Upwelling at the inshore edge of the Agulhas Current

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Abstract

Evidence for upwelling along the landward side of the Agulhas Current is presented. An analysis of old and new hydrographic data, surface temperature observations and satellite measurements show that this upwelling occurs in a tightly circumscribed geographic area. Centred at Port Alfred, it has a lateral range along the Agulhas Current from 85 to 300 km. Intermittent outcropping of upwelled water occurs more than 40% of the time and changes the surface temperatures dramatically. Below the upper layers this upwelling is more persistent and durable. It derives its water from the upper to middle levels of South Indian Central Water. This process may have a profound effect on the nutrient availability, the stratification and the primary productivity of specifically the eastern Agulhas Bank south of South Africa.

Keywords: Upwelling; Agulhas Current

1. Introduction

Upwelling along the edge of the Agulhas Current is found in two instances. Upwelling of water between the shoreward side of the current and the continental slope is a normal occurrence along its full length and is already evident in the temperature sections published by Darbyshire (1964) and those shown in Fig. 1. Water with \( \sigma_t \) values greater than 26.60 is found deeper than 400 m along the continental slope at Durban (Fig. 1B). Downstream, at Port Elizabeth, it is at 150 m,
i.e. it has moved onto the shelf itself. This suggests that this process is not merely the normal upward inclination of an isopycnal as part of the structure of a western boundary current, but represents rather the actual vertical movement of the denser, colder water mass. This type of upwelling inshore of western boundary currents, probably concentrated in the bottom Ekman layer, forms an inherent part of the dynamics of all western boundary currents (Condie, 1995). It has, for instance, been described for the Gulf Stream by Hsueh and O’Brien (1971) and by Blanton et al. (1981), for the Kuroshio by Nagata (1970) and for the East Australian Current by McClean-Padman and Padman (1991) and by Tranter et al. (1986).

The second category of persistent upwelling associated with the Agulhas Current is found at locations where the shelf width increases along the path of the current. This happens, for instance, at the northern end of the Natal Bight, a wider part of the shelf between Durban and Richard’s Bay (viz. Fig. 1). Here an upwelling cell is found year-round (Lutjeharms et al., 1989b) in which cold, nutrient-rich waters is carried from central water depths onto the shelf. This water has a marked influence on the physical water characteristics of the whole Natal Bight (Lutjeharms et al., 1999) as
well as on the nutrients, the biota and biological primary productivity of this region (e.g. Carter and D’Aubrey, 1988; Carter and Schleyer, 1988). This upwelling is unrelated to local winds (Pearce, 1977; Lutjeharms et al., 1989b). Gill and Schumann (1979) have described a mechanism by which a coastal jet, such as the Agulhas Current, will cause enhanced upwelling on its inshore side on passing from a narrow shelf to a wider shelf. Upwelling at such locations along western boundary currents should therefore not be unique to the Agulhas Current. It has in fact also been observed along the Kuroshio (Lutjeharms et al., 1993) and the East Madagascar Current (Lutjeharms and Machu, 1999).

The second location along the east coast of South Africa where, according to this proposed mechanism, such upwelling should occur is where the shelf starts widening as the Agulhas Current passes from East London to Port Elizabeth (viz. Fig. 2) along the eastern extremes of the Agulhas Bank. Upwelling has been suggested to occur here based on data collected during oceanographic research cruises (e.g. Bang, 1970; Lutjeharms and Roberts, 1988), from satellite imagery (Lutjeharms, 1981; Walker, 1986) and from airborne radiation thermometry (Schumann, 1987). Neither the occurrence frequency of this suggested upwelling nor its spatial dimensions have as yet been investigated or described. Since this cell might well play as important a role for the whole Agulhas Bank as does its counterpart for the Natal Bight, such a preliminary description is important. It is therefore the aim of this contribution to give such a description.

The upwelling at the eastern extremity of the Agulhas Bank should not be confused with two other upwelling processes that also occur at the peripheries of this continental shelf region. Wind-driven upwelling along the coastline, and particularly at prominent head-lands, occurs during periods of strong and persistent easterly winds (Schumann et al., 1982). This brings colder water, already on the shelf, up from below the thermocline. Along the continental shelf-edge, intense shear-edge eddies, driven by the passing Agulhas Current (Lutjeharms et al., 1989a; Goschen and Schumann, 1990), upwell cold water in their cores. It has been suggested (Chapman and Largier, 1989) that the water drawn up in these eddies may eventually move onto the Agulhas Bank, intensifying the seasonal thermocline from below. Both these upwelling processes are probably important components of the heat and salinity budgets of water on the Agulhas Bank. At present they are unquantified and lie outside the scope of this investigation.

2. Data sources

To carry out a sufficiently detailed descriptive analysis of both the spatial and the temporal characteristics of the waters of the far eastern Agulhas Bank, all available data sources have been used.

2.1. VOS sea surface temperatures

Sea surface temperatures collected from commercial, voluntary observing ships (VOS) from 1960–1991 were examined for quality and geographic distribution in
Fig. 2. (a) A characteristic disposition of the southern Agulhas Current as expressed in the distribution of temperatures at the sea surface. This portrayal is from thermal infrared measurements of the NOAA satellite for 11 January 1994. (b) Bathymetry for the same ocean region. Note, in particular, the widening of the continental shelf downstream of Port Alfred that constitutes the Agulhas Bank.
the area of interest. There was a total of 79,407 observations, most collected during the period 1967–1975. Observations were distributed about equally per calendar month. The proximity of commercial ship routes close to the coast in this region results in a large number of observations (about 5000) for every 1/2° latitude by 1/2° longitude block. About 3% of the data had to be rejected due to incorrect locations.

An analysis of the records shows that sea surface temperatures were preferentially recorded to a precision of 0.5 or 1.0°C, limiting the value of these data for regions where small temperature changes are to be expected. In the study region, however, temperature differences of 3 to 10°C have been observed, justifying the selective use of these data. Data were divided into 1/4° × 1/4° blocks and mean temperatures and standard deviations calculated for each block.

2.2. *Hydrographic data*

Observations of temperature, salinity, dissolved oxygen and nutrients for the region of interest were collected from a number of sources. A total of 1934 oceanographic stations were acquired from the SADCO (South African Data Centre for Oceanography) for the period 1960–1983. Most of these were collected between 1969 and 1975 and during the calendar months October and June. On average 100 stations were occupied during all other calendar months. These data came from a large number of organisations, using different measuring techniques, and there has been little control over the quality or accuracy of the data. We also made use of new, unpublished data to draw a number of pertinent hydrographic sections.

2.3. *Thermal infra-red satellite imagery*

The principal source of thermal infra-red data for sea surface temperatures was the NOAA series of polar-orbiting satellites. The sensor used is the AVHRR (advanced very high-resolution radiometer) measuring i.a. in the 10.5 and 11.5 μm frequency bands. The spatial resolution is 900 m × 900 m at nadir, along the flight path. For this investigation images from NOAA-9, -10 and -11 were used for 1988 and NOAA-11 up to 1995. Data were geographically adjusted to a Mercator projection, contrast enhanced and atmospherically corrected to obtain sea surface temperatures correct to better than 0.5°C (McClain et al., 1985). The availability of useful images is a function of the degree of cloudiness over the region. It would have been ideal to match all hydrographic sections to good satellite images. We were unable to find such matches due to the small number of sections and the high percentage of cloudy days in the region.

A detailed analysis of these data, and for relatively cloud-free days, was carried out for the period January to September 1991. Histograms for the distribution of the sea surface temperatures for a masked area was calculated for this data set. This series of images also allowed the lateral dimensions of the upwelling cell to be established, the 17°C isotherm being deemed a good indicator of the extent of upwelled water at the sea surface. Spatial resolution for these data is dependent on the distance from the subsatellite path, but is better than 5 km for all parts of these images.
3. Results and discussion

3.1. Thermal expression

The most noticeable feature of any upwelling system is its contrasting temperature to that of ambient waters. The available temperature data allow one to establish the geographic extent of the presumed upwelling cell quite precisely.

The thermal characteristics of the far eastern Agulhas Bank upwelling and its general environment, as distinguishable in a thermal infra-red satellite image, is shown in Fig. 2(a). It may be compared to the bottom topography of the identical region (Fig. 2(b)). The rectilinear landward border of the Agulhas Current upstream of Port Elizabeth, along the narrow part of the shelf, shows a very strong horizontal temperature gradient. Downstream of Port Elizabeth the shelf widens to form the Agulhas Bank. The Agulhas Current continues to follow this shelf edge here, but exhibits an increasing tendency to meander. These meanders are accompanied by shear-edge features such as warm plumes and cyclonic eddies. Cold surface water was present on this occasion in the acute angle between the inshore border of the Agulhas Current and the coast, upstream of Port Elizabeth. This water was substantially colder than the surface waters over the greater part of the adjacent Agulhas Bank itself. This indicates that observations of sea surface temperatures in the general vicinity of Port Alfred can conclusively show the presence of upwelled water at the sea surface here, as well as the relative location of surface waters of the Agulhas Current.

Averages of sea surface temperature for the full year, based on VOS data (Fig. 3(a)), clearly show the core of the Agulhas Current offshore, with a downstream cooling from 23 to 22°C between Port St Johns and Port Elizabeth. A strong horizontal gradient in surface temperature locates the inshore boundary of the current. This current border closely follows the 200 m isobath. The temperature gradient of the current border is sharpest at East London and farther downstream since it is here that cooler inshore water (< 20°C) is found. However, there is no unequivocal indication in the average sea surface temperatures of an upwelling cell in the vicinity of Port Alfred when compared with temperatures off Port Elizabeth and surroundings.

The variations for all available temperature observations of the sea surface delineate a distinct and well-circumscribed region of greater variability along the coast between Mbashe and Port Alfred. Downstream from Port Alfred it lies farther offshore (Fig. 3(b)). It has, however, been demonstrated that the current location is very stable from Port Elizabeth to Durban (Fig. 1; Gründlingh, 1983).
known to increase markedly downstream of Port Elizabeth (Lutjeharms et al., 1989a), but temperature variability based on such meandering would depend on the difference in temperatures between that of shelf water and of current water. Much colder water over the shelf would increase the variability considerably wherever such cold water is
found and this seems to be occurring off Port Alfred only (Fig. 3). This forces one to conclude that this variability is principally due not to meandering but indeed to the prevalence of intermittent upwelling in the region. More supporting evidence is, however, required firmly to support this supposition.

The surface distributions are based on a multitude of data. There are far fewer hydrographic stations for the region at which observations have been made over the full depth of the water column (Fig. 4). Averages based on such hydrographic data show the characteristic high temperatures of the Agulhas Current core (22–23°C) in a rather patchy way. The inshore border, shown by an enhanced thermal gradient downstream of Port St Johns, is evident from the sea surface to a depth of at least 80 m. Coldest inshore water, presumably upwelled, is found throughout the water column at Port Alfred and at Port Elizabeth. This water is considerably colder than the inshore waters upstream of Port St Johns. Caution is, however, advisable in accepting the absolute temperature values, or the precise delimitation of the geographic area of colder water, based on this severely limited data set. Nevertheless, these data show unequivocally that this region of considerably colder water is persistent and is not only a surface phenomenon.

Given that surface observations of colder water are therefore representative of the greater part of the water column in this upwelling cell, an assemblage of a set of satellite-derived sea surface temperatures may be useful for establishing finer detail of the location of this upwelling region (Fig. 5). This analysis was done for a full year. A representative five-month period only is shown in Fig. 5 in order to prevent clutter.

![Diagram showing temperatures at different depths along the southeast coast of South Africa](image-url)

**Fig. 4.** Temperatures at different depths along the southeast coast of South Africa, from hydrographic data. The 200 m isobath is shown as a dotted line; temperature fields below 17°C are hatched.
Fig. 5. An ensamblage of outlines of cold upwelled water inshore of the Agulhas Current for the period January to May 1991. Satellite imagery in the thermal infrared was used for this portrayal. The 17°C isotherm was used as an indicator of the edge of upwelled water at the sea surface for each case.

of the diagram. Since the surface expression of this upwelling does not exhibit any clear seasonality (see later) and since the Agulhas Current has been shown to have no clear seasonal pattern in its flow behaviour (Pearce and Gründlingh, 1982), this period is probably representative of the average geographic disposition of this cold water. It shows (Fig. 5) that the upwelling extends from Mbashe in the north to the eastern edge of Algoa Bay. The core of the upwelling lies at Port Alfred. The clear delimitation of this upwelling shown by these data supports the concept of an upwelling cell, i.e. an entirely localised phenomenon. Because it is collected so regularly, satellite thermal imagery may also provide a source of data to evaluate the temporal characteristics of the upwelling.

3.2. Temporal characteristics

The surface expression of upwelling obtained from thermal infrared imagery was analysed for a period of 6 yr. There were 273 images available for this period, about 12% of the total possible, that were deemed sufficiently cloud-free to be able to establish unambiguously the presence or absence of upwelling in the region of interest. To fall into the category of upwelling, the water inshore of the Agulhas Current at
Port Alfred would have had to have been much colder than the inshore waters either upstream or downstream of here. For these cloud-free images, the presence of upwelled water at the sea surface was evident 45% of the time. Upwelling occurred between Cape Padrone, the eastern side of Algoa Bay, and Port Alfred on 45% of the cloud-free days; between Cape Padrone and East London 49% of the time and extended as far upstream as Port St Johns on only 5% of these days. The time series of these occurrences (not shown here) suggests no temporal patterns, be they seasonal or otherwise. There seems no imperative reasons why cloud-cover should be correlated with the absence or presence of upwelling at the sea surface. The above percentages, derived from satellite imagery, may therefore be reliable indicators of the overall occurrence frequency of upwelling in this region. Even if this were not the case, it is clear that this surface outcropping of upwelled water is a highly recurrent process (Table 1). From the data presented so far it is clear that there is a core region for the upwelling off Port Alfred. It would be important to establish more reliably the preferred dimensions of this upwelling cell.

### 3.3. Spatial characteristics

Variation in the surface expression of the upwelling centred at Port Alfred is strikingly visible in two satellite images, 25 days apart, given in Fig. 6. On 30 March 1991 the core temperature of the upwelling cell, at the sea surface, was 11°C lower than that in the Agulhas Current and at least 5°C lower than adjacent shelf waters. On 5 March there was no distinguishable difference between the sea surface temperatures off Port Alfred and those of the greater Agulhas Bank.

The surface areas for each temperature class for these dates is given in Fig. 7. The number of pixels (picture elements), each about 900 m x 900 m, in which a specific temperature was observed, is given for the region within the mask portrayed in Fig. 6. Pixels for clouds have been excluded. On 5 March the water temperatures over the shelf area were between 18 and 24°C; the modal temperature being 20.5°C, with a standard deviation of but 1.8°C. The core temperature of the Agulhas Current was 26.5°C with a range from 24 to 28°C. On 30 March (Fig. 7) the core temperature as well as the areal distribution of temperatures for this part of the Agulhas Current were not much changed. Temperature distributions over the shelf were, by contrast, dramatically different. By far the greatest part of this water had temperatures between

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<tbody>
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<td>0</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>1</td>
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<tr>
<td>Extend to Port Alfred</td>
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<td>25</td>
<td>11</td>
<td>14</td>
<td>7</td>
<td>3</td>
<td>1</td>
<td>68</td>
<td>45</td>
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<tr>
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<td>12</td>
<td>4</td>
<td>21</td>
<td>12</td>
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<td>1</td>
<td>8</td>
<td>5</td>
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<tr>
<td>Number of useful images</td>
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<td>38</td>
<td>16</td>
<td>37</td>
<td>21</td>
<td>16</td>
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Fig. 6. Sea surface temperatures along the edge of the Agulhas Current during a well-developed upwelling event (upper panel, 30 March 1991) and when there was no evidence at the sea surface of upwelling, 25 days previously (lower panel, 5 March 1991). A temperature scale is given. The borders of the region for which areal temperature coverage has been calculated (Fig. 7) has been superimposed on the upper panel. White areas over the sea represent clouds.
15 and 19°C. The lowest temperature was 13.2°C. Two maxima in the areal coverage of the lower temperatures are evident in Fig. 7 for 30 March. The higher temperatures, centred at 18.5°C, represent water on the Agulhas Bank downstream of the upwelling cell. It was substantially colder than on 5 March, suggesting mixing of shelf and upwelled water since at least 21 March when the first signs of upwelling became evident in available satellite imagery. The second areal maximum of temperatures for 30 March (Fig. 7) is centred at about 16°C and represents the cold upwelled water that is totally absent on 5 March. A detailed analysis of the areas covered by water of specific temperatures and how these varied with time over a long period was not possible because of continual, partial cloud cover that make the establishment of a sufficiently large number of absolute areal values impossible.

The upwelled water present on 30 March extended from Cape Padrone to a point just south of Port St. Johns. A further estimate of the lateral dimensions of the upwelling was obtained from 8 upwelling events evident in the satellite imagery for the year 1991. These events were judged to be independent on the basis of an absence of upwelled water at the sea surface both before and after each event. The most developed stage for each event was selected for measurements (Table 2). Although the widest extent of the upwelling wedge was observed to change from 15 to 45 km, the most striking variability lies in the full alongstream distance that can vary from 85 to 300 km.

If the surface expression of this upwelling is so intermittent (viz., Figs. 3(b) and 6), whereas the average temperatures at depth (Fig. 4) point to a more persistent, subsurface, cold feature, identifying the source of this water would be of substantial
importance. This could be achieved by investigating the hydrographic, and in particular the temperature–salinity, characteristics of the water involved.

3.4. Hydrographic characteristics

The geographic distribution of available oceanographic stations inshore of the Agulhas Current is by no means optimal for this type of analysis (Fig. 8(a)). The majority are bottle stations and few lie close inshore. The T/S scattergram for these stations (Fig. 8(b)) shows the characteristic values for South West Indian Deep Water, as well as South West Indian Central Water (cf. Wyrtki, 1971; Lutjeharms, 1991). For temperatures in excess of 12°C, i.e. from about the mid-depth of the Central Water, there is increasing scatter in the T/S plot, but with some tell-tale weighting for certain loci. The most saline locus exhibits a salinity maximum of about 35.6 at about 17.5°C. This is South West Indian Subtropical Surface Water and is found in the centre of the Agulhas Current (Swart and Largier, 1987). The less saline locus is South Indian Tropical Surface Water with temperatures of up to 26°C. This water is found preferentially in the inshore core of the Agulhas Current (Gordon et al., 1987; Beal and Bryden, 1999).

The water on the shelf inshore of the Agulhas Current is characterised by a mixture of surface water of about 22°C and South West Indian Central Water between 14 and 12°C. These temperature ranges are also characteristic of the general shelf region upstream of the Agulhas Bank (Fig. 8; Beckley and Van Ballegooyen, 1992), even as far upstream as the Natal Bight north of Durban (Lutjeharms et al., 1999). The region between Port Elizabeth and Port St. Johns therefore is no exception in this respect. It would be instructive to investigate if there are any substantial differences in T/S characteristics for specific parts of the shelf. The data numbers (viz., Fig. 8) are unfortunately insufficient to do this with any degree of reliability.

Nonetheless, T/S scattergrams for two station lines across the shelf from Port Alfred are useful (Fig. 9) to demonstrate the differences in the T/S characteristics of the water column during an outcropping event and during a period when the water on the shelf was well-stratified (Beckley and Van Ballegooyen, 1992). A period of several days elapsed between occupation of the innermost and the outermost stations; this line is therefore not synoptic. In May/June 1990 upwelled water colder than 17°C was observed below 100 m (Fig. 9(a)). This was shallower than anywhere else upstream at

### Table 2
Representative dimensions (km) of the upwelling cell of the eastern Agulhas Bank during 1991

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<thead>
<tr>
<th>Dimension</th>
<th>Mean</th>
<th>S.D.</th>
<th>Max</th>
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<tr>
<td>Width at widest extent</td>
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<td>15</td>
</tr>
<tr>
<td>Width at narrowest extent</td>
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<tr>
<td>Length</td>
<td>179</td>
<td>77</td>
<td>300</td>
<td>85</td>
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the time. Most of the water over the shelf had temperatures greater than 20°C. By way of contrast, in October 1990 the greater part of the shelf was covered with water colder than 17°C. Water warmer than 20°C was found overlying only the start of the shelf break in October. This shown temperature change is not due to a seasonal effect. The seasonal pattern for the water column structure over the Agulhas Bank consists of very strong vertical stratification in summer and total vertical homogeneity to a depth of at least 75 m due to mixing by the end of winter, i.e. by September/October (Lutjeharms et al., 1996). The situation at Port Alfred, with the coldest bottom water during October 1990 (Fig. 9(b)), is therefore anomalous and suggests that this represents an upwelling event and not the normal seasonal cycle on the Agulhas Bank. This non-seasonal upwelling situation is also clearly apparent in the T/S scattergrams (Fig. 9, lower panels).

During a situation where the upwelling had not outcropped (Fig. 9(a), May/June 1990) the seaward stations in the Agulhas Current proper (dots) clearly show the South Indian Tropical Surface Water with temperatures in excess of 22°C as well as the salinity minimum at about 17.5°C representing South West Indian Subtropical Surface Water. Shelf waters (circles, Fig. 9(a)) cover more or less the same temperature range but characteristically have a much narrower salinity range, indicating the greater degree of mixing on the shallow shelf. In the case where upwelling had outcropped (Fig. 9(b)), waters offshore were much the same, whereas water on the shelf was colder by at least 9°C with a salinity reduced by 0.2. Although some water still fell
Fig. 9. Two hydrographic sections, across the continental shelf at Port Alfred (upper panels), showing temperatures during May/June 1990 (a) and during October 1990 (b) (after Beckley and Van Ballegooyen, 1992). The temperature/salinity scattergrams for each section is given in the lower panels; circles representing the two inshore stations, dots the seaward stations.

In the salinity range 35.3–35.4, the greatest volume lay between 35.0 and 35.2. This water clearly has its origin in the central part of the South West Indian Central Water (Swart and Largier, 1987).

This difference between upwelled and non-upwelled shelf water is even more pronounced between two adjacent stations carried out in this region during the Combined Agulhas Cruise of March, 1969 (Bang and Pearse, 1970). One station was off Port Alfred in the core of the outcropping of upwelled water (station 204, Fig. 10); the other 130 km westwards on the Agulhas Bank opposite Algoa Bay (station 203) two days previously. The T/S curves for these two stations show the temperatures at
station 203 extending from 20.34°C at the sea surface to 12.16°C at 70 m depth. In contrast, the highest temperature in the upwelling cell was 14.86°C, the lowest 12.29 at 50 m depth. Except near the sea floor, salinities at station 203 all exceeded 35.20. In the upwelling cell all salinities were 35.00 and lower.

Averaged temperatures in the inshore upwelling zone off Port Alfred (Fig. 4) lie between 14°C and 17°C at 80 m depth. From the T/S scattergram for shelf waters of the region (Fig. 8(b)) one may therefore infer that this water is from the core of the South West Indian Central Water. This T/S scattergram is consistent with a concept of waters with salinity of 35.2 and temperature of 13°C, from this Central Water, being upwelled and their temperatures subsequently increased by heating to at least 22°C. Atmosphere-to-ocean heat fluxes in this region are sufficient to bring about this degree of heating (Rouault et al., 1999). The few surface salinity measurements in the vicinity of Port Alfred (not shown here) have a relatively low mean salinity of 35.3, lower than that of the adjacent surface waters of the Agulhas Current. Water with a temperature of 13°C and a salinity of 35.2 is found at a depth of about 600 m in the central part of the South West Indian Ocean gyre, i.e. seaward of the Agulhas Current.

Water upwelled from this depth should have a substantially higher nutrient content than that usually found on the shelf. To investigate this, three sets of data that include measurements of dissolved nutrients are shown in Fig. 11. They have been selected, as far as the data base allows, to represent different parts of the shelf. The stations off Port Alfred lay, unfortunately, slightly too far downstream to be in the core of the upwelling cell. Those just downstream of East London were at the periphery of the upwelling (viz., Figs. 3 and 4), whereas those further north-east were even more so. All three sets (Fig. 11(b)) exhibit very similar T/S characteristics. The stations off Port
Alfred in general have lower temperatures and lower salinities, suggesting the presence of upwelled water. The presence of upwelled water is even more conspicuous in the T/nutrient relations.

Both the silicate and the nitrate values (Fig. 11(c) and (d)) for the region off Port Alfred show the widest range of values for these nutrients and by far the largest number of high readings. This clearly supports the contention that upwelling at the far eastern Agulhas Bank contributes a high nutrient load to this part of the shelf. The degree of upwelling of this water inshore of the Agulhas Current may perhaps be identified most clearly by some additional synoptic sections across the region of interest.

3.5. Hydrographic sections

The coastal parts of hydrographic sections undertaken perpendicular to the coastline at Port Alfred during 1990 and 1992 are shown in Figs. 12 and 13. Station spacing varied, but all stations extended to within 10 m of the ocean floor. It is difficult reliably
Fig. 12. Hydrographic sections across the continental shelf in the vicinity of Port Alfred showing isotherms to the bottom, for four occasions in the period 1990 to 1992. Different bathymetries are due to slightly different locations or angles to the coast.
Fig. 13. A line of hydrographic stations undertaken during the outcropping of upwelling in January 1992. The upper panel shows the geographic location of the stations near Mbashe on the southeast coast of South Africa (a). Temperatures are given in (b), salinities in (c) and nitrates in (d).
to establish how representative these sections are since very few such sections have been carried out in this region.

In September 1990, in austral spring, temperatures of surface waters over the greater part of the shelf region were below 17°C, indicative of the presence of upwelled water (Fig. 12). Water with temperatures below 12°C had moved up the continental slope and formed the bottom water over the seaward side of the shelf. Over the greater part of the shelf a weak thermocline was present. In July 1991, the following austral winter, water over the continental slope had a temperature of 22°C, about 4°C warmer than the preceding spring. Bottom water on the shelf was 14–15°C. Over the shelf edge a considerably more intense thermocline was, in consequence, present. Water colder than 17°C was observed at the sea surface only in a zone 20 km wide next to the coast. The vertically homogeneous nature of the water column here is most probably due to wind-induced mixing in the austral winter, but the low temperatures indicate an upwelling origin of this water. In contrast, in January 1992 (Fig. 12) there was a well-developed thermocline over the full width of the shelf with uniform temperatures exceeding 23°C for surface waters up to the shelf edge. Bottom water with temperatures of less than 10°C on the central part of the shelf might possibly have been a remnant of a previous strong upwelling event at the shelf edge. In April 1992 (Fig. 12) the seasonal thermocline was even better developed with cold, upwelled water of less than 15°C forming the bottom layers.

The section portrayed in Fig. 13 shows warm (>22°C) South Indian Tropical Water of the Agulhas Current extending over the adjacent continental shelf only up to the 150 m isobath. The tell-tale higher salinities (>35.40) offshore, in the core of the Agulhas Current, clearly delineate the presence of South West Indian Subtropical Surface Water. Although there was a weak thermocline over the shelf, all waters had temperatures below 19°C and salinities below 35.30. Upwelling along the shelf slope had brought water colder than 10°C to a depth of about 100 m. This water had a salinity of about 34.70 and a dissolved nitrate content greater than 20 mg at m⁻³. As a result, water over the bottom of the shelf had a temperature of 12°C, salinity of 35.00 and a nitrate content of 10 mg at m⁻³. This section demonstrates the role of upwelling along the slope edge in feeding cold, nutrient-rich water onto the shelf, priming it for outcropping at the sea surface under the appropriate wind conditions. Such an outcropping event occurred in October of the same year (Fig. 14).

Surface waters over the shelf on this occasion were consistently cooler than 17°C (Fig. 14(b)). There was no thermocline and most waters had salinities below 35.30. Surface nitrate values were all above 8.0 mg at m⁻³, but below 50 m depth they were even above 10 mg at m⁻³. This section was situated in what may be considered the core of this upwelling cell (Fig. 14(a)). The manner in which winter wind mixing over the shelf creates a uniform cold, fresher and nutrient-rich water layer at the sea surface is self-evident. Based on this, and the other hydrographic sections and data, a few specific conclusions can be made about the geography and the forcing mechanisms of the upwelling cell of the far eastern Agulhas Bank.
Fig. 14. A line of hydrographic stations undertaken during the outcropping of upwelling in October 1992. The geographic location of the stations near Port Alfred on the southeast coast of South Africa is given in (a), temperatures in (b), salinities in (c) and nitrates in (d).
3.6. Mechanisms

It is clear from the currently available data that the upwelling inshore of the Agulhas Current is geographically concentrated off Port Alfred. The data indicate that it is only here that subsurface upwelling at the shelf edge is substantial and frequent. There is no evidence that this upwelling is in response to the possible downstream intensification of the Agulhas Current. Such a process would bring about a uniform increase in the inshore upwelling along the current’s full length, something that has not been observed.

There is also the possibility that the upwelling is largely wind-driven. The geographically limited domain of the upwelling mitigates against this, as does the subsurface character of the upwelling. If the shoreward movement in the bottom Ekman layer (Schumann, 1986) were the prime source of water to the upwelling cell, it would most likely be relatively invariant. The large and intermittent temperature variations at the sea surface would then be due to the outcropping of already upwelled water at irregular intervals, probably brought about by wind action. An analysis of wind data for this region (Schumann, 1989; Schumann and Martin, 1991) has demonstrated that the principle directional axes of the coastal wind field at Port Elizabeth are parallel to the coastline. This suggests (Schumann et al., 1988) that the dominant winds from the north-east would, by Ekman drift, remove the surface layer over the upwelling cell at Port Alfred seawards and thus expose the shelf-edge upwelled water. The dominant south-westerly wind would theoretically tend to do the opposite. This process has in fact been observed in some preliminary observations (Rouault et al., 1995). The local wind action might thus serve to bring water already upwelled at depth to the sea surface, but would not be the primary cause for this very localised upwelling process itself.

It may therefore be concluded that this intense and persistent upwelling is located only where the shelf width increases along the Agulhas Current’s path. This is consistent with the mechanism put forward by Gill and Schumann (1979). Cold, dense, South West Indian Central Water that is moved onto the bottom of the shelf at Port Alfred as part of this process, could subsequently cover extensive parts of the Agulhas Bank and contribute substantially to its vertical stratification. Furthermore, higher concentrations of nutrients brought to the surface here and retained when the water is heated while in contact with the atmosphere, would contribute to higher levels of biological primary productivity. There are suggestions of such enhancement in pigment concentrations in this upwelling cell, measured by the coastal zone colour scanner of the NIMBUS-7 satellite. Furthermore, there are indications of increased biological activity here at higher trophic levels as well (e.g. Beckley and Van Ballegooyen, 1992). It has in fact been shown that the distribution of zooplankton and even certain fish species (e.g. horse mackerel) are closely correlated to the disposition of temperatures of water masses in this region (Barange, 1994).

4. Conclusions

Hydrographic sections demonstrate that some upwelling occurs at the continental slope along the full length of the Agulhas Current. Hydrographic data for this whole
region show, however, that water temperatures over the shelf are by far the lowest downstream of Mbashe, at the eastern limit of the Agulhas Bank. A clearly circumscribed upwelling cell is centred here at Port Alfred. Fed by water upwelled from Central Water depths it is detectable at the sea surface only on an intermittent basis.

This surface expression is evident about 45% of the time at Port Alfred itself, but less frequently further north. At Port St. Johns it is seen only about 5% of the time. During a fully developed outcropping event the surface waters in the upwelling cell may be at least 5°C colder than the adjacent shelf water over the Agulhas Bank. Comparisons between the temperature/salinity characteristics of water in the upwelling cell show it to be very similar to that of the rest of the Agulhas Bank, consisting of South West Indian Central Water mixed at the surface with South Indian Tropical Surface and South West Indian Subtropical Surface Water. Both these latter two water masses are most probably derived from the surface layers of the adjacent Agulhas Current. The South West Indian Central Water is upwelled from depths exceeding 500 m. Average vertical stratification off Port Alfred follows the seasonal pattern of the greater Agulhas Bank, but may be interrupted at irregular intervals by the outcropping of upwelling water that destroys the stratification.

The extreme temperature contrasts at the sea surface between the upwelling cell and the adjacent Agulhas Current make this region an ideal natural laboratory for studying air–sea interaction. These aspects have recently been investigated as part of a dedicated research cruise (Rouault et al., 1995). Since the ocean temperatures along the eastern seaboard of South Africa have been implicated in rainfall along this coastline (Jury et al., 1993), and since the vegetation index shows the highest variability for the whole of southern Africa directly inshore of this particular upwelling cell (Rouault et al., 1995), a more rigorous understanding of this peculiar upwelling process is clearly required. A detailed investigation on the relationship of the wind forcing to the outcropping process is called for.

Results from either analytical or numerical models, with realistic forcing, could help in reducing the choice of the possible forcing processes for this upwelling. However, true quantitative tests of the most applicable upwelling theory will be possible only when considerably better data are available.

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