (line B, Fig. 11) with a section in the centre of the Bight (line G, Fig. 12) demonstrates the effect of upwelling at the northern part of the Natal Bight clearly. Water of 19°C was found at a depth of

70 m in the centre of the Bight, but at 10 m depth in the upwelling cell (station 9, Fig. 11). No water colder than 20°C was found on that part of the shelf shallower than 50 m away from the upwelling cell (Fig. 12). The upward movement portrayed in the temperature distributions is mirrored almost exactly in the nitrate section (Fig. 13). The salinity sections reinforce these portrayals (Figs. 14 and 15). At station line G the

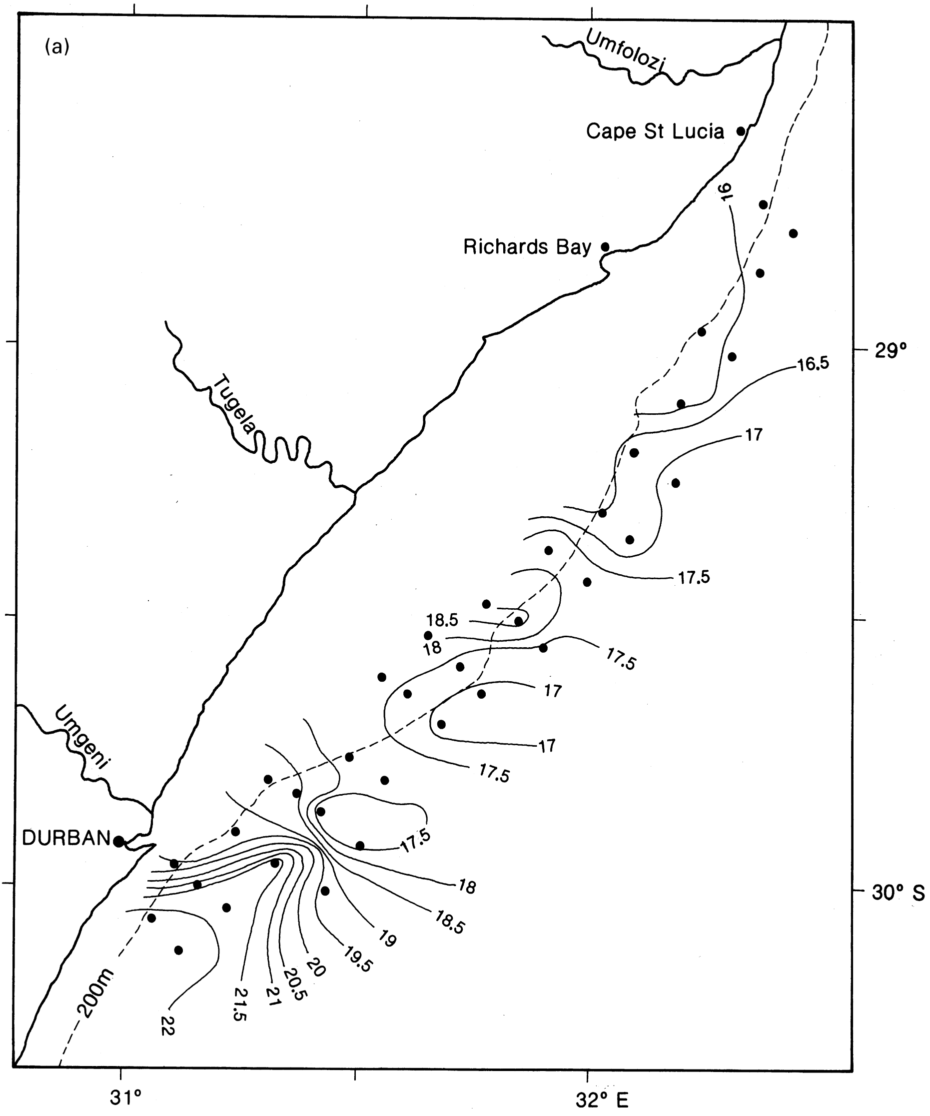

Fig. 8. The same as for Fig. 2, except for 100 m depth. The salinity values have been simplified by subtracting 35.00 and multiplying the remainder by 100.

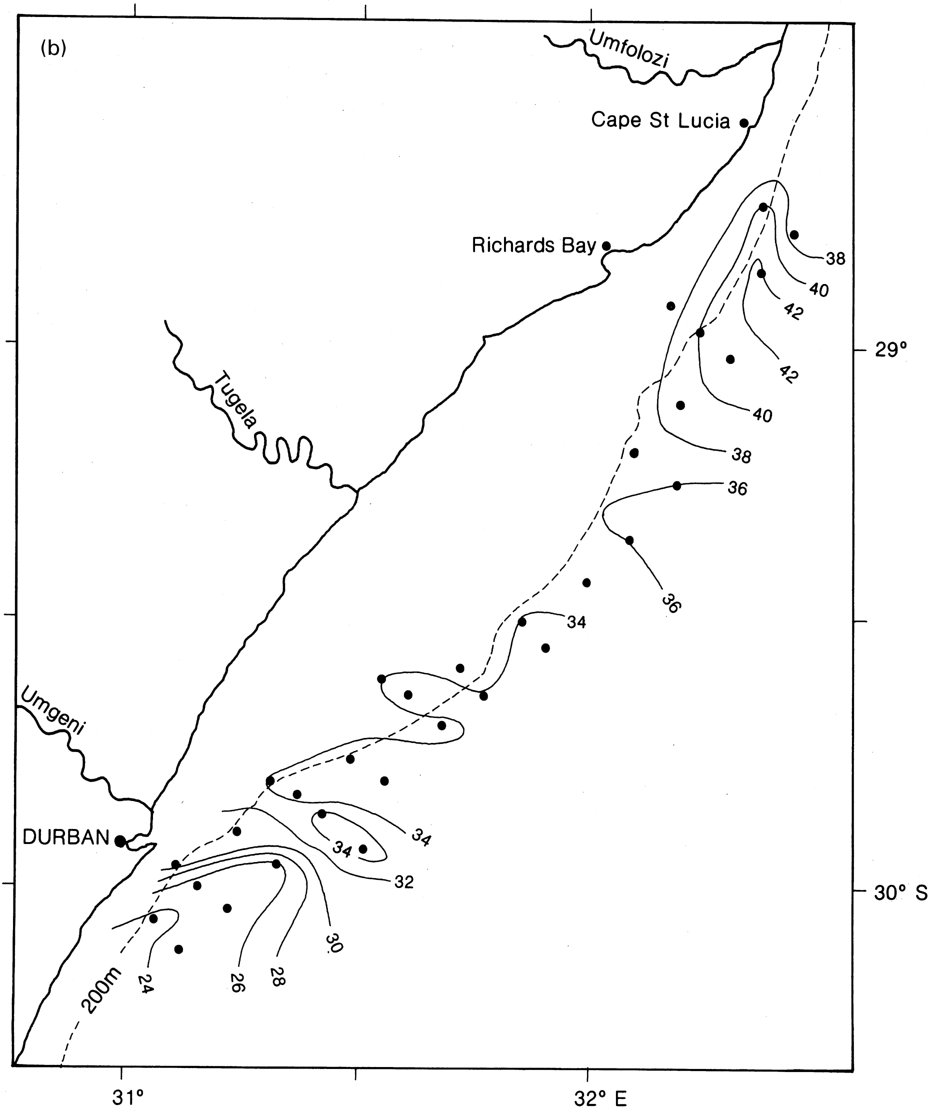

Fig. 8. (*Continued.*)

most saline water was 35.32 at a depth of 100 m. At station line B, in the upwelling cell, the core of the South Indian Subtropical Surface Water at 35.42 was located at 100 m depth. The Subtropical Surface Water had therefore been moved upward by at least 48 m in the St Lucia upwelling cell. The distribution of various hydrographic variables at 10 m depth (Fig. 2) shows the subsequent advection of the water from this upwelling

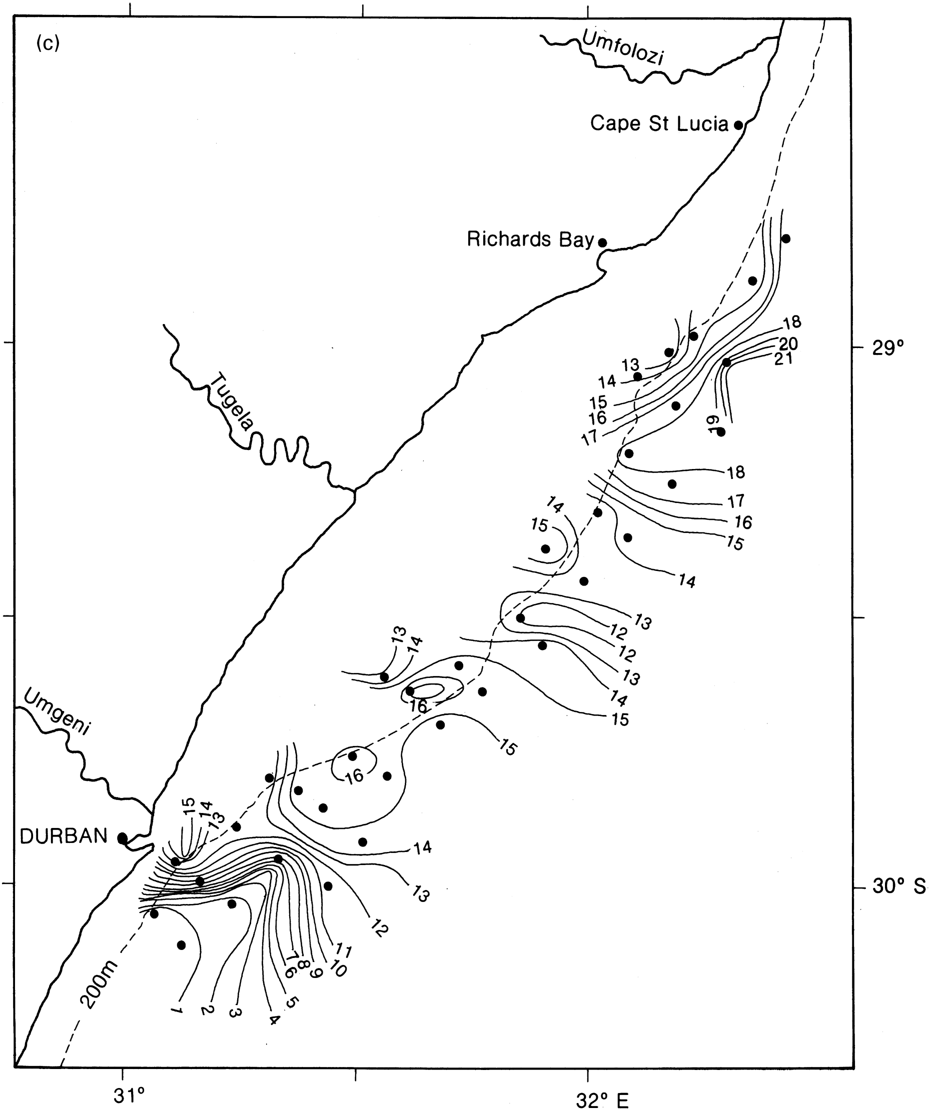

Fig. 8. (*Continued.*)

cell over the rest of the Natal Bight by inference from the decreases in concentration. This was at the sea surface; at greater depths this may be different.

At 50 m depth lower temperatures (Fig. 7a), higher salinities (Fig. 7b) and higher nutrients (Fig. 7c) extended all the way to the mid-shelf front just north of the Tugela (Fig. 2), much the same as they did closer to the surface. The elevated values all extended seawards of the 200 m isobath at this depth. At 100 m depth the picture becomes more obscured. The water with lower temperatures still extended from the upwelling cell to roughly the latitude of the Tugela mouth (Fig. 8a) but there also were patches of lower temperatures further downstream along the edge of the Agulhas Current. The salinity distribution (Fig. 8b) shows a tongue of higher salinity along the

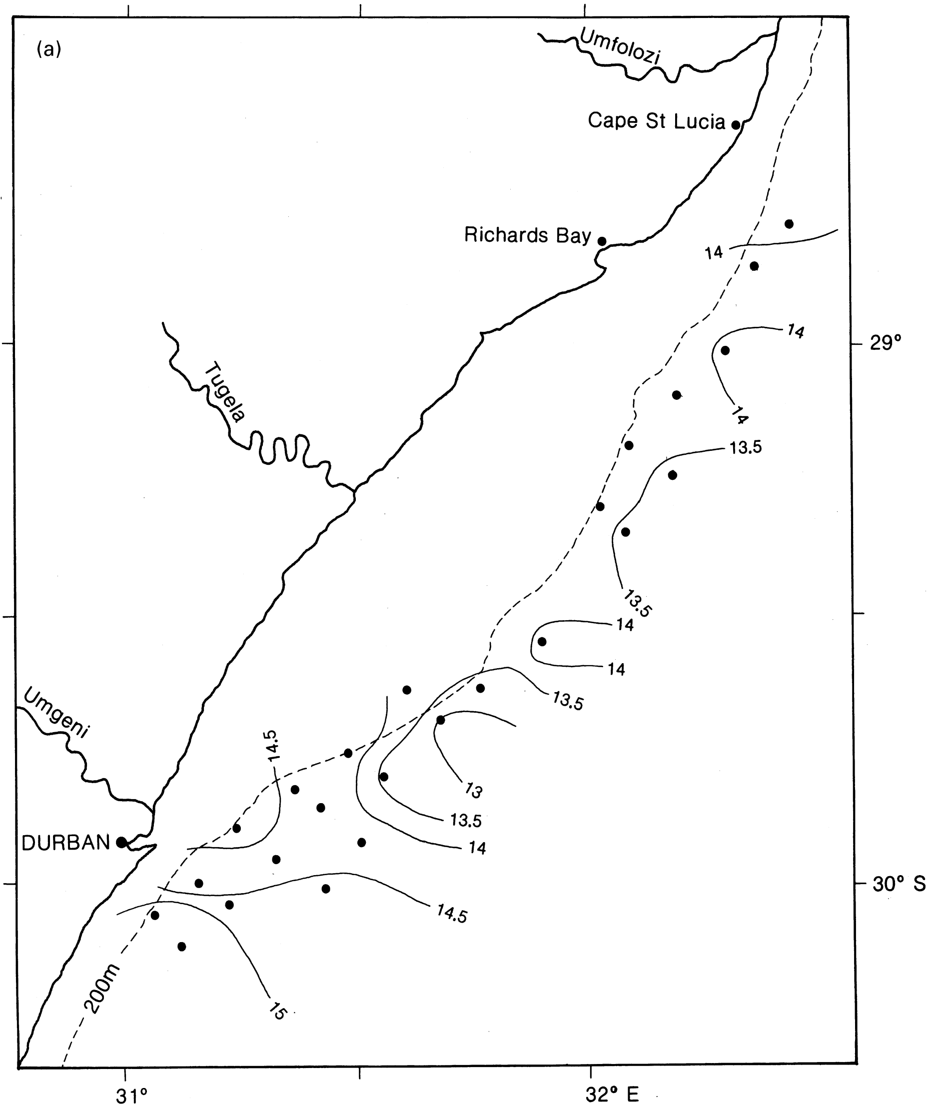

Fig. 9. The same as for Fig. 2, except for a depth of 200 m. The salinity values have been simplified by subtracting 35.00 and by multiplying the remainder by 100.

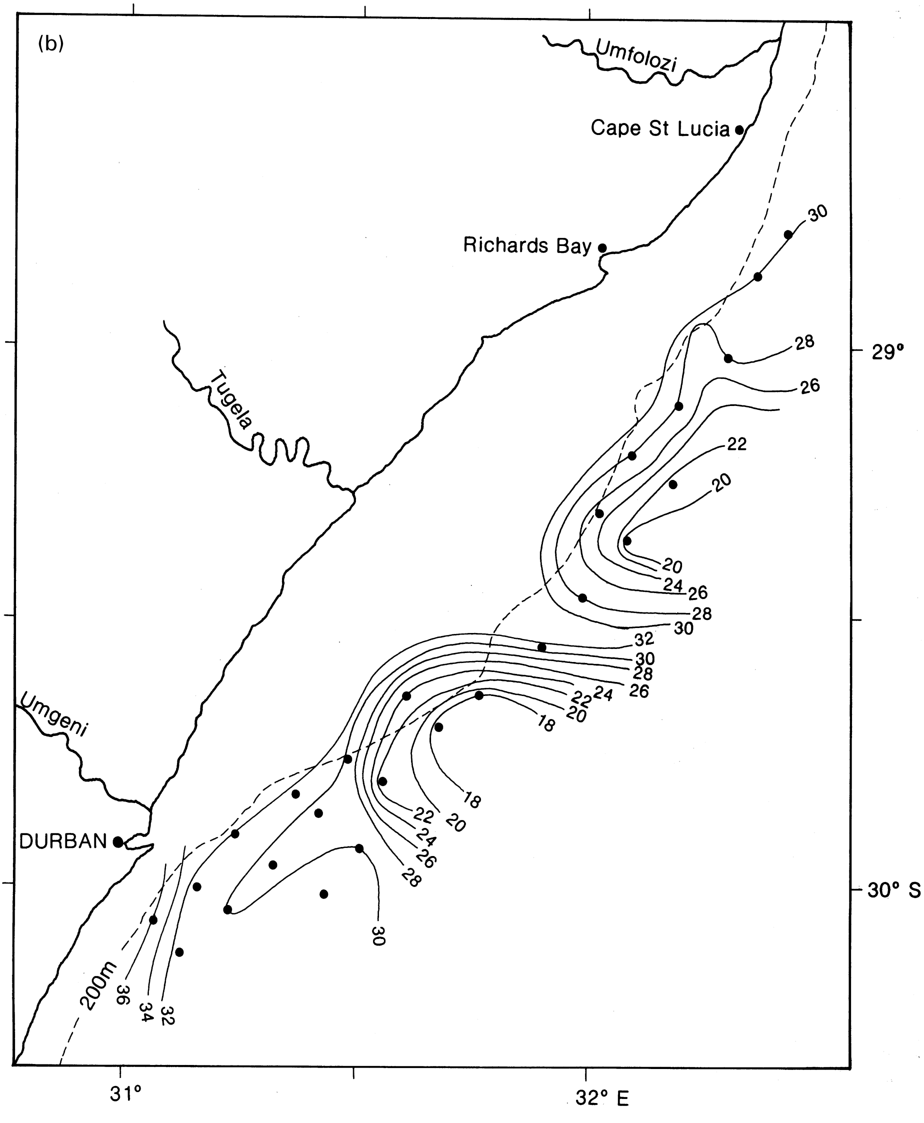

Fig. 9. (*Continued.*)

northern shelf edge of the Natal Bight. This possibly describes the movement of South Indian Subtropical Surface Water towards the centre of the upwelling cell. The nitrate distribution shows a similar increase in values at the shelf slope (Fig. 8c), but gives no indication of the subsequent movement over the shelf. At 200 m (Fig. 9) there no longer was any evidence of the upwelling.

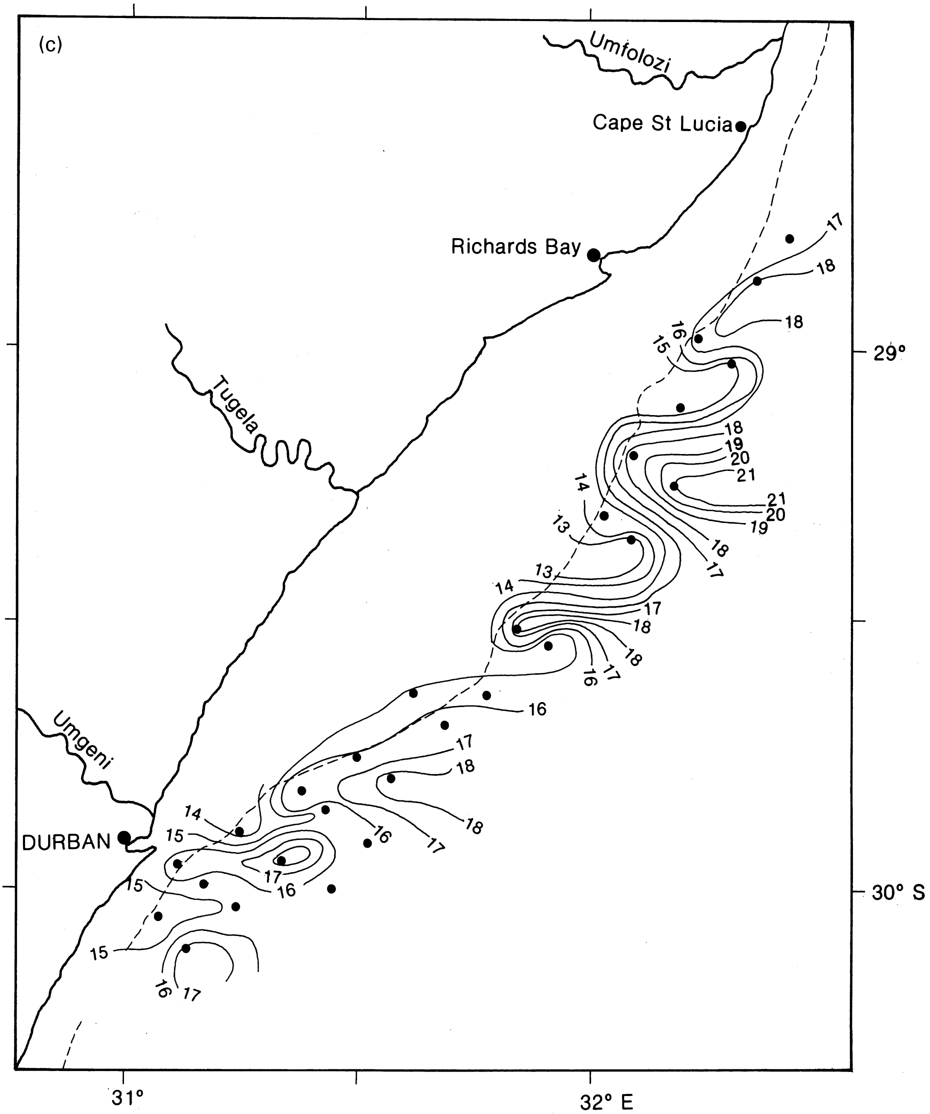

Fig. 9. (*Continued*.)

One may therefore conclude that the St Lucia upwelling cell has a marked influence on the waters of the whole northern Natal Bight, but that this is most evident in the upper 100 m of the water column. At greater depths there is evidence of the water moving onto the shelf near St Lucia, but not of subsequent movement over the shelf. Since the greater part of the shelf is shallower than 100 m, the possibility is not

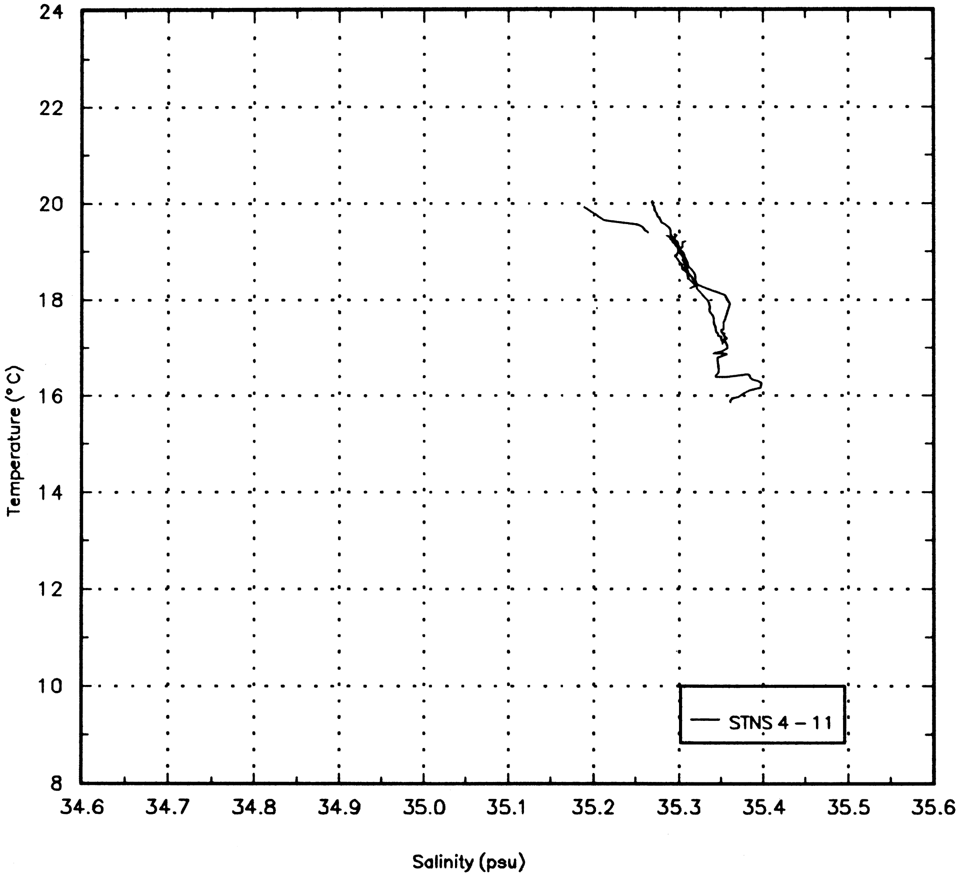

Fig. 10. The temperature/salinity relations for all measurements made in the region of the St Lucia upwelling cell during July 1989.

excluded that bottom water at the upwelling cell may move southward to cover the greatest part of the shelf.

3.4. Bottom water movement

The bottom flow on the Natal Bight can be inferred roughly from changes in the values of the hydrographic variables at the innermost stations of each station line. This is shown in those figures which show the distribution of these variables at different depths (Figs. 2 and 7–9). Since nitrate values exhibit the strongest gradients, nitrate will be used as a tracer for these purposes. The innermost stations in Fig. 2c, at 10 m depth, probably represent the flow to a depth of 30 m or so, this being the depth of water here. The movement of water, judged by the decrease in nitrate values, was

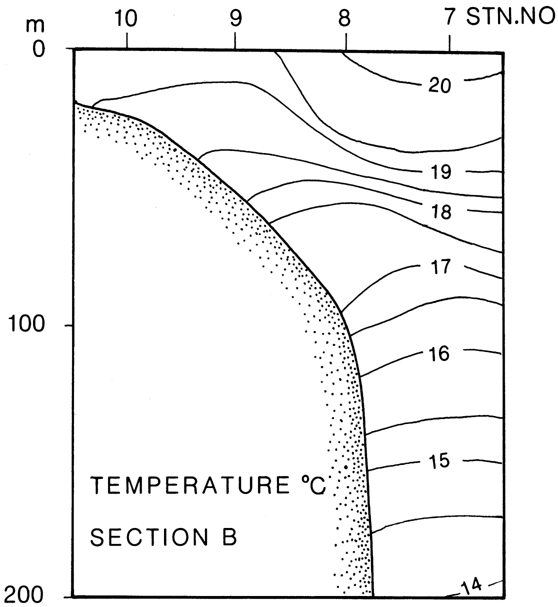

Fig. 11. The vertical distribution of temperature across the St Lucia upwelling cell. The location of station line B is shown in Fig. 1.

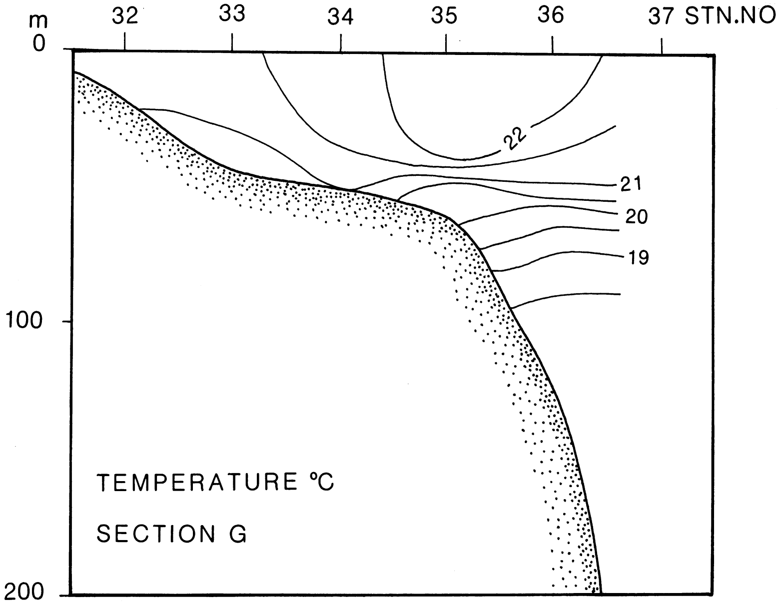

Fig. 12. The vertical distribution of temperature in the centre of the Natal Bight. The location of this station line, G, is given in Fig. 1.

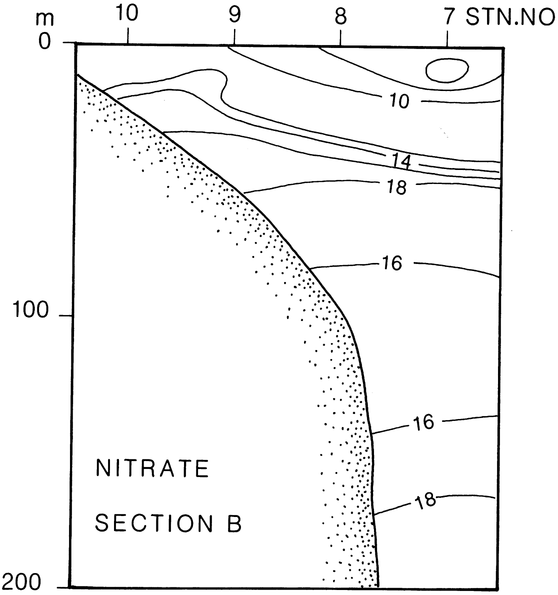

Fig. 13. The vertical distribution of dissolved nitrate on station line B across the St Lucia upwelling cell (Fig. 1). This nitrate section may be compared to the temperature section of the same line given in Fig. 11.

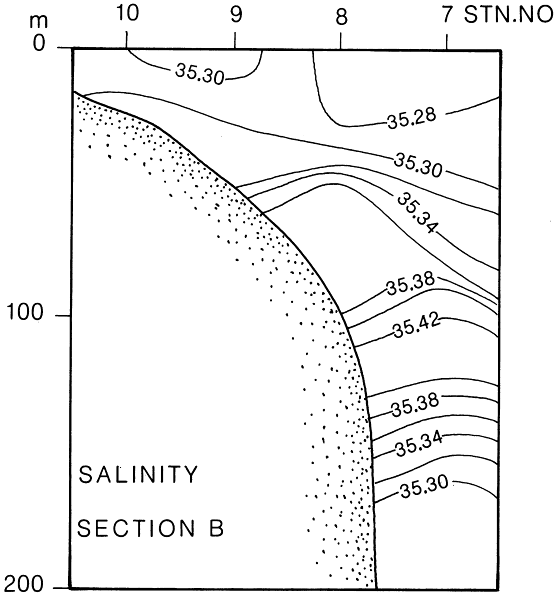

Fig. 14. The vertical distribution of salinity across the St Lucia upwelling cell. The location of this line is given in Fig. 1.

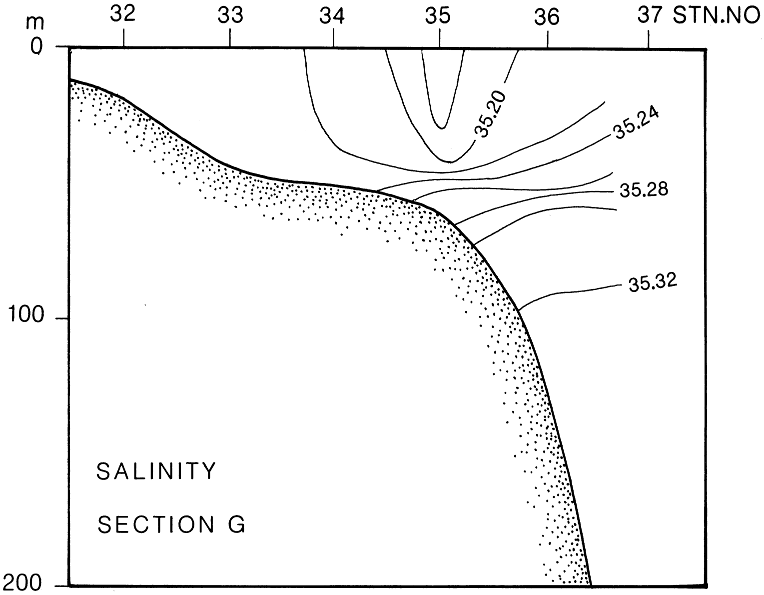

Fig. 15. The vertical distribution of salinity along station line G across the centre of the Natal Bight. The location of this line is given in Fig. 1.

southwards. At 50 m depth the landward stations would again be close to the sea floor. Once more, both temperature values (Fig. 7a) and nitrate concentrations (Fig. 7c) suggest a general movement southward in the bottom layers as inferred from the southward decreases in concentrations. Even at 100 m depth (Fig. 8a) a southward decrease in temperature at the innermost stations in water of this depth implies a general southward movement. This holds true for almost the entire northern part of the shelf, the gradients in the south being too weak to come to any conclusions about the movement of water. At most stations on the shelf the nitrate values show a strong increase in the bottom 20 m or so. To test the suggestion that this bottom water had been derived from the north, a vertical section of nitrate values was constructed in an alongshelf direction. This was done by creating an artificial station line from the middle stations of each line that had been carried out during the cruise. This section is portrayed in Fig. 16.

The nitrates over the Bight show a notable increase with depth at almost all locations, with the exception of the landward stations of lines H and I (Fig. 1). At these stations values of nitrate were low throughout the well-mixed water column. There is a clear indication that the high nitrate values found over the northern part of the Bight were derived from the St Lucia upwelling cell and that from here this bottom water had moved southward to cover the greater part of the shelf. Since nitrate values of 17 μmol/kg were found in the upwelling cell (e.g. Station 17, Fig. 16) deeper than 40 m, one would expect these higher values to have covered only parts of the shelf that deep

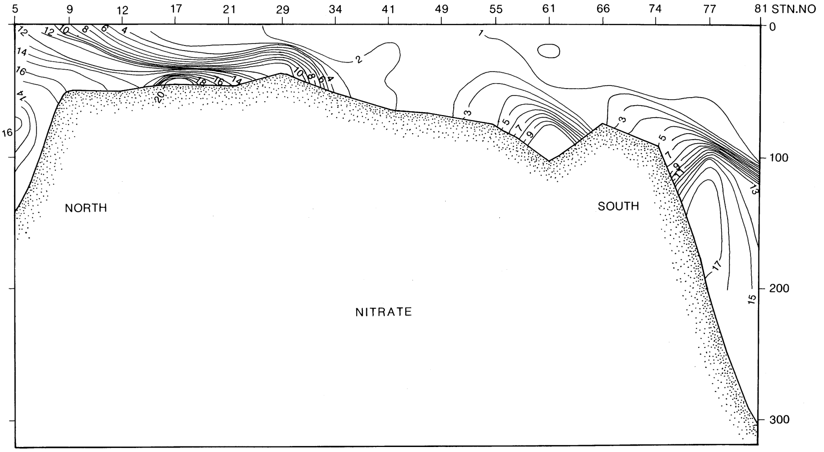

Fig. 16. The vertical distribution of dissolved nitrate along the centre of the Natal Bight from Cape St Lucia, North to Durban, South. The geographic location of these stations on the shelf can be gleaned from Fig. 1.

or deeper. This was indeed the case (Meyer et al., 1999). The highest nutrient values on the seafloor in this section (Fig. 16) were found at Station 17. This may suggest that this was some kind of source. This is not so. Selecting different stations to the north than the ones used in Fig. 16 shows that this water did come from the St Lucia upwelling cell. The bottom water gradually lost its high nutrient characteristics on its way southward, with the exception of the middle of the Bight where no high nutrient values were found (Fig. 16). This inferred movement of bottom water is similar to the analogous situation for the Agulhas Bank, farther along the Agulhas Current (Lutjeharms and Meyer, 1999; Lutjeharms et al., 1996).

South of the shelf, at Station 77 in Fig. 16, there also was a pocket of high nutrients, but at a considerably greater depth than on the shelf itself. This is not related to enriched nutrients on the shelf, but due to nutrients upwelled with deeper water in an eddy at this position at this time.

3.5. *Eddy of Durban*

As mentioned above, the station lines near Durban had to be extended seaward to reach the edge of the warm Agulhas Current (Fig. 1), whereas this was not necessary for the station lines to the north of here. This leads to the suspicion that what was being observed off Durban on this occasion was the start of a Natal Pulse, with an eddy being formed inshore of the Agulhas Current at Durban. The satellite image for 23 July 1989 (Fig. 3) is consistent with this hypothesis, showing a substantial meander in the trajectory of the Agulhas Current off Durban. If this was indeed a Natal Pulse, it would subsequently have moved downstream at a rate of about 20 km/d (Lutjeharms and Roberts, 1988). The satellite image of 29 July 1989, although partially obscured

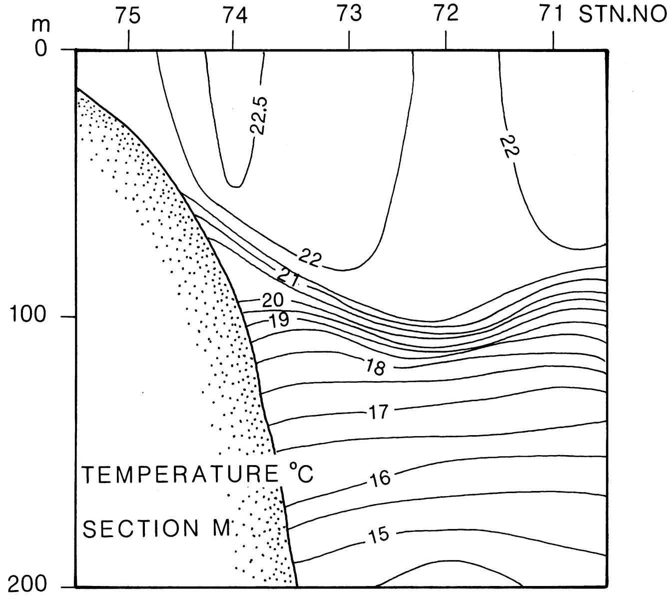

Fig. 17. The vertical distribution of temperature along station line M off Durban. The location of this line is given in Fig. 1.

by cloud, shows a meander at the position where a Natal Pulse that had started at Durban on 23 July would have had to have been six days later. This gives one confidence that this feature was truly the start of a Natal Pulse, making these the first observations at sea of such an event. What did it look like in the hydrographic data?

The core of the meander was not so clearly evident in the temperatures of the surface layers, but was quite distinct in the salinities. A core of higher salinity values is evident in the distribution at a depth of 10 m (Fig. 2b) and 50 m (Fig. 7b). There even is evidence for this feature at greater depths. A nucleus of higher nutrients was found at this spot up to a depth of 200 m (Fig. 9c). All this seems to establish the core of this slightly anomalous water at station 72 on line M (Fig. 1). In this regard the distributions of the various hydrographic variables along this station line are instructive.

The temperature section (Fig. 17) shows the warmest water in the upper layers at station 74, close inshore, and at the most seaward station, 71. If this is compared with the satellite image (Fig. 3) one may conclude that the seaward water was in the core of the Agulhas Current whereas the warm surface water closer inshore was surface water derived from the Agulhas Current that was moving northward. This would indicate a cyclonic motion for the surface water.

Temperature has the greatest influence on the water density in this region (Pearce, 1977), implying that the temperature section would approach that of the density and would therefore be suggestive of the geostrophic motion. At first glance the inclinations of the isotherms in the upper 150 m suggest anticyclonic motion, but at greater depth there are signs of a dome of cold water that would have the opposite effect. The presence of such a cold dome is well-known for this region (Pearce, 1977; Pearce et al., 1978; Lutjeharms et al., 1989b), extends to greater depths and is always associated with anti-cyclonic motion. The distribution of the hydrographic variables points to a cyclonic eddy centred over the cold dome.

The distribution of the salinities across this eddy (Fig. 6) substantiates what is shown by the temperatures (Fig. 17). In the uppermost layers the lowest salinities, associated with Indian Tropical Surface Water, are found in the shoreward edge of the Agulhas Current and in the coastal plume of warm water moving north. The characteristic salinity minimum that represents the South Indian Subtropical Surface Water lay at a depth of 150 m. The dome of cold water at station 72 was distinguished by lower salinities showing evidence for the effects of the South Indian Central Water below (Fig. 5). This upward movement of deeper, colder and nutrient richer water in this eddy is also evident in the nutrient section given in Fig. 16 notwithstanding the slightly different location of station 77 (Fig. 1). From the combination of satellite information, lateral distributions of variables and the vertical sections across the feature it is clear that this was a cyclonic eddy that had upwelled water in its core and that had most probably started a journey southward as part of a Natal Pulse (Lutjeharms and Connell, 1989). This process may potentially cause a substantial exchange of water between the shelf and the deep sea. The movement of water from offshore onto the shelf at the St Lucia upwelling cell is another mechanism that facilitates water movement across the shelf. What evidence do the data from this cruise give for an exchange of water along the rest of the shelf?

3.6. Water exchange along the edge of the shelf

At the sea surface there is some evidence for warmer, less saline water from the Agulhas Current to have moved over the seaward side of the Agulhas Bank (Figs. 2a and b). This was largely restricted to the southern part of the Bight. It is most likely that this would be in the form of shear edge plumes (Gründlingh and Pearce, 1990), but the thermal contrasts on this occasion were insufficient to detect this in the infrared imagery (Fig. 3). At 50 m depth (Fig. 7) there is no clear evidence of water from offshore moving onto the shelf, except perhaps in the general vicinity of Durban. There were regions of higher temperatures and lower salinities in this shelf region while they were found only off the shelf in regions further north. This in general also holds true for greater depths (Figs. 8 and 9). Deeper in the water column the shelf edge was increasingly associated with an alongshore front (e.g. Fig. 9b), except just north of Durban. This suggests that the cyclonic motion here was conducive to bringing offshelf water onto the shelf. The vertical sections across the shelf demonstrate this even more clearly.

The temperature section portrayed in Fig. 12 is characteristic of most of the sections across the greater part of the shelf edge of the Natal Bight on this occasion. The isotherms, isohalines and lines of equal nitrate all exhibit a tendency to bend downward towards the coast. In this way enhanced horizontal gradients are formed that are incompatible with the concept of water moving onto the shelf. This section (Fig. 12) may be compared with temperature sections at other locations such as the upwelling cell (Fig. 11) and the eddy off Durban (Fig. 17) where the upward slope of isotherms in a landward direction suggests a shoreward inflow of offshore water. One may therefore conclude that there is little evidence of much exchange of water along the shelf edge of the Natal Bight on this occasion. The exceptions are the upwelling cell in the north, the eddy off Durban and the overflow of water from the uppermost layer of the Agulhas Current over parts of the southern Bight.

4. Conclusions

These results represent the first and only coverage of the whole Natal Bight with hydrographic stations. In a variable shelf regime of this kind one cannot expect the results to be representative for all time. However, placing previous studies with more limited geographical coverage into the framework of what has been found here gives one confidence about certain features that manifest themselves consistently.

First, the upwelling cell at Cape St Lucia is the conduit through which colder, saltier and nutrient-rich water from the South Indian Subtropical Surface Water is brought onto the shelf. From here it moves southward over the greater part of the Natal Bight at all depths. Vertical increases in salinity and nutrients over most of the Bight suggest that the waters upwelled at St Lucia are injected into the water column of the shelf at different depths and then flood the shelf at these particular depths. The water with highest nutrients forms the basal layer of at least the northern part of the shelf. The influence of this upwelled water on the phytoplankton productivity of the Bight therefore is substantial, suggesting that the St Lucia upwelling cell probably controls the ecosystem of the Bight or plays a pre-eminent role in it.

There is no strong evidence for the movement of offshore water onto the shelf of the Natal Bight south of the upwelling cell, except in the very surface layers and near Durban. Indian Tropical Surface Water from only the upper part of the Agulhas Current moves onto the shelf, most probably chiefly in the southern half of the Bight. Occasional cyclonic movement near Durban, where the shelf is narrower than to the north, will cause water from the Agulhas Current to be advected onto the shelf in a northerly direction near the shore.

Third, the waters on the shelf consist of Indian Tropical Surface Water and South Indian Subtropical Surface Water only. There is no evidence that substantial amounts of South Indian Central Water are ever upwelled onto the Natal Bight. The shelf is probably too shallow for this to happen. This water is however found at the continental slope of the Bight.

One may hypothesise that the circulation of water in the Natal Bight will, under persistent conditions of low wind stress, be influenced predominantly by the passing Agulhas Current, thus exhibiting an overall cyclonic component. It is not realistic to expect such a circulation to be uniform or persistent in such shallow water. The recurrent eddy off Durban may be the source of the cyclonic motion embedded in Natal Pulses instead of the previously assumed cyclonic circulation of the Natal Bight itself.

There is evidence that during the Natal Bight Cruise of July 1989 river outflow had some freshening effect on waters close inshore and that the general flow at the coast was in a northerly direction. There also are indications that a weak surface front bisected the central part of the Bight on this occassion. It is not known how representative these features are of the average circulation and hydrography of the Bight.

It remains to be established how consistent the input of water onto the shelf is at the St Lucia upwelling cell. Since the nutrient supply through this cell probably is the main factor controlling the biota of the whole shelf, this should clearly be the principal focus of any research endeavour to understand the ecology of the Natal Bight. The Agulhas Bank south of Africa has very similar characteristics to that of the Natal Bight. The input of cold upwelled water onto the bottom of that shelf materially affects the seasonal stratification of its water column as well as its nutrient supply. This may be true of the Natal Bight as well. This needs to be investigated.

Acknowledgements

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References

Anderson, F.P., Gründlingh, M.L., Stavropoulos, C.C., 1988. Kinematics of the southern Natal coastal circulation: some historic measurements 1962–63. South African Journal of Science 84, 857–860.

Biastoch, A., Reason, C.J.C., Lutjeharms, J.R.E., Boebel, O., 1999. The importance of flow in the Mozambique Channel to seasonality in the Agulhas Current system. Geophysical Research Letters 26, 3321–3324.

Carter, R., d'Aubrey, J., 1988. Inorganic nutrients in Natal continental shelf waters. In: E.H. Schumann (Ed.), Coastal Ocean Studies off Natal, South Africa, Lecture Notes on Coastal and Estuarine Studies, Vol. 26. Springer, Berlin, pp. 131–151.

Carter, R.A., Schleyer, M.H., 1988. Plankton distributions in Natal coastal waters. In: E.H. Schumann (Ed.), Coastal Ocean Studies off Natal, South Africa, Lecture Notes on Coastal and Estuarine Studies, Vol. 26. Springer, Berlin, pp. 152–177.

De Ruijter, W.P.M., van Leeuwen, P.J., Lutjeharms, J.R.E., 1999. Generation and evolution of Natal Pulses: solitary meanders in the Agulhas Current. Journal of Physical Oceanography 29, 3043–3055.

Flemming, B., Hay, R., 1988. Sediment distribution and dynamics on the Natal continental shelf. In: E.H. Schumann (Ed.), Coastal Ocean Studies off Natal, South Africa, Lecture Notes on Coastal and Estuarine Studies, Vol. 26. Springer, Berlin, pp. 47–80.

Gill, A.E., Schumann, E.H., 1979. Topographically induced changes in the structure of an inertial coastal jet: applications to the Agulhas Current. Journal of Physical Oceanography 9, 975–991.

Gordon, A.L., Lutjeharms, J.R.E., Gründlingh, M.L., 1987. Stratification and circulation at the Agulhas retroflection. Deep-Sea Research 34, 565–599.

Gründlingh, M.L., 1974. A description of inshore current reversals off Richards Bay based on airborne radiation thermometry. Deep-Sea Research 21, 47–55.

Gründlingh, M.L., Pearce, A.F., 1990. Frontal features of the Agulhas Current in the Natal Bight. South African Geographical Journal 72, 11–14.

Gründlingh, M.L., Stavropoulos, C.C., Watt, L.J., 1988. The R. V. *Meiring Naudé*; Two decades of support to physical oceanography. South African Journal of Science 84, 746–748.

Harris, T.F.W., 1972. Sources of the Agulhas Current in the spring of 1964. Deep-Sea Research 19, 633–650.

Lutjeharms, J.R.E., Connell, A.D., 1989. The Natal Pulse and inshore counter currents off the South African east coast. South African Journal of Science 85, 533–535.

Lutjeharms, J.R.E., Jorge da Silva, A., 1988. The Delagoa Bight eddy. Deep-Sea Research 35, 619–634.

Lutjeharms, J.R.E., Roberts, H.R., 1988. The Natal Pulse; an extreme transient on the Agulhas Current. Journal of Physical Oceanography 93, 631–645.

Lutjeharms, J.R.E., Thomson, J.A., 1993. Commercializing the CSIR and the death of science. South African Journal of Science 89, 8–14.

Lutjeharms, J.R.E., van Ballegooyen, R.C., 1988. Anomalous upstream retroflection of the Agulhas Current. Science 240, 1770–1772.

Lutjeharms, J.R.E., Catzel, R., Valentine, H.R., 1989a. Eddies and other border phenomena of the Agulhas Current. Continental Shelf Research 9, 597–616.

Lutjeharms, J.R.E., Gründlingh, M.L., Carter, R.A., 1989b. Topographically induced upwelling in the Natal Bight. South African Journal of Science 85, 310–316.

Lutjeharms, J.R.E., Meyer, A.A., Ansorge, I.J., Eagle, G.A., Orren, M.J., 1996. The nutrient characteristics of the Agulhas Bank. South African Journal of Marine Science 17, 253–274.

Lutjeharms, J.R.E., Meyer, A.A., 2000. The origin and circulation of the bottom water on the Agulhas Bank, South Africa. Continental Shelf Research, submitted for publication.

Lutjeharms, J.R.E., Cooper, J., Roberts, M., 2000. Dynamic upwelling at the inshore edge of the Agulhas Current. Continental Shelf Research 20, 737–761.

Malan, O.G., Schumann, E.H., 1979. Natal shelf circulation revealed by Landsat imagery. South African Journal of Science 75, 136–137.

Meyer, A.A., Lutjeharms, J.R.E., de Villiers, S., 2000. The nutrient characteristics of the Natal Bight. Journal of Marine Research, submitted for publicaton.

Mostert, S.A., 1983. Procedures used in South Africa for the automatic photometric determination of micronutrients in sea-water. South African Journal of Marine Science 1, 731–753.

Pearce, A.F., 1977. Some features of the upper 500 m of the Agulhas Current. Journal of Marine Research 35, 731–753.

Pearce, A.F., 1978. Seasonal variations of temperature and salinity on the northern Natal continental shelf. South African Geographical Journal 60, 135–143.

Pearce, A.F., Schumann, E.H., Lundie, G.S.F., 1978. Features of the shelf circulation off the Natal coast. South African Journal of Science 74, 328–331.

Schumann, E.H., 1981. Low frequency fluctuations off the Natal coast. Journal Geophysical Research 86, 6499–6508.

Schumann, E.H., 1982. Inshore circulation of the Agulhas Current off Natal. Journal of Marine Research 40, 43–55.

Schumann, E.H., 1986. The bottom boundary layer inshore of the Agulhas Current off Natal in August 1975. South African Journal of Marine Science 4, 93–102.

Schumann, E.H., 1987. The coastal ocean off the east coast of South Africa. Transactions of the Royal Society of South Africa 46, 215–229.

Schumann, E.H., 1988. Physical oceanography off Natal. In: E.H. Schumann, (Ed.), Coastal Ocean Studies off Natal, South Africa, Lecture Notes on Coastal and Estuarine Studies, Vol. 26, Springer, Berlin, pp. 101–130.

SCOR/UNESCO, 1966. Determination of photosynthetic pigments in sea-water. Monographs on Oceanographic Methodology 1, 11–18.

Van Leeuwen, P.J., de Ruijter, W.P.M., Lutjeharms, J.R.E., 2000. Natal Pulses and the formation of Agulhas rings. Journal of Geophysical Research 105, 6425–6436.

Valentine, H.R., van Ballegooyen, R.C., Lutjeharms, J.R.E., 1991. Data report on the Natal Bight Cruise, July 1989. CSIR Report EMA-D 9107, 15 pp. + figures.