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The nutrient characteristics of the Natal Bight, South Africa

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Abstract

The Natal Bight is an unusually wide part of the continental shelf off southeastern Africa, bordered on its seaward side by the intense Agulhas Current. A description of the distribution of nutrients in the bight is given based on the first research cruise that has covered the whole region. It is shown that the main source of nutrients is the St. Lucia upwelling cell. From here, nutrient-rich water is carried southward over the northern part of the bight, particularly along the bottom. At the surface, this insertion of nutrients is accompanied by an increase in chlorophyll-*a*. Intermittent inflows of surface water from the Agulhas Current, particularly over the southern part of the bight, diminish the nutrient content of the waters there. A recurrent lee eddy off the southern termination of the Natal Bight upwells nutrients in its core. A simple model demonstrates that primary productivity may be sustained along the shelf edge by upwelling and that the southward flow of nutrients is affected by considerable mixing.

Keywords: Nutrients; Continental shelf; South Indian Ocean

1. Introduction

The east coast of southern African is characterised by a very narrow continental shelf and a steep continental slope, which lend the necessary support for the stable trajectory of the northern Agulhas Current (De Ruijter et al., 1999). The commencement of this typical western boundary current is generally taken to be off the far northern Kwazulu–Natal/Mozambique coast (Lutjeharms et al., 1981; Saetre and Jorge Da Silva, 1984; Gründlingh and Pearce, 1984). It is along this coastline that the Natal Bight forms a distinctive break or offset in the shape of the continental shelf (Fig. 1). The Natal Bight is about 160 km long and is about 50 km wide at its broadest, off the mouth of the Tugela River. According to Schumann (1988), the Agulhas Current sweeps poleward along the Natal Bight with the core just off the shelf break. The waters on this part of the continental shelf are, therefore, markedly affected by the Agulhas Current (Schumann, 1988; Lutjeharms et al., 2000a; Pearce, 1973).

The Natal Bight has already been identified as a special and distinctive part of the ocean margin, where cold, nutrient-rich water is brought onto the shelf from deeper down the water column (Lutjeharms et al., 1989; Schumann, 1986) especially in the far-northern region of the Natal Bight, between Richards Bay and Cape St. Lucia (Lutjeharms et al., 2000a). The upwelling of this nutrient-rich water onto the bight has been observed to have a substantial influence on phyto-

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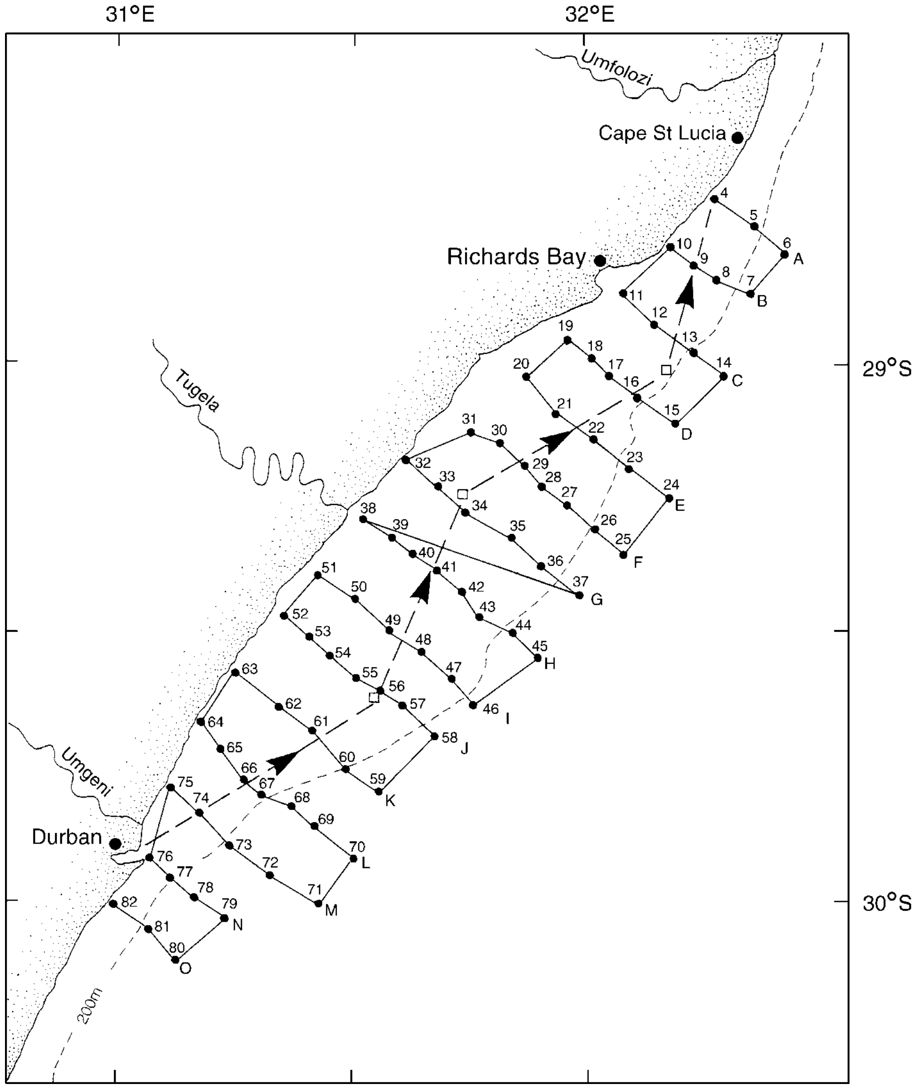


Fig. 1. Distribution of hydrographic stations undertaken over the continental shelf off southeastern Africa during the *Natal Bight Cruise* of July 1989. Station numbers and station line designations are given. Arrows denote the initial direction of sailing.

plankton productivity over the whole bight (Carter and Schleyer, 1988; Carter and d'Aubrey, 1988). Lutjeharms et al. (2000a) have, therefore, stressed that an investigation of the nutrient distribution over the Natal Bight is essential to a better understanding of its ecology.

This paper presents the first detailed description of the nutrient characteristics of the Natal Bight as a unit. Nutrient information is used to deduce the shelf circulation and to validate meso-scale features that have been inferred using only temperature and salinity (Lutjeharms et al., 2000a). Previous, historical observations of nutrients have been used to deduce water movement only near Richards Bay and Durban.

Nutrient distributions in the Richards Bay area exhibit large vertical and horizontal gradients (Carter and d'Aubrey, 1988). It has been suggested that these gradients may be attributed to the origin of water on the continental shelf, sporadic upwelling off Richards Bay, biological modification of nutrient levels and the meandering of the Agulhas Current inshore. Oliff (1973) and Pearce (1977) have demonstrated a negative horizontal gradient in nutrient concentration with distance offshore at Richards Bay. This gradient can be attributed to the Agulhas Current that has low nutrient concentrations (Carter and d'Aubrey, 1988). During upwelling events at Richards Bay, water from around 100 m comes to the surface (Pearce, 1977). This can lead to increases in surface concentrations of nitrate–nitrogen from 1.0 to 7.0 μmol/l (Oliff, 1973) although the levels usually reached are around 4.0 μmol/l (Pearce, 1977).

It has been suggested that the upwelling in the vicinity of Cape St. Lucia is topographically driven by the passing Agulhas Current at the downstream side of a broadening continental shelf (Lutjeharms et al., 1989) and it has been compared with a similar situations found further downstream at Port Alfred (Lut-

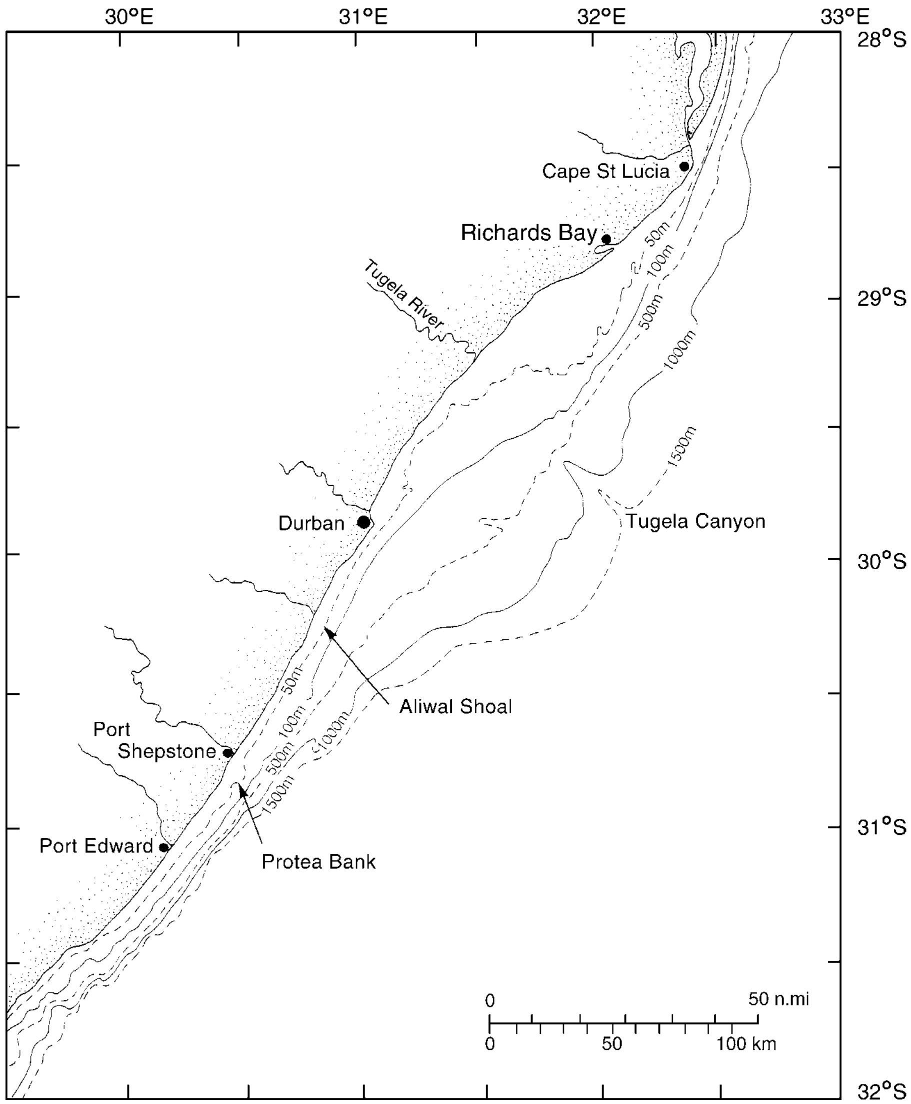


Fig. 2. General bottom topography of the Natal Bight and adjacent continental slope. A few specific bottom features are indicated.

jeharms et al., 2000b) and off the coast of southern Mozambique (Lutjeharms and Machu, 2000).

Investigations on the influence of outflow from the Richards Bay estuary have shown that it is small relative to the scale of variability of nutrient concentrations in the nearshore waters (Oliff, 1973). Peak nitrate–nitrogen levels within Richards Bay estuary attained 20 μmol/l (Begg, 1978) and, taking the dilution factor into account, a maximum increase of around 1 μmol/l can be expected in the nearshore surface water during periods of strong outflow (Carter and d'Aubrey, 1988).

The water column dynamics in the Durban shelf region, at the other, poleward, end of the Natal Bight, are also due to the Agulhas Current rather than local wind events (Carter and d'Aubrey, 1988). The dominant effect of the passing current is a recurrent eddy situated 20 to 40 km off Durban (Pearce et al., 1978; Anderson et al., 1988). Carter and d'Aubrey (1988) and Pearce et al. (1978) have shown that this cyclonic

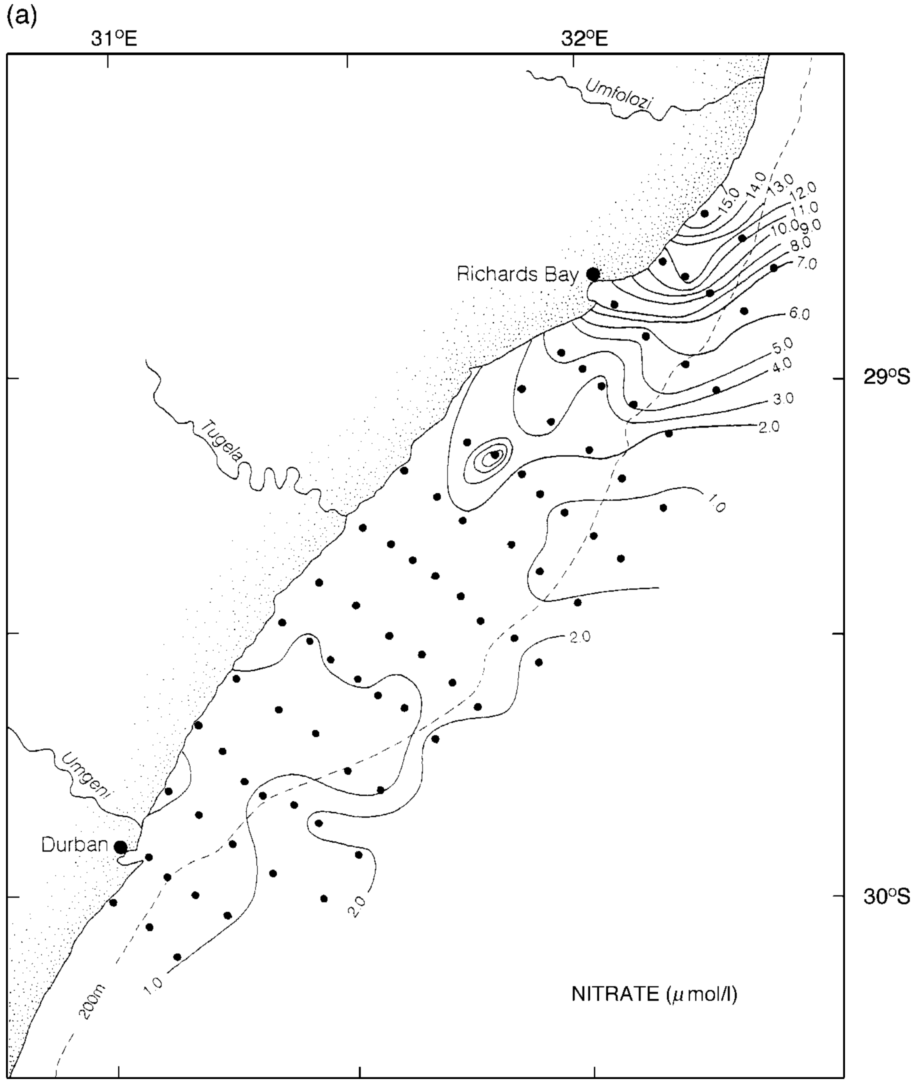
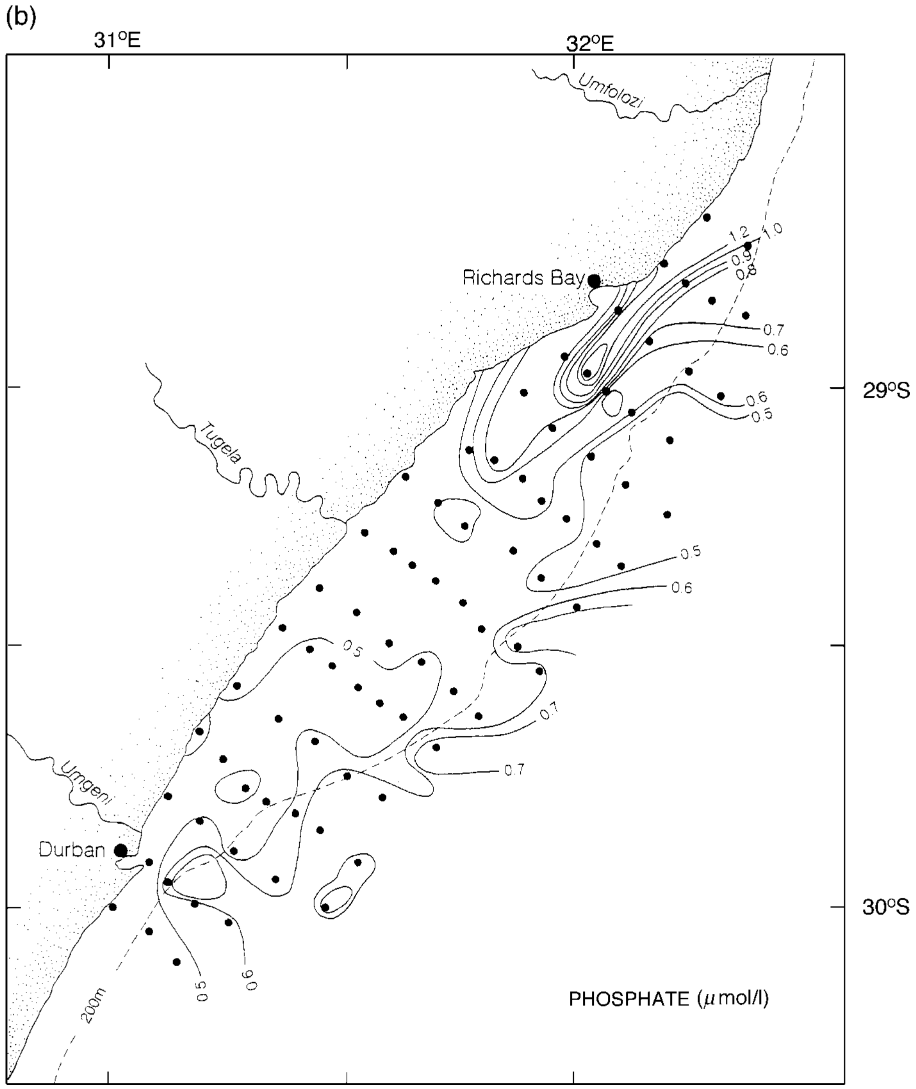


Fig. 3. (a) Distribution of dissolved nitrate at 10-m depth at the Natal Bight in July 1989. (b) Distribution of dissolved phosphate at 10-m depth at the Natal Bight in July 1989. (c) Distribution of dissolved silicate at 10-m depth at the Natal Bight in July 1989.



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feature causes the uplift of deep, colder, nutrient-rich water. In the absence of this eddy, a well-developed surface mixed layer is found to extend to about 50 m with maximum gradients in the nitrate–nitrogen profiles lying below 60 and 100 m. However, in the presence of the eddy, the mixed layer depth can be reduced to around 30 m and the depth of the nutricline decreases to about 40 m (Carter and d'Aubrey, 1988). Burchall (1968) has measured nitrate–nitrogen concentrations in the water column at a depth of 50 m, 7 km off Durban and found an average concentration of 2.32 µmol/l. By comparison, the average nitrate–nitrogen concentration in 0–50-m depth for the Durban shelf waters was 2.22 µmol/l (Carter and d'Aubrey, 1988). Horizontal gradients in the region are generally weak (Carter and d'Aubrey, 1988).

A basic understanding of the circulation in the Natal Bight is helpful in understanding the nutrient distribution. Lutjeharms et al. (2000a) have been the first to investigate the hydrography and water masses

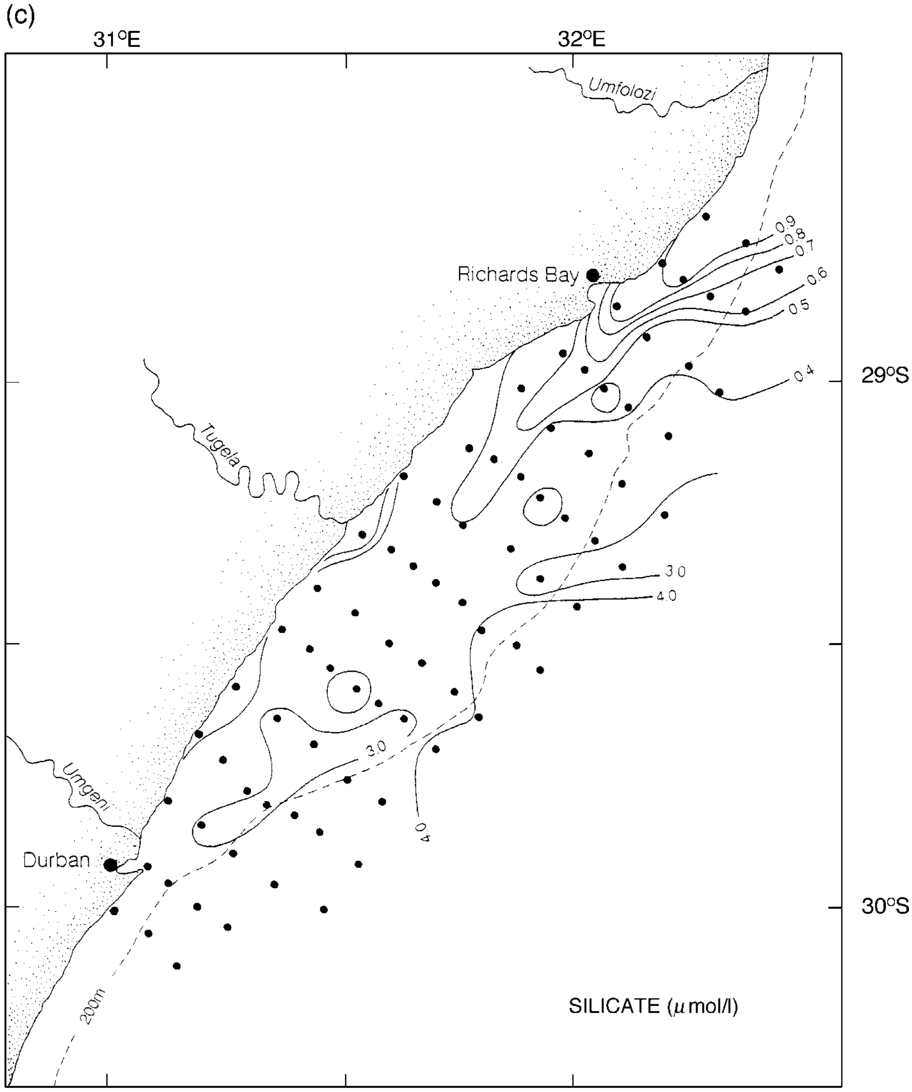

Fig. 3 (*continued*).

of the Natal Bight as a whole. They found that the upwelling cell at Cape St. Lucia is the conduit through which colder and saltier South Indian Subtropical Surface Water is moved onto the shelf. This water is subsequently transported southward over the greater part of the Natal Bight at all depths. Near Durban, Indian Tropical Surface Water, from only the upper part of the Agulhas Current, moves onto the shelf in the form of warm water plumes (Lutjeharms et al., 2000a) in a northerly direction near the shore. The waters on the shelf, therefore, consist of Indian Tropical Surface Water and South Indian Subtropical Surface Water only (Lutjeharms et al., 2000a).

The need for reliable nutrient data for the Natal Bight, to understand better the nutrient distribution and ecology of this important continental shelf region, led to the first hydrographic survey of the Natal Bight as a unit.

2. Data and methods

The *Natal Bight Cruise* (16–22 July 1989) consisted of 15 short lines of hydrographic stations more or less perpendicular to the coast (Fig. 1), covering the continental shelf from north of Richards Bay to just south of Durban. The seaward extent of each section was determined by the location of the edge of the Agulhas Current. In this way, the width of the shelf at each location was covered (viz. Fig. 2).

The survey proceeded from north to south in a regular pattern. However, after completing station 37, the weather deteriorated to such an extent that more than 30 h were lost between stations 37 and 38 (Valentine et al., 1991). This was unfortunate since the rapid switch from northeasterly to strong southwesterly winds at this time could have resulted in changes in the circulation of the Natal Bight. After resuming the survey at station 38, no further interruptions to the observational programme occurred.

(a)

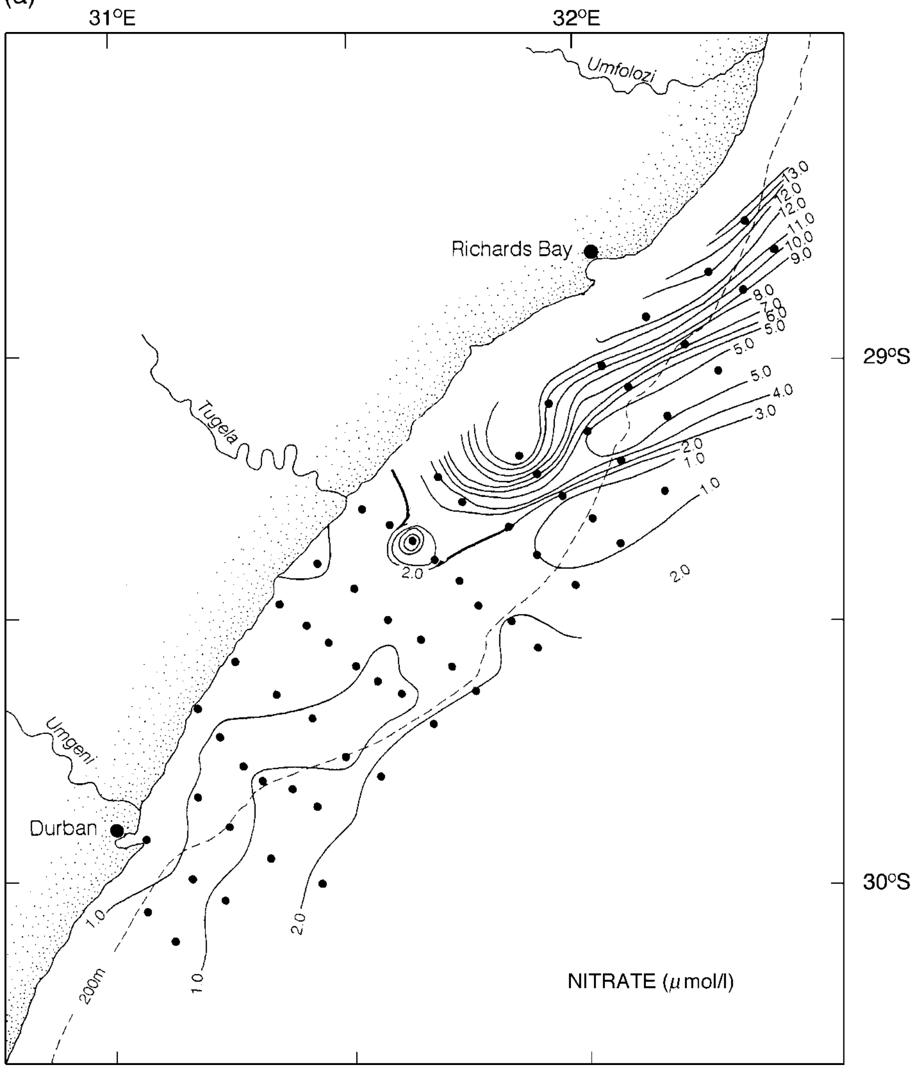

Fig. 4. (a) Distribution of dissolved nitrate at 30-m depth at the Natal Bight in July 1989. (b) Distribution of dissolved phosphate at 30-m depth at the Natal Bight in July 1989. (c) Distribution of dissolved silicate at 30-m depth at the Natal Bight in July 1989.

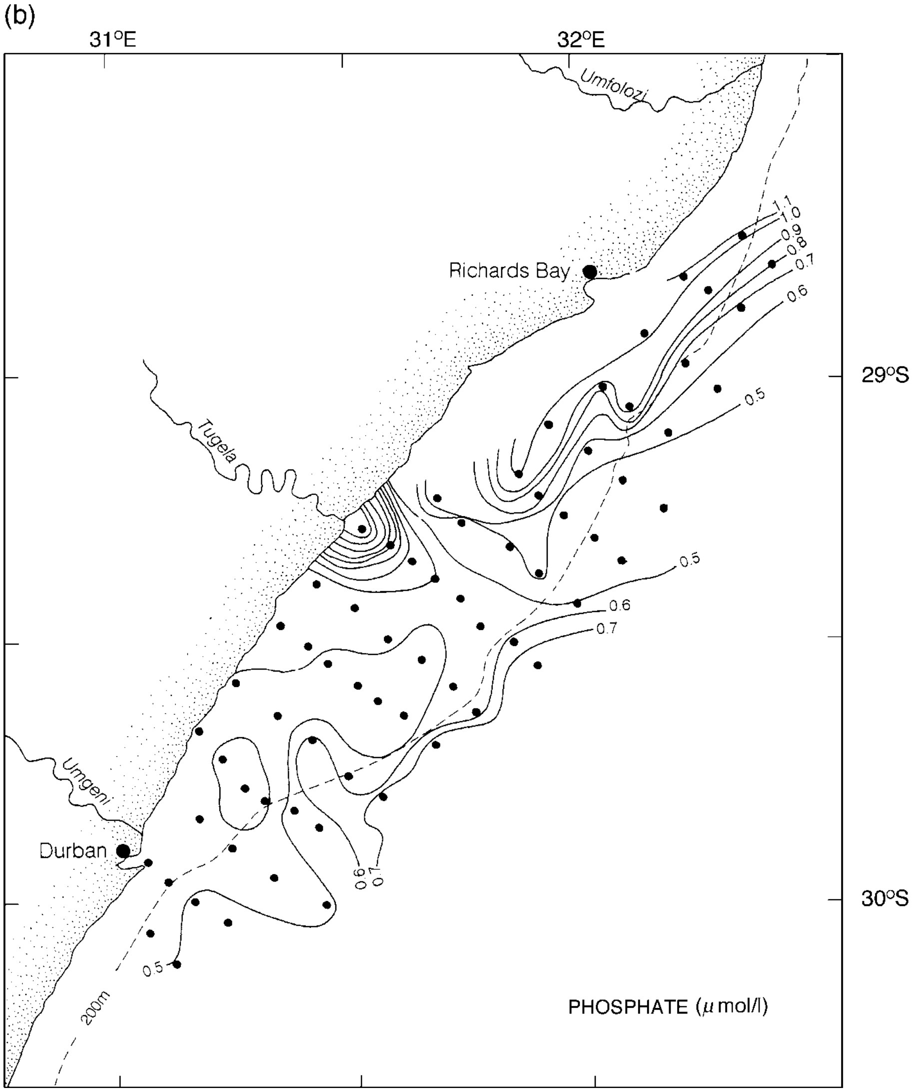

Fig. 4 (*continued*).

Eighty-two hydrographic stations were carried out that sampled 90% (80% in foul weather) of the water column at each station (Lutjeharms et al., 2000a) except for the inshore stations of two sections (stations 31 and 32) at which only surface measurements were taken due to bad weather. 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. Water samples were taken at standard depths of 5, 10, 20, 30, 40, 50, 75, 100, 125, 150, 175 and 200 m. Samples were used to calibrate CTD salinity measurements and were taken for nutrients analyses as well as for chlorophyll-*a* determinations. Results from the temperature and salinity observations are discussed in detail elsewhere (Lutjeharms et al., 2000a). No nutrients samples were taken below a depth of 200 m during this cruise.

Silicate, nitrate and phosphate were determined with a Technicon Auto Analyser by a slightly modified version (Windt, personal communication) of the method described by Mostert (1983). Chlorophyll-*a*

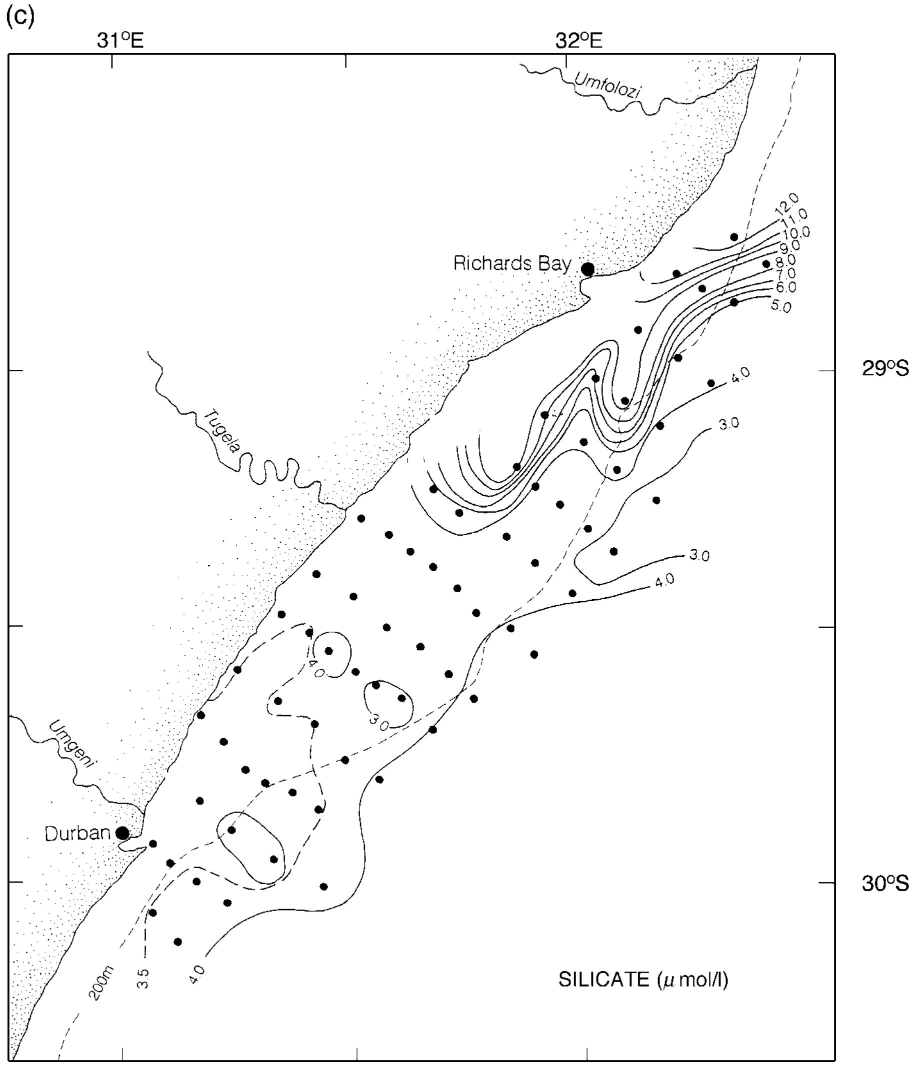

Fig. 4 (*continued*).

samples were frozen on board immediately after filtration and their concentrations determined in the home laboratory, shortly after, using standard methodology (SCOR/UNESCO, 1966).

3. Results and discussion

3.1. Nutrient distributions

The horizontal distributions for nitrate, phosphate and silicate are presented for depths of 10, 30, 75 and 125 m (Figs. 3–6). From these nutrient distributions, the Natal Bight can be considered to have consisted of three distinct nutrient provinces during this cruise: a northern Natal Bight (lines A–F), a central Natal Bight (lines G–I) and a southern Natal Bight (lines J–O; Fig. 1).

3.1.1. Northern Natal Bight

The concentrations at 10-m depth lay in the range 0.15–15.30 μmol/l for nitrate, 0.35–1.64 μmol/l for phosphate and 2.52–9.41 μmol/l for silicate. At 30 m, the ranges were 0.18–18.27, 0.37–1.39 and 2.40–

12.22 μmol/l, respectively (Fig. 4). At most stations, there was a marked vertical gradient in the nutrients. Strong horizontal gradients were observed for all nutrients, both in the offshore and in a poleward direction. The strong offshore nutrient gradient can be ascribed to the juxtaposition of water with a relatively high nutrient content that had been upwelled onto the continental shelf off Richards Bay and the nutrient-deficient Agulhas Current Water at the continental shelf break. The weaker alongshore gradient indicates that the region just north of Richards Bay is the source of the nutrient-rich water for the northern Natal Bight. At 10-m depth, the concentration of nitrate just north of Richards Bay was higher than 14 μmol/l (Fig. 3a), but decreased rapidly southward to a low of 2 μmol/l, just north of the Tugela River mouth. This southward decrease in nutrient content of the upwelled waters may be due to biological assimilation or mixing

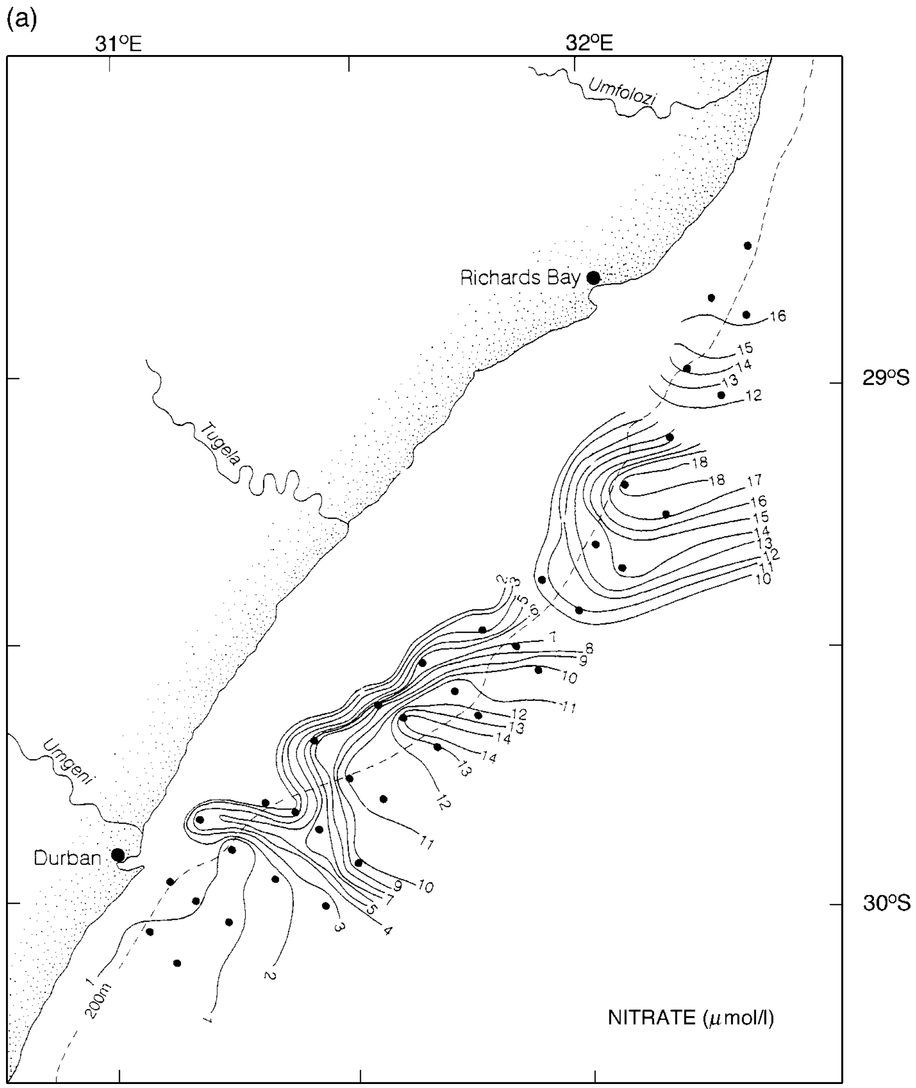

Fig. 5. (a) Distribution of dissolved nitrate at 75-m depth at the Natal Bight in July 1989. (b) Distribution of dissolved phosphate at 75-m depth at the Natal Bight in July 1989. (c) Distribution of dissolved silicate at 75-m depth at the Natal Bight in July 1989.

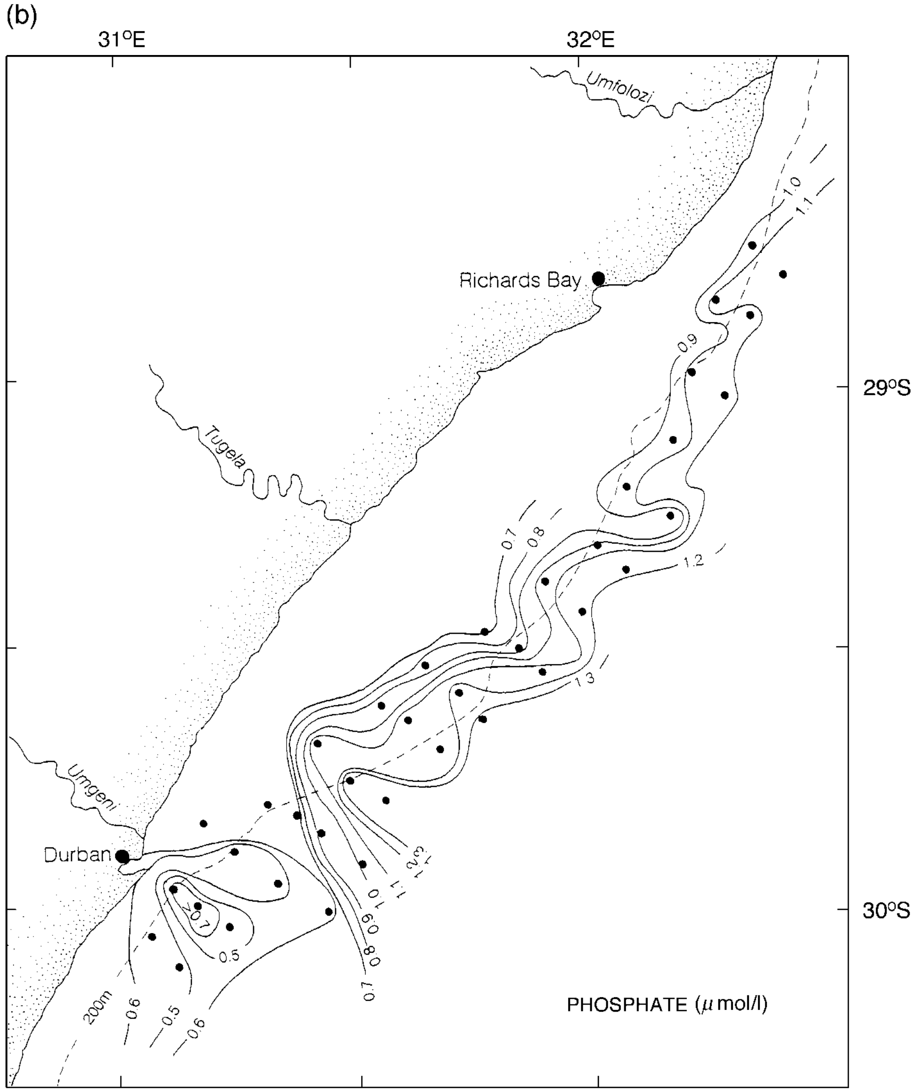

Fig. 5 (*continued*).

with ambient water masses or a combination of these two mechanisms. The negative nutrient gradients alongshore, therefore, indicate a southward movement of the upwelled water away from its source (Fig. 3). This movement may be due to horizontal shear interaction between the Agulhas Current and the water on the shelf and to a southward density flow of the cold upwelled water over a deepening continental shelf. The depth increases from Richards Bay, where it is about 50 m, to 100 m near Durban (Fig. 2).

3.1.2. Central Natal Bight

The water of the central Bight had moderate nutrient concentrations between 1.01–1.86 μmol/l (nitrate), 0.48–0.72 μmol/l (phosphate) and 3.50–4.69 μmol/l (silicate) near the sea surface (10-m depth; Fig. 3). This water lay between the nutrient-rich upwelled water from the north and the nutrient-poor waters from a warm water plume to the south. Except near the mouth of the Tugela River, the nutrient concentrations at 30 m were generally similar

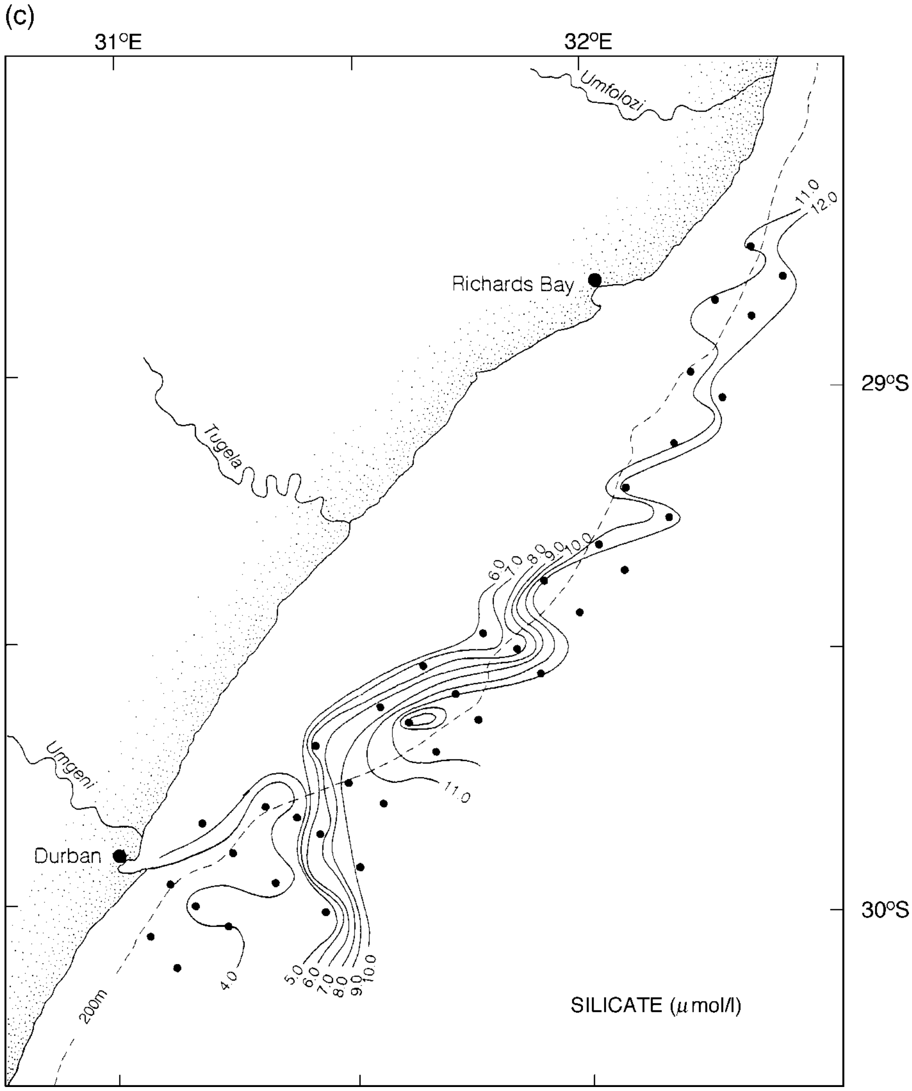

Fig. 5 (*continued*).

to those at 10 m, indicating a well-mixed upper layer away from the river. The nutrient data at the river mouth suggest subsurface outflow (Fig. 3c) that extended as far as 25 km from the shore (Fig. 4). At 10-m depth, silicate concentrations of more than 4.0 μmol/l were found near the mouth compared to 3.0 μmol/l over the rest of the central Natal Bight. The phosphate values at the river mouth (Fig. 4b) are particularly indicative and suggest a much more pronounced outflow at 30-m depth. The concentrations for phosphate decreased from a high of 1.39 μmol/l at the mouth to 0.77 μmol/l about 25 km away as compared to the 0.5 μmol/l for the rest of the central Natal Bight shelf region. At the shelf edge on this line of stations (i.e., in the Agulhas Current), the values are also higher.

3.1.3. Southern Natal Bight

The water over the entire southern Natal Bight (i.e., over the shelf, shallower than 200 m) between the surface and 50-m depth was associated with Indian Tropical Surface Water found in the coastal plume of warm water moving northward close inshore (Lutjeharms et al., 2000a). This warm water inshore had a low nutrient content and created a positive offshore nutrient gradient with slightly higher nutrient water at the shelf break. Nutrient concentrations lay between 0.15 and 1.65 μmol/l (nitrate), 0.35 and 0.65 μmol/l (phosphate) and 2.66 and 4.05 μmol/l (silicate), respectively, at 10-m depth (Fig. 3). The northward motion of the nutrient-poor warm water plume only extended to stations of line J (Fig. 1), where it met the slightly higher nutrient waters of the central Natal Bight. The nutrient concentrations exhibited hardly any vertical gradient. The water column was well mixed up to 30-m depth in contrast to the northern Natal Bight's substantial vertical nutrient gradient. In the southern Natal Bight at 30-m depth, the nitrate range was 0.18–1.89 μmol/l, that for phosphate 0.37–0.59 and for silicate 2.83–4.05. This well-mixed upper layer was due to the deep (~ 50 m) northward movement of the warm water plume described by Lutjeharms et al. (2000a).

The nutrient distributions at 75 m (Fig. 5) reflect the depth differences of the shelf, particularly between the northern and the southern Natal Bight (all shallower than 200 m). The northern part is much shallower (Fig. 2) and, therefore, lateral exchanges of water between the oceanic regime and the continental shelf are possible at depth for the southern Natal Bight only. South of the Tugela River, oceanic water was found to intrude over the Bight up to 25 km from the coast. Nutrient concentrations at 75 m over the shelf were higher than those for the upper water column and lay in the range between 0.18 and 13.45 μmol/l for nitrate, 0.46 and 5.43 μmol/l for phosphate and 3.03 and 10.73 μmol/l for silicate (Fig. 5). The distribution at 175 m shows a core of high phosphate water directly offshore from Durban that is due to upwelling in the centre of an cyclonic eddy often found here (Pearce et al., 1978; Carter and d'Aubrey, 1988).

This eddy is already evident in the nutrient distribution at 125-m depth (Fig. 6). High concentrations of 18.33 (nitrate), 1.59 (phosphate) and 13.60 μmol/l (silicate) were found in its core in a subsurface maximum at 175 m. The cyclonic motion of the eddy caused water on the continental shelf between lines M and L (Fig. 1) to be advected off the continental shelf. The flow of deeper layers of the Agulhas Current diverged from the shelf edge here. The shelf width of the southern Bight decreases abruptly at Durban causing the current to overshoot and to lie seaward of the continental shelf. It joins the continental shelf edge again well south of Durban. The resultant lee eddy formed inshore of the Agulhas Current may be the mechanism by which oceanic waters are advected onto the southern Natal Bight at deeper layers (75 and 125 m; Figs. 5 and 6).

3.2. Relationship between chlorophyll-a and nutrients

Chlorophyll-*a* and other physical data (Lutjeharms et al., 2000a) show distinct provinces and meso-scale features similar to those observed from these nutrient distributions. In the northern Natal Bight, upwelling of nutrient-rich water created ideal conditions for primary production, which produced the high concentrations of chlorophyll-*a* that were found offshore of Richards Bay (Fig. 7). The chlorophyll-*a* concentration in this area was in excess of 1.5 mg/m^3 and decreased southward to a much lower concentration of 0.5 mg/m^3 just north of the Tugela River mouth. The chlorophyll-*a* concentration decreased in unison with nutrients, temperature and salinity (Figs. 3–6; see also Lutjeharms et al., 2000a). This clearly implicates the area just northeast of Richards Bay as being the prime source of upwelled water onto the continental shelf. It also shows the subsequent southward advection of this upwelled water in the form of an elongated tongue-like feature (Fig. 7). From the distribution of chlorophyll-*a*, it is clear that the upwelled water has a material impact on the primary production and, therefore, also on the ecology of a substantial part of the Natal Bight.

In the southern Natal Bight, the northward moving plume of warm water, which was deficient in nutrients, exhibited very low chlorophyll-*a* values (Fig. 7) even in comparison with the ambient water and, particularly, in comparison with northern Natal Bight waters. Chlorophyll-*a* values of less than 0.1 mg/m^3 were characteristic of this water mass. The central Natal Bight, on the other hand, had chlorophyll-*a* concentrations between 0.1 and 0.5 mg/m^3, intermediate to that of the southern and northern Natal Bight.

3.3. The St. Lucia upwelling cell

Comparing nitrate sections for lines A–F (Fig. 8), the upwelling of nutrient-rich waters onto the continental shelf is clearly evident only for stations of the lines B and C (cf. Fig. 1). Here, water with nitrate concentrations as high as 16 μmol/l was found to be lifted onto the continental shelf from depths of between 60 to 90 m to depths of 40 m and shallower.

At line A, just north of the core of the upwelling cell and south of Cape St. Lucia (cf. Fig. 1), the uplift of nutrient-rich water onto the continental shelf was not evident. However, a lens of high nitrate water (> 16 μmol/l) was observed offshore (Fig. 8, section A). It was about 60 m thick at a central depth of 75 m and almost overhung the continental shelf break. The only oceanic 16 μmol/l nitrate water found offshore was at a depth of 200-m depth, below the Agulhas Current proper.

A dome-like feature of high nitrate water was found on the shelf for lines D–F (Fig. 8) downstream of the upwelling cell's core (cf. Fig. 1). At line F, this high-nutrient water on the shelf was totally detached from any oceanic water mass with similar nitrate content and is, therefore, taken to be derived from the north, i.e., from the upwelling cell at Richards Bay. As observed in

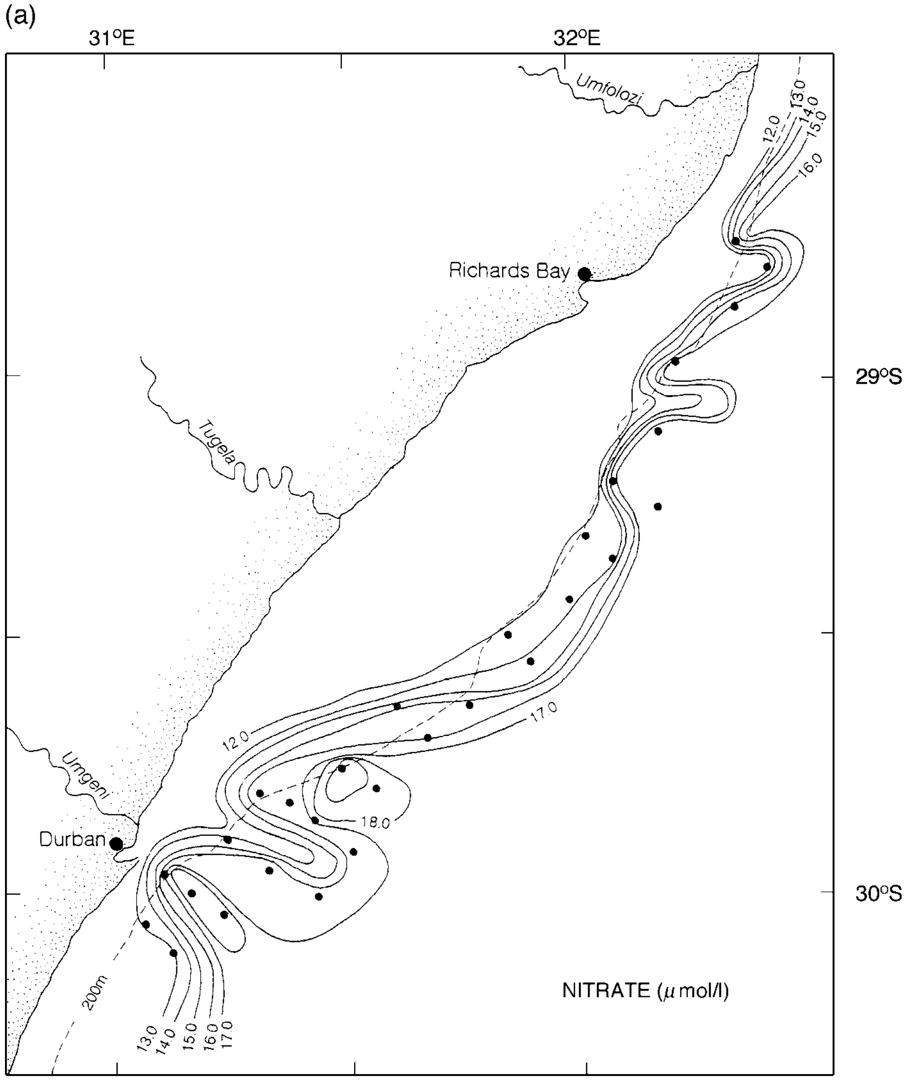

Fig. 6. (a) Distribution of dissolved nitrate at 125-m depth at the Natal Bight in July 1989. (b) Distribution of dissolved phosphate at 125-m depth at the Natal Bight during July 1989. (c) Distribution of dissolved silicate at 125-m depth at the Natal Bight during July 1989.

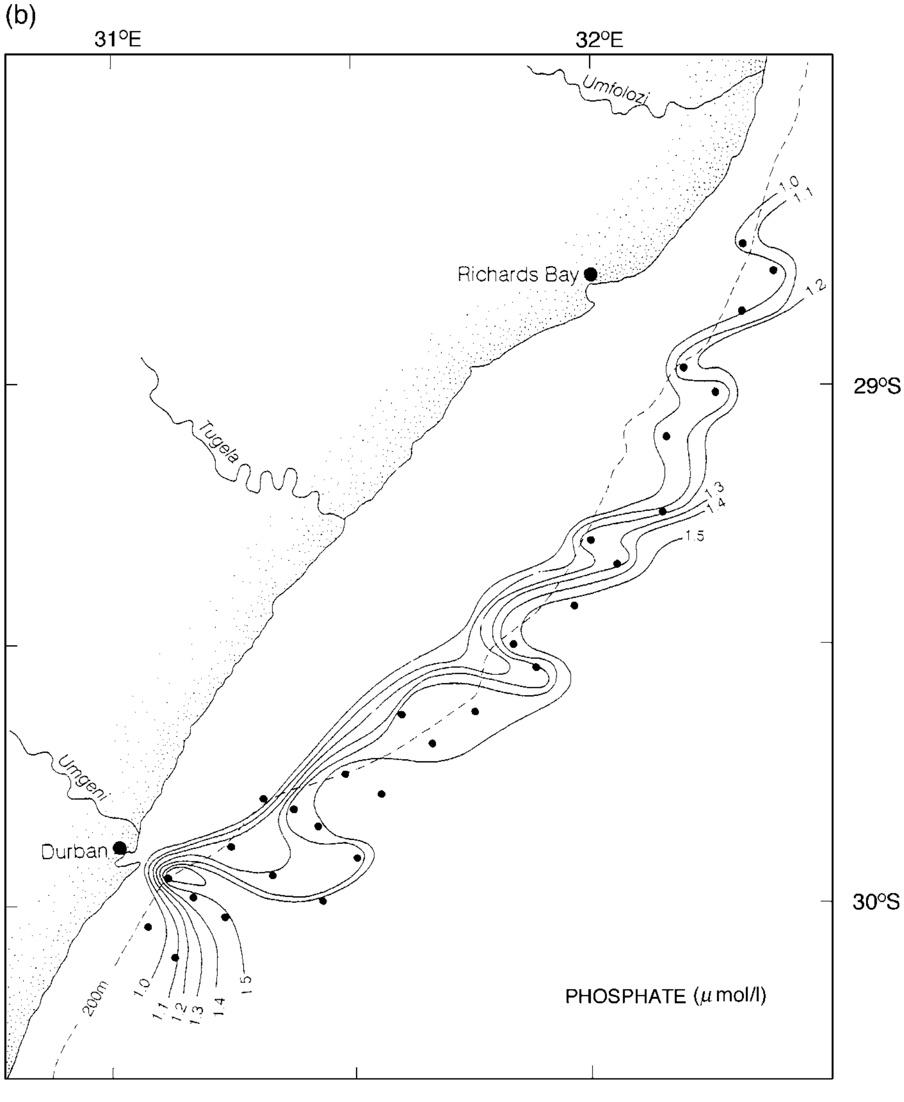

Fig. 6 (*continued*).

the horizontal distributions (Figs. 3 and 4), there is a decrease in nutrient concentration as this upwelled water is advected southward and, therefore, the water found in the dome-like feature at station line F had a much lower nitrate concentration of about 11 μmol/l compared with the 17 μmol/l waters north of it. This probably was due to biological assimilation as suggested by the chlorophyll-*a* distributions (Fig. 7) and/or mixing.

The uplift of nutrient-rich water at station lines B and C was mirrored by temperature and salinity data (Lutjeharms et al., 2000a). They have found this upwelled water to be South Indian Subtropical Surface Water with temperatures of about 19 °C and salinity of about 35.45 psu. At no stage was Central Water found on the continental shelf in the northern Natal Bight, a water mass which is found to be upwelled inshore of the Agulhas Current at Port Alfred farther downstream (Lutjeharms et al., 2000b) at a very comparable shelf configuration. In many respects, the same conditions exist at Richards Bay and Port Alfred, i.e., a widening continental shelf on proceeding downstream with the

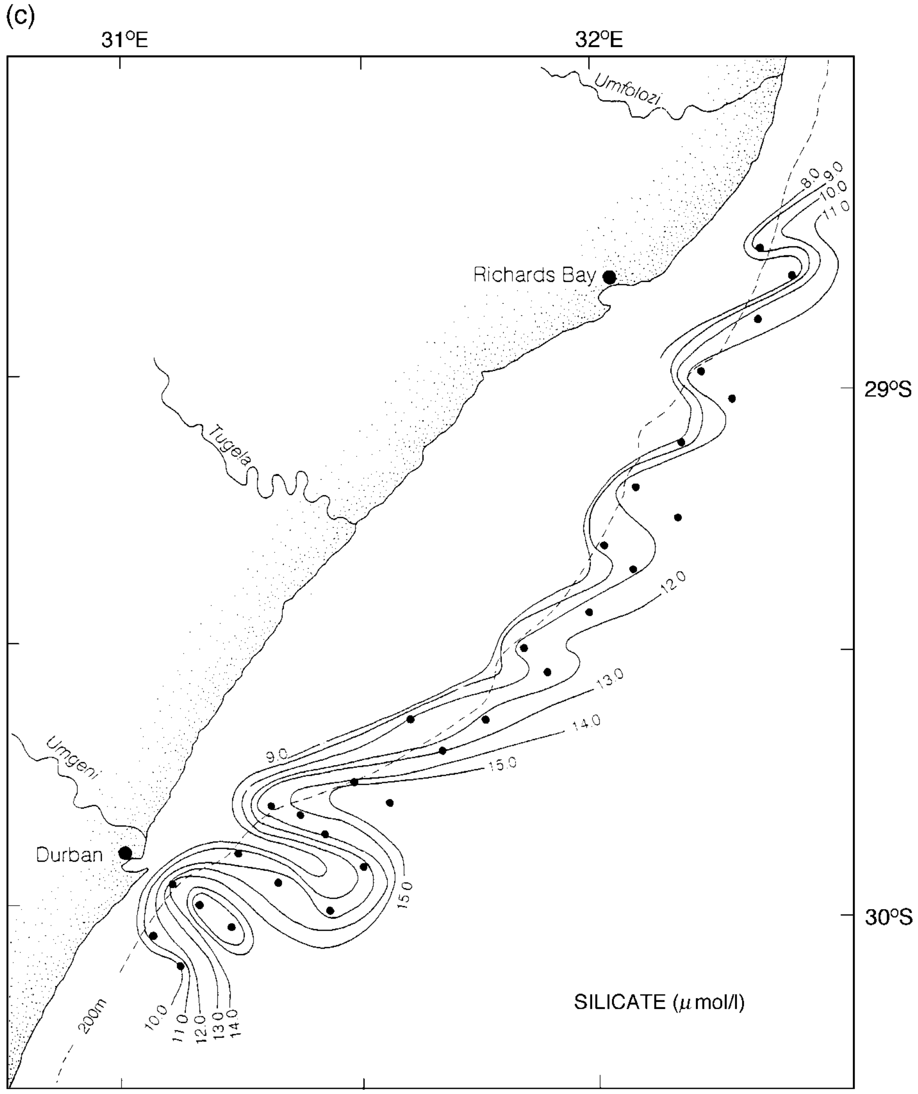

Fig. 6 (*continued*).

flow of the Agulhas Current, conditions conducive for bathymetrically induced upwelling by the Agulhas Current (Gill and Schumann, 1979). Lutjeharms et al. (2000a) have mentioned that the reasons for the difference in the depth of uplift at these two upwelling cells are probably twofold. First, the shelf at Port Alfred is considerably deeper than that for the northern Natal Bight, allowing access to deeper water masses. Secondly, the speed of the Agulhas Current may be higher further downstream, thus enhancing the upwelling effect.

At lines G–J (Fig. 9; cf. Fig. 1), the dome-like feature of high nitrate is not evident. Here, the entire water column over the shelf is well mixed. The enhanced vertical extent of mixing here and further south may well have been due to the storm. Water from the St. Lucia upwelling cell, thus, only extended to the stations of line F during this survey, where this high nutrient water met lower nutrient water of the central Natal Bight. The upwelling cell may, however, be more influential and its water may extend further south during other times and, there-

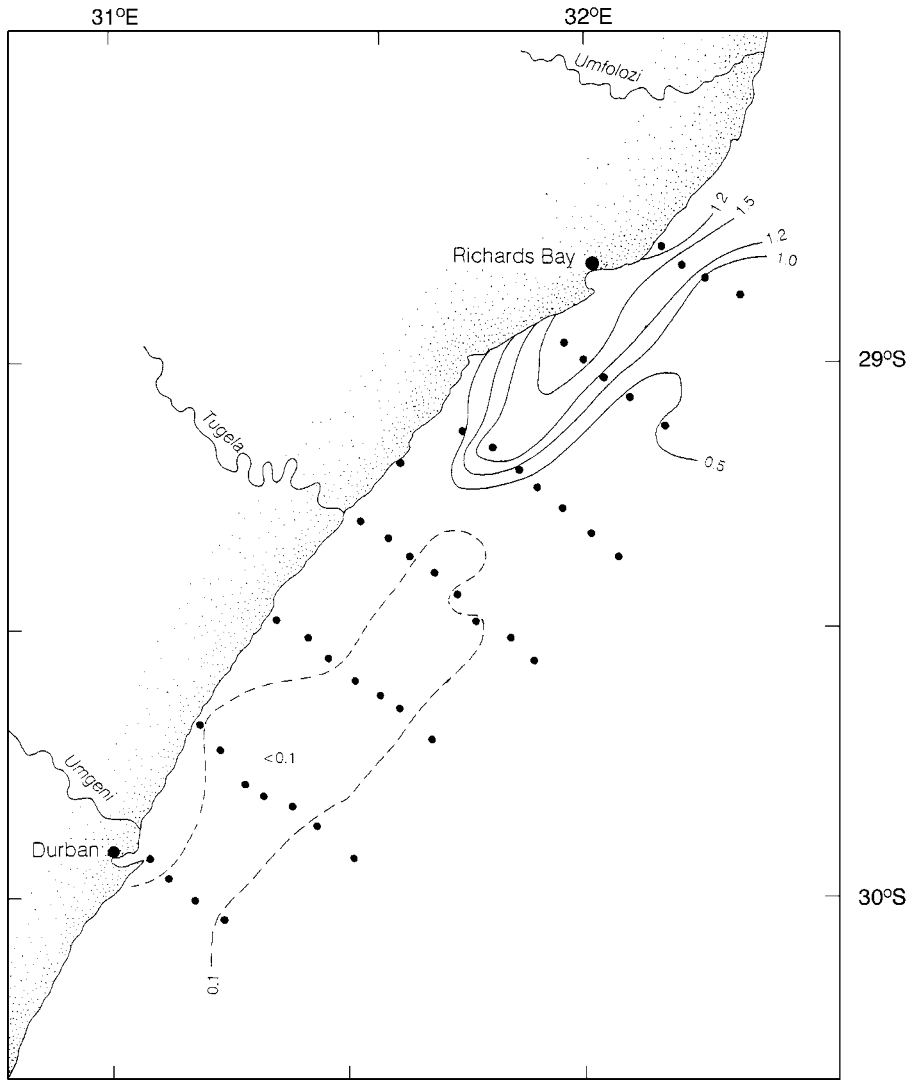

Fig. 7. Distribution of chlorophyll-*a* over the Natal Bight during July 1989. Station positions where chlorophyll-*a* was measured are shown. Units are mg/m^3.

fore, play an even greater role in the ecological dynamics of the entire Bight than suggested by this particular survey.

3.4. The eddy off Durban

As mentioned above, the Agulhas Current is known to overshoot the offset in the shelf-edge at Durban (Fig. 1) and to join the 200 m isobath again south of here (Schumann, 1987). A cyclonic lee eddy, possibly spun up by the Agulhas Current, has been recognised as a quasi-permanent part of the circulation regime at this location (Pearce et al., 1978; Anderson et al., 1988).

Inspecting the nutrient sections for lines K, M and N (Figs. 10 and 11) over the southern Natal Bight (cf. Fig. 1), the characteristic uplift of colder and nutrient-rich water in the core of such a cyclonic eddy is evident for the areas directly offshore from Durban (line N, Fig. 10). This is the same type of cyclonic circulation previously observed by Anderson et al. (1988) and Pearce (1977).

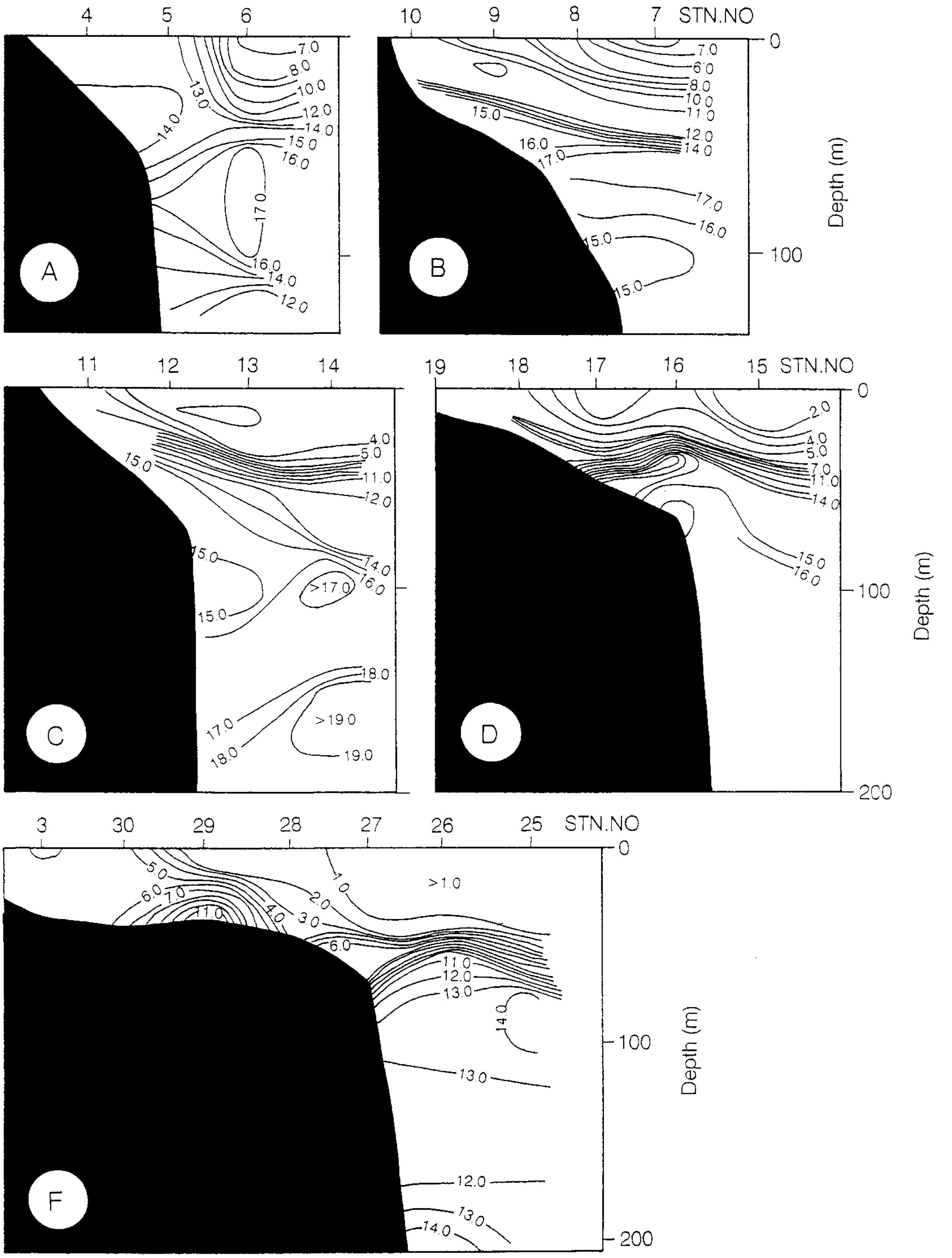

Fig. 8. Sections of dissolved nitrate over the northern part of the Natal Bight during July 1989. The locations of the station lines are given in Fig. 1.

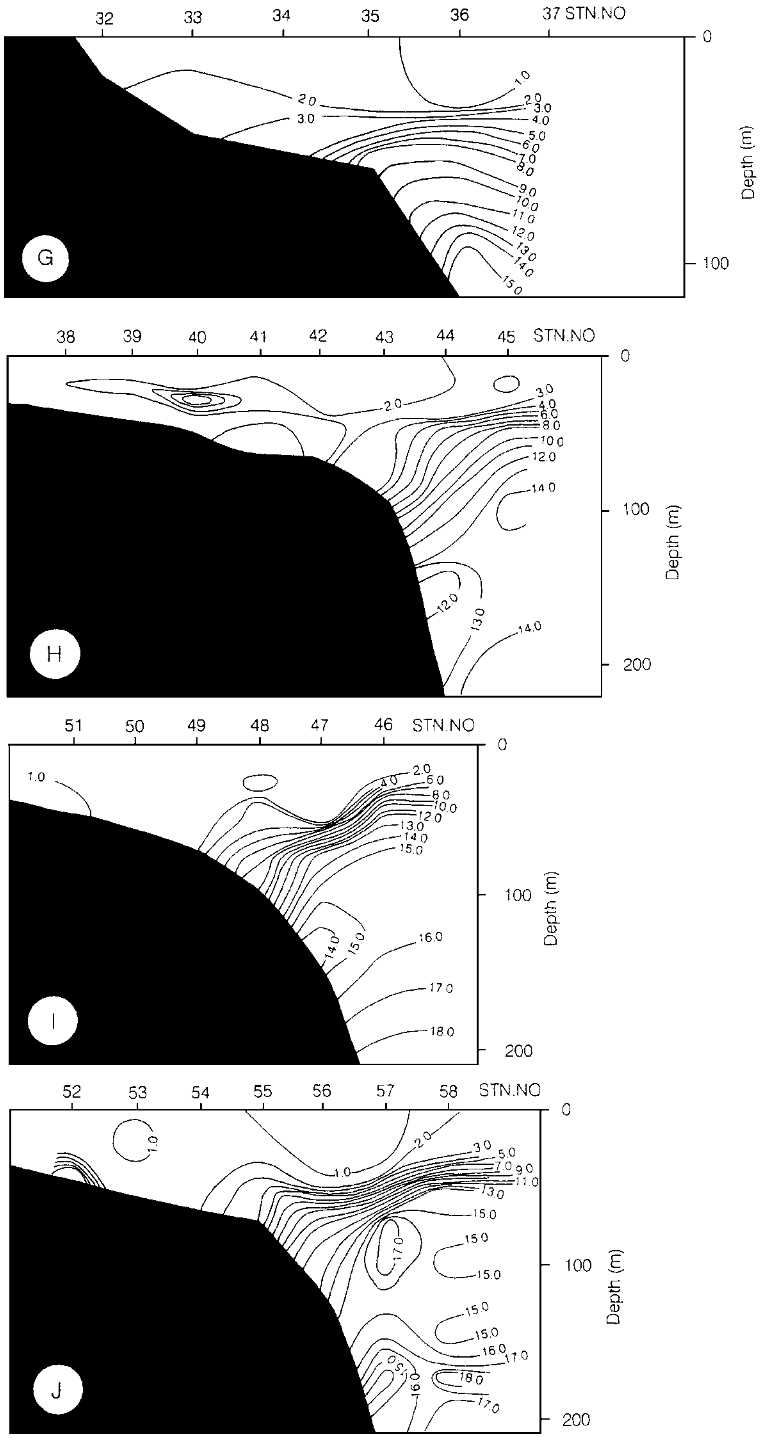

Fig. 9. Sections of dissolved nitrate over the central part of the Natal Bight during July 1989. The locations of the station lines are given in Fig. 1.

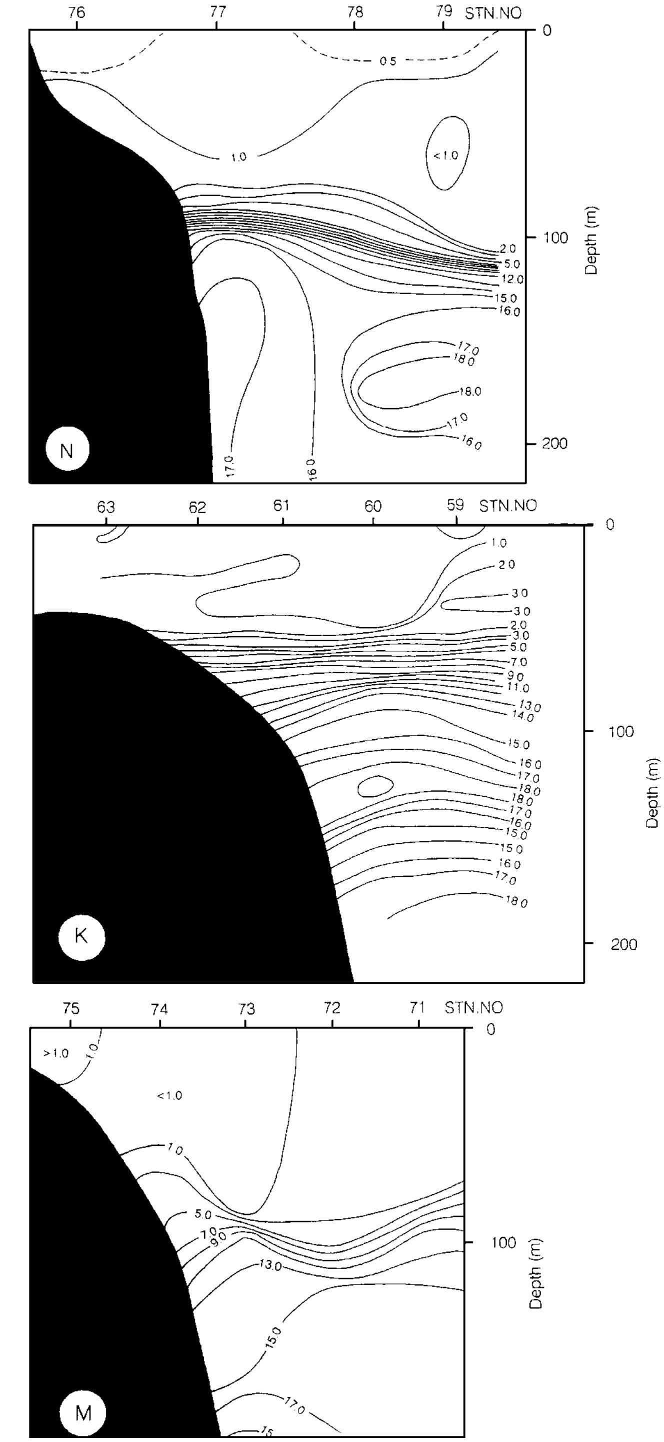

Fig. 10. Sections of dissolved nitrate over the southern extremity (K, M) and south of (N) the Natal Bight during July 1989. The locations of the station lines are given in Fig. 1.

The colder and nutrient-rich water (>17 μmol/l) in the core of the cyclonic eddy only reached upward to a depth of about 120 m on this occasion. However, the uplift of colder and nutrient-rich waters in the core of an eddy situated here has been observed to reach subsurface depths of 30 m (Carter and d'Aubrey, 1988). Above this dome of nutrient-rich water, much lower nutrient water of only 0.6 to 0.9 μmol/l water was found. From the combinations of satellite information (Fig. 7), lateral distributions of variables and the vertical sections across the eddy, it is clear that this cyclonic feature had upwelled water in its core, had probably started a journey southward as part of a Natal Pulse (Lutjeharms et al., 2000a; Lutjeharms and Roberts, 1988; Lutjeharms and Connell, 1989).

The influence of nutrients from the upwelling cell at Cape St. Lucia may profitably be traced using alongshore sections. Such sections for nitrate, phosphate and silicate (Fig. 11)—from Richards Bay to Durban—show that the nutrient-rich waters upwelled in the core of the lee eddy off Durban and do undergo sufficient uplift for this water to reach the edge of the continental

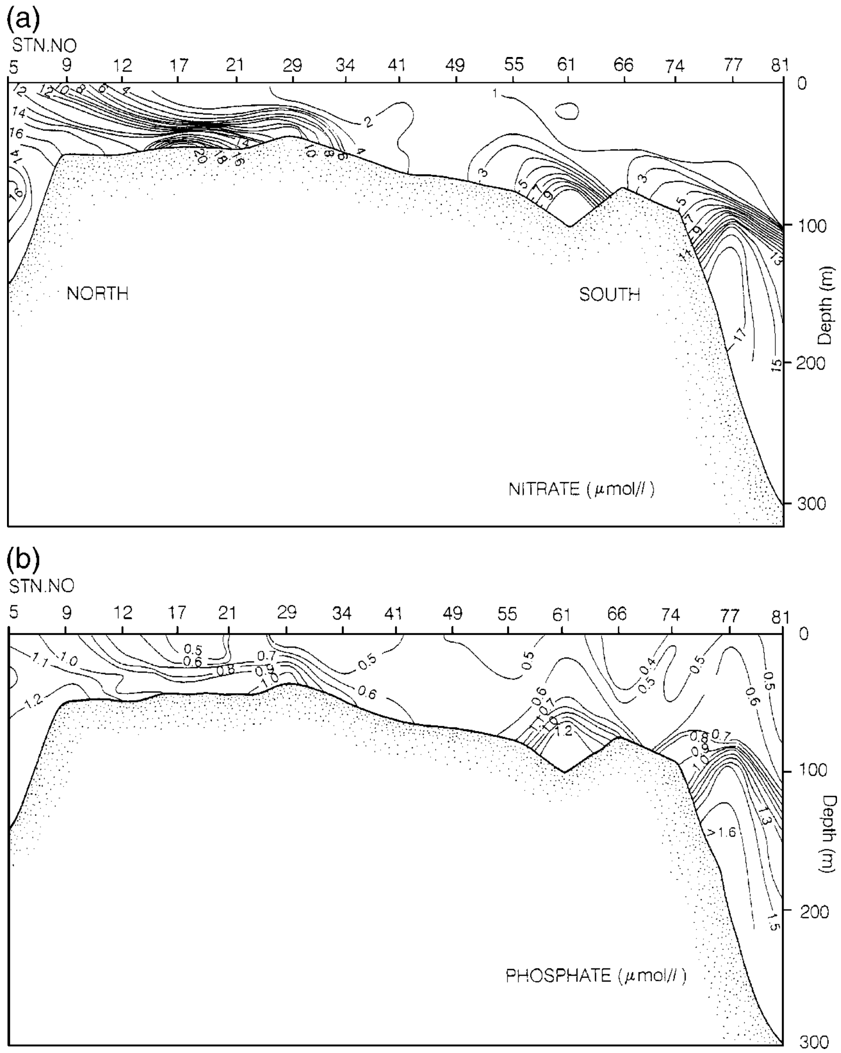

Fig. 11. Alongshore sections of nitrate (a), phosphate (b) and silicate (c) over the Natal Bight. The station numbers along the top border can be compared with those in Fig. 1 to determine the exact location of this line.

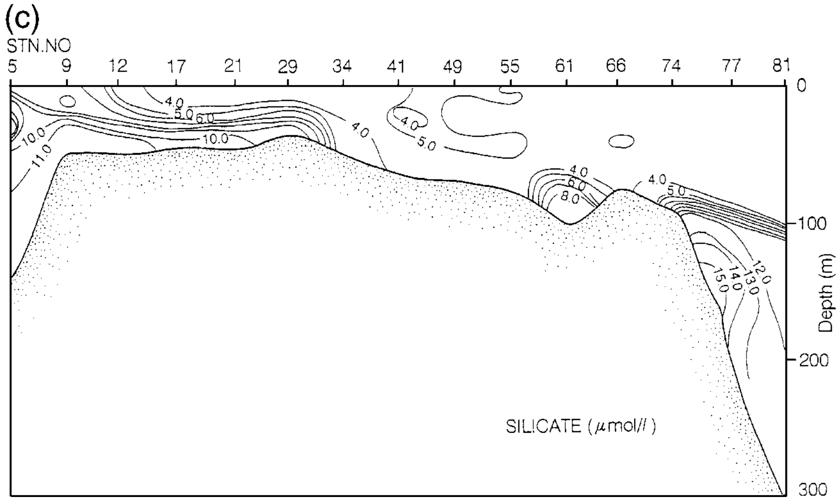

Fig. 11 (*continued*).

shelf. Waters with high nutrient content upwelled in the core of this eddy may, therefore, conceivably be transported in a northerly direction onto and over the shelf. The movement of nutrient-rich water onto the shelf at the St. Lucia upwelling cell is another mechanism that facilitates water movement across the shelf edge. The southward movement of this upwelled water and its extent is evident from Fig. 11.

Just north of Durban, high nutrient water seems to have been brought onto the continental shelf at line K (station 61). This particular station was in deeper water farther offshore than others forming part of this section (cf. Fig. 1) and, thus, had higher nutrients. Nevertheless, nutrient distributions at the 75-m depth (Fig. 5) do indicate some degree of intrusion of water from the oceanic regime, which may be driven by some perturbation in the deeper layers of the Agulhas Current.

The fundamental question to be asked at this stage is the degree to which the process occurring in the St. Lucia upwelling cell determines the nutrient supply to the entire Natal Bight. To this end, we have constructed a simple box model to investigate the nutrient budget for the shelf.

3.5. Nutrient budget

The above description and that by Lutjeharms et al. (2000a) suggest that interaction between water on the Natal Bight and the offshore Agulhas Current occurs mainly by: (1) injection of offshore nutrient-rich water into the deeper waters of the northern Natal Bight, and (2) surface mixing with low-nutrient Agulhas Current water in the southern and central parts of the Bight. Following this, the nutrient dynamics of the Natal Bight could conceivably be described by a model in which the main source of nutrients is upwelling of nutrient-rich water of offshore origin in the north, followed by advection of this nutrient-rich water to the south, with the progressive depletion of its nutrient content by biological production and mixing with adjacent water masses. The validity of this model can be tested by using combined nitrate–phosphate distribution patterns to determine the relative importance of the upwelling/productivity cycle vis-à-vis mixing with adjacent water masses. Thus, one could establish their respective roles in maintaining both surface water and deep water nutrient distribution patterns and north–south gradients.

For this exercise, it is assumed that north–south gradient in the surface water is maintained by upwelling of nutrient-rich water from below, that the main nutrient sink is conversion into particulate organic matter by biological production (depleting NO_3 and PO_4 in a Redfield ratio of 16:1, thus taking care of the time derivative) and that southward advection occurs with negligible horizontal and vertical mixing with adjacent water masses. It is also assumed that there is negligible southward flow on the shelf from north of Cape St. Lucia and, hence, that $U_v \cong V_u$. Without any reliable, in situ current observations at this location, it is difficult to tell how sound this last assumption is. Based on this set of assumptions, the nitrate and phosphate fluxes can be described as follows:

$$V_u \times [NO_3]_{Nd} = U_v \times [NO_3]_{Ns} + PN, \quad (1)$$

$$V_u \times [PO_4]_{Nd} = U_v \times [PO_4]_{Ns} + PP, \quad (2)$$

$$(1) + (2) \rightarrow [NO_3]_{Nd} - [NO_3]_{Ns} = 16 \times ([PO_4]_{Nd} - [PO_4]_{Ns}), \quad (3)$$

with the parameters defined as: PN = particulate nitrate flux (biological production, mol/year); PP = particulate phosphate flux (mol/year) = $^{PN}/_{16}$; V_u = volume of upwelled water per annum (m^3/year); U_v = volume of water advected horizontally to the south = V_u to balance upwelling flux (conservation of mass); $[X]_{Nd}$ = concentration of X at depth in northern Natal Bight; $[X]_{Ns}$ = concentration of X at surface in northern Natal Bight.

Eq. (3) can be applied at each station to test the validity of the assumption that the surface water nutrient values result from biological production, sustained by vertical upwelling, with negligible effect of mixing processes as illustrated in Fig. 12a. From the combined NO_3–PO_4 data, it is clear that coastal pro-

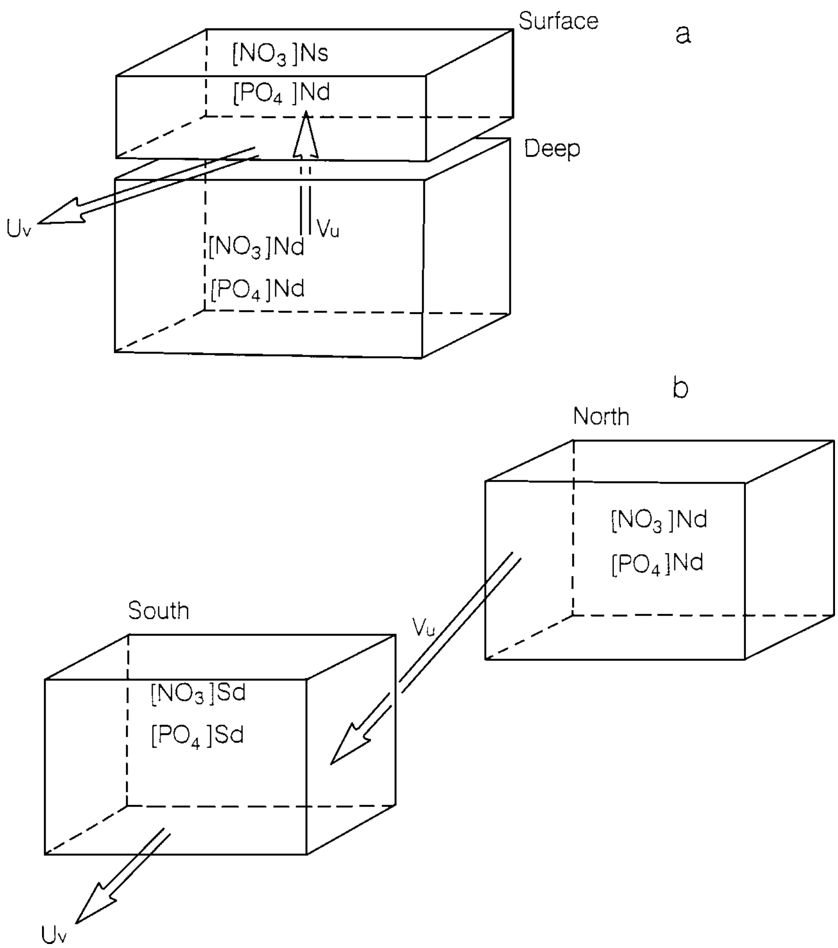

Fig. 12. Configuration of two simple models to establish the role of mixing relative to biological production to sustain the nutrient levels in the surface waters of the Natal Bight. In (a), the assumption that the main source of nutrients is upwelling, followed by advection and the progressive depletion by biological action as well as mixing with adjacent waters (Eq. (3)). In (b), the effect of productivity is contrasted to that of mixing as the water mass is advected southward (Eq. (4)).

cesses exert a significant influence on surface nutrient distributions in coastal areas with surface values enriched in nitrate and phosphate relative to deeper waters observed at several stations close to the coast. Stations that adhere to the principle of minimal mixing, i.e., upwelling sustained productivity, cluster around the shelf edge (Fig. 13). This may imply that shelf-edge upwelling occurs to some extent along most of the Natal Bight and not only in the north. This hypothesis is consistent with the surface chlorophyll distribution in the Bight at the time (Fig. 7). This exhibits a band of high chlorophyll values along the shelf edge and the apparent intrusion of low chlorophyll water from south to north along the inner bight. A few of the vertical sections exhibit nutrient distributions that might be interpreted as shelf-edge upwelling (e.g., line D, Fig. 8; line G, Fig. 9; etc.). However, in none of these cases is there evidence that the water with higher nutrients outcrops into the upper 50 m of the water column. An alternate explanation for the high chlorophyll values

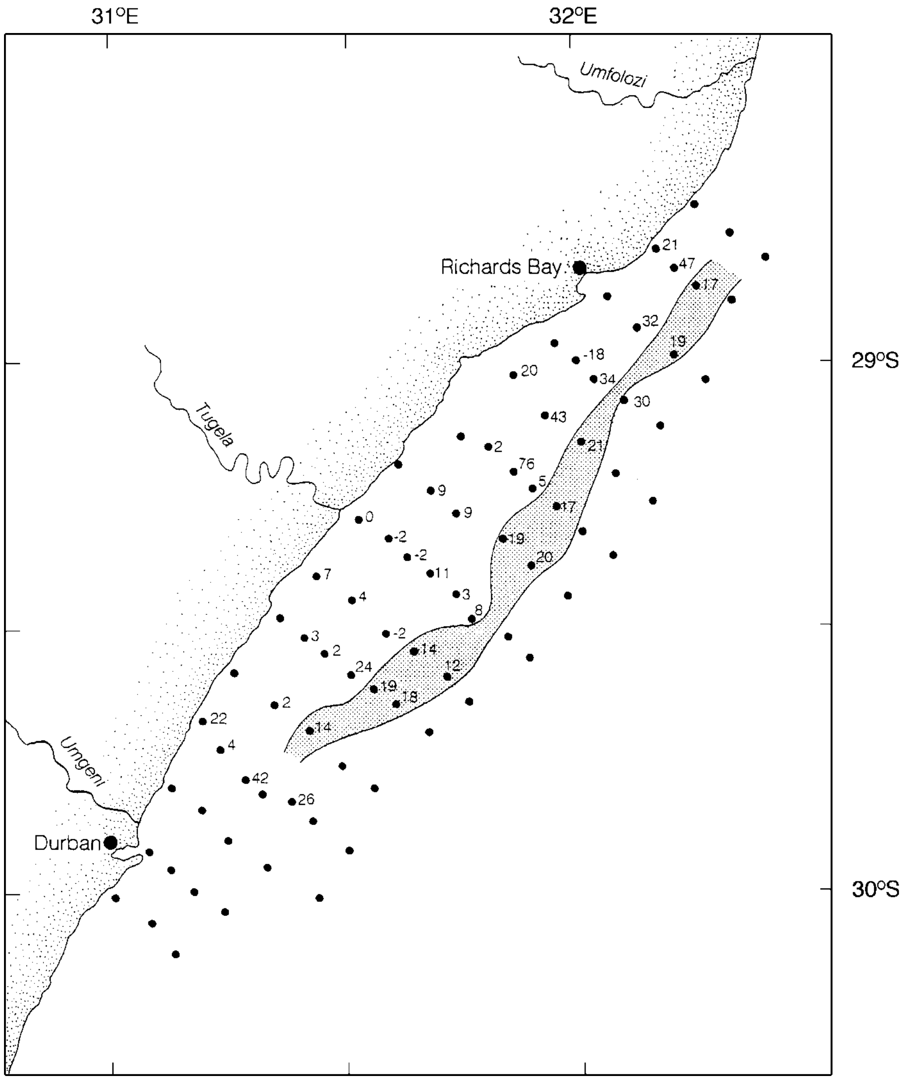

Fig. 13. Distribution of stations on the Natal Bight where, according to model results, there was minimal mixing and where primary productivity is therefore considered to be sustained by upwelling, according to a simple advective/mixing model.

along the edge of the Agulhas Current might be the tendency for the water from the upwelling cell to be dragged along the current edge. This has been observed (e.g., Lutjeharms et al., 1989).

A similar exercise can be carried out to test the extent to which the north–south water depletion in nutrient can be ascribed to biological productivity accompanying the southward flow as opposed to mixing with surrounding waters of variable nitrate:phosphate values. If it is assumed that minimal mixing occurs between the southward-moving deep tongue of nutrient-rich water and surrounding low-nutrient water masses, then a similar set of equations to the above can be solved to give:

$$[NO_3]_{Nd} - [NO_3]_{Sd} = 16 \times ([PO_4]_{Nd} - [PO_4]_{Sd}). \quad (4)$$

This simple model is illustrated in Fig. 12b. The results (Fig. 14) suggest that the assumption of southward advection, accompanied by sustained biological

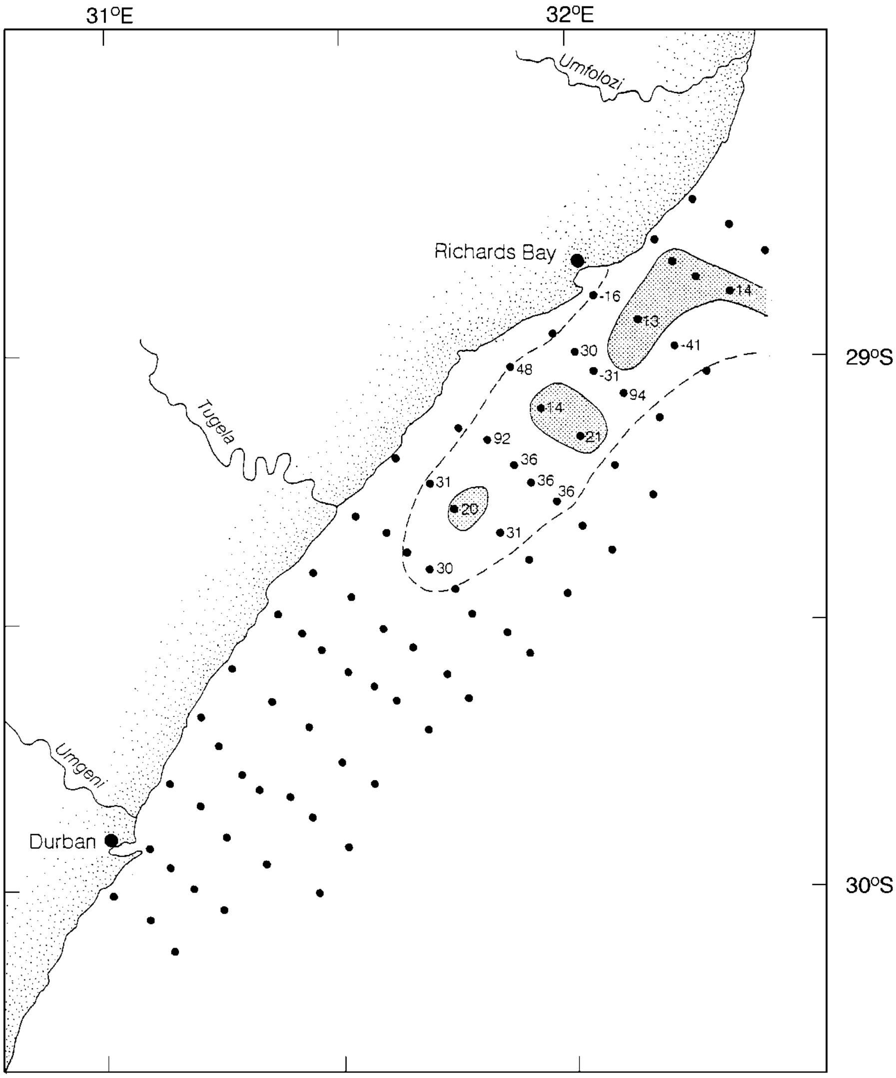

Fig. 14. Distribution of stations on the Natal Bight where, according to model results, primary production was sustained mainly by horizontal advection.

production and minimal lateral mixing, holds to some extent along a very fragmented path in the northern bight. Extensive mixing of this nutrient-rich water with both offshore and inshore water bodies is evident (Fig. 14). The assumed southward flow of nutrient-rich water may, therefore, be disrupted spasmodic or altered by storm events such as occurred about halfway during this cruise.

4. Conclusions

The distribution and movement of nutrients over that part of the southeast African shelf that constitutes the Natal Bight demonstrates a number of things.

First, it shows that the Agulhas Current controls the nutrient distribution over the largest part of the bight. It does this predominantly by forcing upwelling at its northern end in a site-specific upwelling cell between Richards Bay and Cape St. Lucia. It has previously (Lutjeharms et al., 1989, 2000a) been shown that this upwelling is largely wind-independent and a function of the local shelf/current configuration. This St. Lucia upwelling cell is the main source of nutrients for the whole bight. From here, nutrients are moved southwestward with an attendant increase in primary productivity. Wisps of higher concentrations of nutrients may occasionally be advected downstream at the shoreward edge of the current. The Agulhas Current also controls the nutrient distribution at the southern extremity of the Natal Bight. It does this by the creation of a lee eddy at Durban that forces nutrient-poor surface water from the Agulhas Current onto the shelf. In this way, the Agulhas Current may create three nutrient provinces on the bight shelf: an enhanced northern province, a deprived southern one and a central one that lies somewhat in between. These conclusions based purely on the nutrient distributions are in good agreement with what is currently known about the water circulation in and adjacent to the Natal Bight.

Secondly, it is concluded that the influence of the outflow of the Tugela River on the nutrient distributions in the Natal Bight as a whole is noticeable, but small. On this occasion the flow was above the mean. Since this outflow varies enormously, a large flood event in the catchment area could conceivably change the river's influence on the shelf waters substantially. Such event-driven variability also has a considerable effect on all the other conclusions.

Since the Natal Bight, in general, is shallow, wind mixing is bound to play a substantial role on the vertical stratification of its water masses. This means that the southward penetration of nutrient-rich bottom water may be rapidly curtailed by any strong wind event. It is even possible that the termination of the clear nutrient signal in July 1989 in the central part of the bight was the result of the storm that hit the cruise halfway through its southward progress. The eddy off Durban is also subject to high levels of variability. Its presence is known to be extremely intermittent and its intensity very variable. This may have implications for the movement of nutrient-poor surface water from the Agulhas Current onto the Natal Bight. These considerations make it imperative that more observations of this kind be carried out to establish the representativeness of the results gained during this first bight-wide cruise carried out in 1989.

Acknowledgements

This was one of the last research cruises carried out on that dapper little vessel, the R.V. *Meiring Naudé*, before it succumbed to the commercialisation of the CSIR and was sold. We thank Captain Foulis and his crew for their enthusiastic support of the research during the cruise, Mr. Roy van Ballegooyen for acting as chief scientist and the full scientific team for their help. They are all mentioned by name in the appropriate data report (Valentine et al., 1991). Financial support by the Foundation for Research Development as well as by the University of Cape Town made the completion of this analysis possible. We are most grateful for the thorough and critical comments by an anonymous reviewer that made us recheck all the nutrient values and their contouring, allowing us to correct a number of errors.

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