Continental Shelf Research, Vol. 9, No. 7, pp. 597–616, 1989.
Printed in Great Britain.
0278–4343/89 $3.00 + 0.00

Eddies and other boundary phenomena of the Agulhas Current

J. R. E. LUTJEHARMS,* R. CATZEL† and H. R. VALENTINE*

(*Received* 11 *August* 1988; *in revised form* 19 *January* 1989; *accepted* 27 *February* 1989)

Abstract—Shear-edge features of the Agulhas Current include meanders, plumes and eddies. A descriptive study of these phenomena based on 10 years of satellite imagery and two directed research cruises in the area is presented. It is demonstrated that the mean location of the landward boundary of the Agulhas Current becomes more diffuse downstream and that its modal location relative to the 200 m isobath depends on distance downstream. Border perturbations are discernible at least 65% of the time. Amplitudes of current meanders grow downstream, as do all dimensions of border plumes and eddies associated with them. The phase speed of these meanders is 21 km day^{-1}. Border eddies adjacent to the shelf are clustered in two preferred areas. Penetration of warm water associated with border phenomena onto the Agulhas Bank increases downstream. All these border features may extend throughout the water column of the shelf.

INTRODUCTION

THE borders of the Agulhas Current are characterized by a number of mesoscale circulation phenomena due, for the greater part, to the horizontal shear between the current and the relatively quiescent water overlying the adjacent continental shelf (BANG, 1972; LUTJEHARMS, 1981; GOSCHEN and SCHUMANN, 1988). These features in many ways resemble those found on similar western boundary currents, such as the Gulf Stream.

Meanders on the Gulf Stream have been shown by MAUL *et al.* (1978) to be prevalent along the full length of the current but to differ in their amplitudes from one geographic area to another. The largest amplitudes were associated with the Gulf Loop Current. Using a five-year record of Gulf Stream border positions derived from satellite imagery, OLSON *et al.* (1983) have found a steady increase in the variance of border location on distance downstream from Florida. Topography of the shelf edge, in particular the Charleston Bump, was shown to increase downstream current meandering substantially. VAZQUEZ and WATTS (1985) have shown that meanders with periods of 33–50 days are the most energetic. The phase speed for these meanders decreases downstream while they show a measurable growth rate in the same direction (WATTS and JOHNS, 1982).

Eddies are often associated with meanders on the north wall of the Gulf Stream (VUKOVICH and CRISSMAN, 1980). LEE *et al.* (1981) have defined these frontal eddies as cyclonic, cold-core eddies based on their flow and water mass properties. These eddies have also been called "spin-off" eddies and shown to be underpinned by an upwelling of cold water (CHEW, 1981). Eddies are usually made visible in sea surface temperature

* National Research Institute for Oceanology, CSIR, P.O. Box 320, Stellenbosch 7600, South Africa.
† Department of Oceanography, University of Cape Town, Private Bag, Rondebosch 7700, South Africa.

distributions by attendant warm filaments or "shingles". Such eddies, induced by the upwelling, bring about a subsurface exchange of shelf and slope water (CHURCHILL *et al.*, 1986).

In some respects the known behaviour of border phenomena of the Agulhas Current is markedly different. All along the east coast of Southern Africa the northern Agulhas Current follows the continental shelf edge quite closely with no perceptible regular meandering (GRÜNDLINGH, 1983) or large border eddies. There are two exceptions to this strong lateral path stability. At irregular intervals an extreme transient disturbance or solitary meander, called the Natal Pulse, moves down the Agulhas Current forcing it far offshore (LUTJEHARMS and ROBERTS, 1988). The other exception is the circulation which occurs in the coastal offset called the Natal Bight, between 29° and 30°S where the distance between current and coastline is considerably greater and seemingly sufficient for shear-edge eddies to develop (MALAN and SCHUMANN, 1979). Only as the Agulhas Current flows past Port Elizabeth and encounters the wide expanse of continental shelf south of Africa called the Agulhas Bank (Fig. 1) is significant meandering behaviour, similar to that of the Gulf Stream, observed routinely (LUTJEHARMS, 1981; SCHUMANN and VAN HEERDEN, 1988). It would seem that the differences in topography of the shelves past which the Gulf Stream and Agulhas Current flow are responsible for the differences in border behaviour. Contrary to observations in the Gulf Stream system, no shear-edge eddies have as yet been observed to spin off and to separate completely from the Agulhas Current. In all cases eddies remained adjacent to and tied to the boundary of the Agulhas Current.

EAGLE and ORREN (1985) have reported on the only regularly occupied line of hydrographic stations stretching across part of the Agulhas Bank. Their record, which spans a number of years, has led them to the remarkable conclusion that bottom flow of cold water onto the Agulhas Bank is mostly a seasonal phenomenon. If, as has been assumed for both the Gulf Stream and the Agulhas Current, onflow of bottom water is to a large extent a function of upwelling in the core of shear-driven edge eddies, this result would imply that the prevalence or intensity of these eddies would be seasonal. If, on the other hand, upwelling is due to Ekman veering in the bottom boundary layers of the current along the shelf edge (HSUEH and O'BRIEN, 1971) this would imply seasonal changes in the current. No strong seasonal behaviour has, however, been observed in the flow behaviour of the Agulhas Current (GRÜNDLINGH and PEARCE, 1982).

Stimulated by these results of EAGLE and ORREN (1985), SWART and LARGIER (1987) have suggested that it is the cyclonic frontal eddies which are responsible for forcing both warm Subtropical Surface Water and cold, less saline Indian Ocean Central Water onto the continental shelf of the Agulhas Bank. They state that it is the advectively induced vertical juxtaposition of these water masses which establishes the remarkably intense thermocline over the greater part of the shelf. This hypothesis of a predominantly advectively (LARGIER and SWART, 1987) driven thermocline has not yet been proven conclusively. WALKER (1986) has, for instance, described extensive upwelling over the middle of the Agulhas Bank, while LARGIER and SWART (1987) themselves have drawn attention to a relatively persistent band of upwelling bordering the zone where shear-edge phenomena are most prevalent. SCHUMANN *et al.* (1982) have furthermore shown that extensive upwelling occurs at times along the headlands of the adjacent south coast. All these upwelling phenomena would counteract the influence of warm water advected along the surface. Because the thermocline on the Agulhas Bank plays a crucial role in

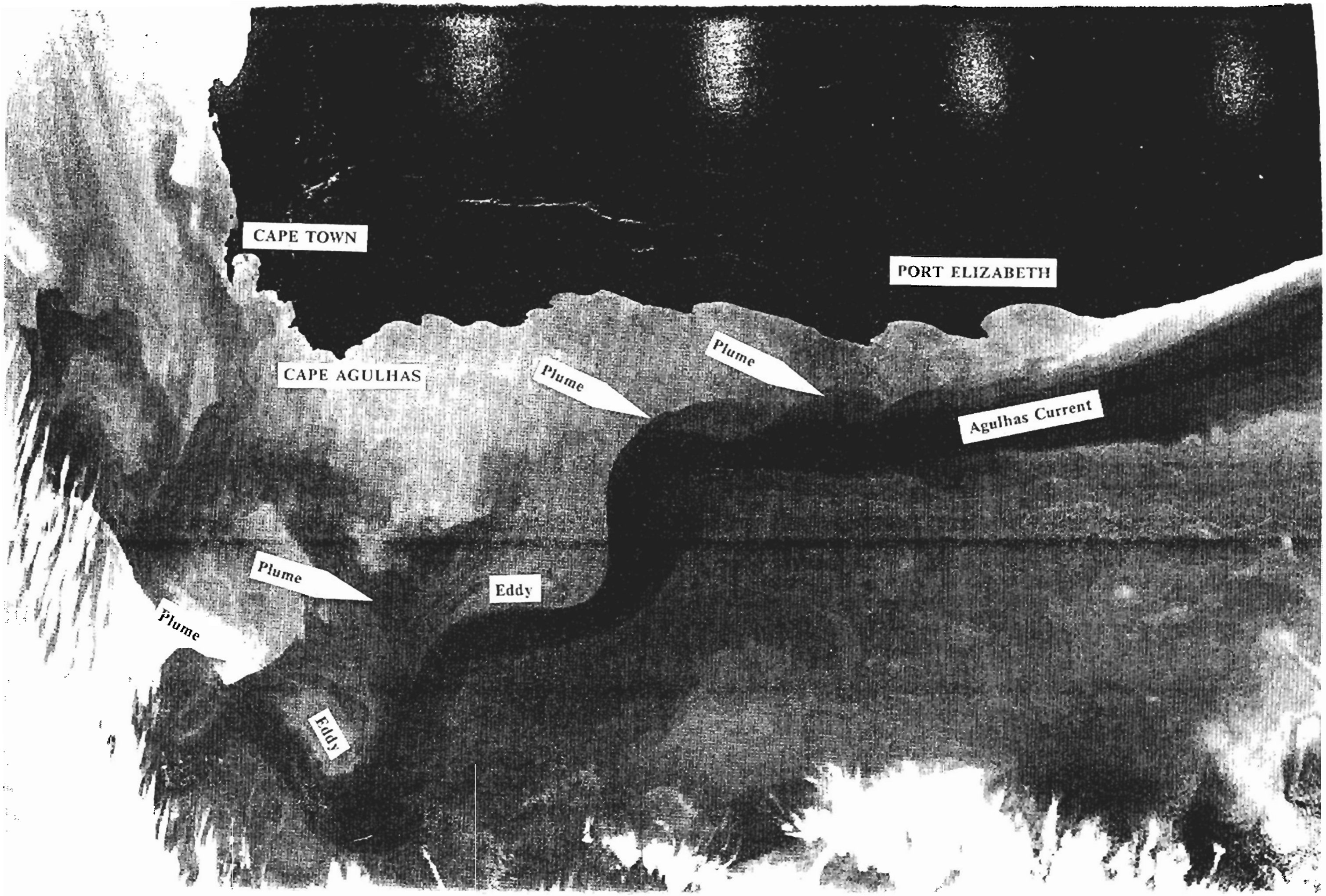

Fig. 1. A characteristic and representative portrayal of the surface expression of the southern Agulhas Current and border phenomena. It is a thermal infra-red satellite image for 16 August 1985 from the AVHRR (Advanced Very High Resolution Radiometer) on board NOAA 9. Dark hues indicate warmer water. Particularly evident are meanders on the current, shear edge plumes and filaments drifting into the southeast Atlantic Ocean.

the vertical distribution of phytoplankton (Carter *et al.*, 1987) and because the Agulhas Bank is the recognized main spawning area for anchovy, the main pelagic fisheries stock of the area, understanding the factors which maintain the thermocline here is of considerable interest.

It is, therefore, important to establish the prevalence, preferred geographic location and nature of all border phenomena of the Agulhas Current, particularly along the edge of the Agulhas Bank.

DATA AND METHODS

Two sources of data were used for this study. Two cruises specifically planned to study the thermal structure of the water masses overlying the Agulhas Bank as synoptically as possible were carried out in the autumn and spring of 1968 (Lutjeharms *et al.*, 1981; Lutjeharms and Valentine, 1983). The data from these cruises form the first data source. In the first of these cruises, from 20 to 27 March 1968, seven cruise lines extending from the coast across the Agulhas Bank and the Agulhas Current and spaced about 80 km apart were carried out (Fig. 2). Temperature readings with an accurately calibrated mechanical bathythermograph (BT) were obtained at close spatial intervals. Experience before and after this cruise has shown that the thermal signature by itself is highly representative of the nature of the density structure in these water masses and sufficient to establish the nature of shear-edge border phenomena in the area. The second cruise was carried out between 3 and 12 September 1968 and consisted of 150 BT dips, again along seven cruise lines (Fig. 3).

The second data source consists of a collection of thermal infra-red satellite images for the area built up since 1978. For the purpose of this study 1928 images from the METEOSAT satellite series were used for statistical analyses because a useful sequence of daily images were received while the satellites were operational (Catzel and Lutjeharms, 1987). METEOSAT I was active in 1978 and 1979 while METEOSAT II came on stream in 1982 and is still operational. The METEOSATs are geostationary satellites placed over the crossing of the Greenwich meridian and the equator. Their radiometers measure in the range 10.5–12.5 μm. The resolution achieved at the sub-satellite point, or nadir, is a nominal 5 × 5 km. With increased distance to the area south of Africa this resolution is decreased. These data were suitably contrast-enhanced in the appropriate oceanic radiance range observed in the area. No atmospheric corrections or calibration was undertaken. Once again, experience has shown (J. Agenbag, personal communication) that the horizontal thermal gradients at the border of the Agulhas Current are so strong that any of the usual, atmospheric corrections to the data do not materially influence the geographic location of the fronts. Nevertheless, it should be noted that temperatures are not absolute. No accurate satellite navigation or geographic correction was carried out. The South African south coast was used as a base line throughout and all distance measurements normalized to it. It is estimated that location errors of no more than 15 km might result.

Detail of the surface expression of border features was studied, where possible, using a collection of 769 images from the NOAA orbiting satellite series. Images from NOAA 5 to 9 were available, spaced at irregular time intervals. These satellite products have a sub-satellite track resolution of 900 × 900 m which facilitates the identification of much smaller phenomena than is possible from METEOSAT images. The Advanced Very

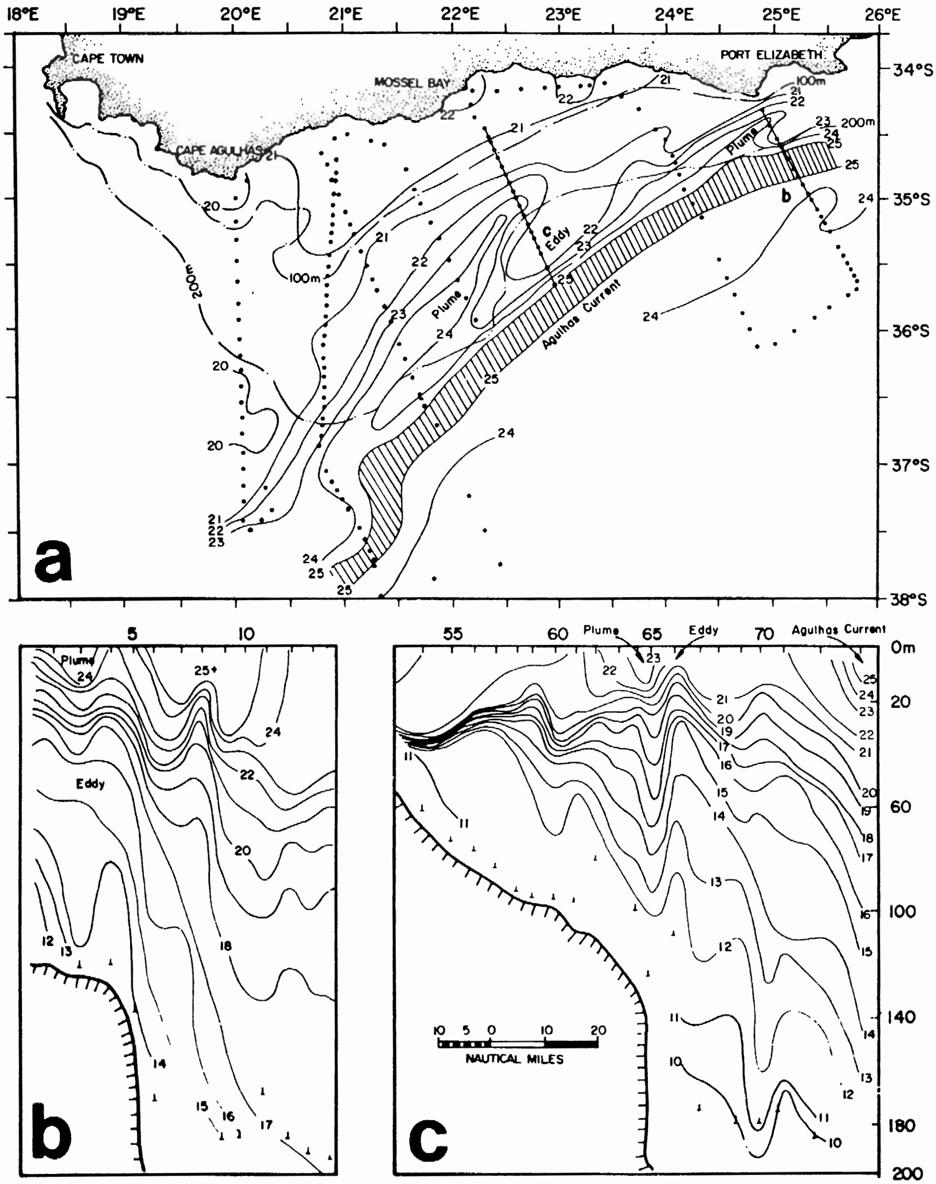

Fig. 2. (a) Distribution of temperature at 10 m over the Agulhas Bank in March 1968. Lines of dots indicate positions of bathythermograph dips along cruise tracks. Broken lines are for the 100 and 200 m isobaths. The core of the Agulhas Current is shaded. The location of the two sections portrayed in (b) and (c) is shown. (b) Temperature section across a border eddy southeast of Port Elizabeth. Little anchors here and elsewhere show the maximum depth to which measurements were made. (c) Temperature section across a border eddy south of Mossel Bay.

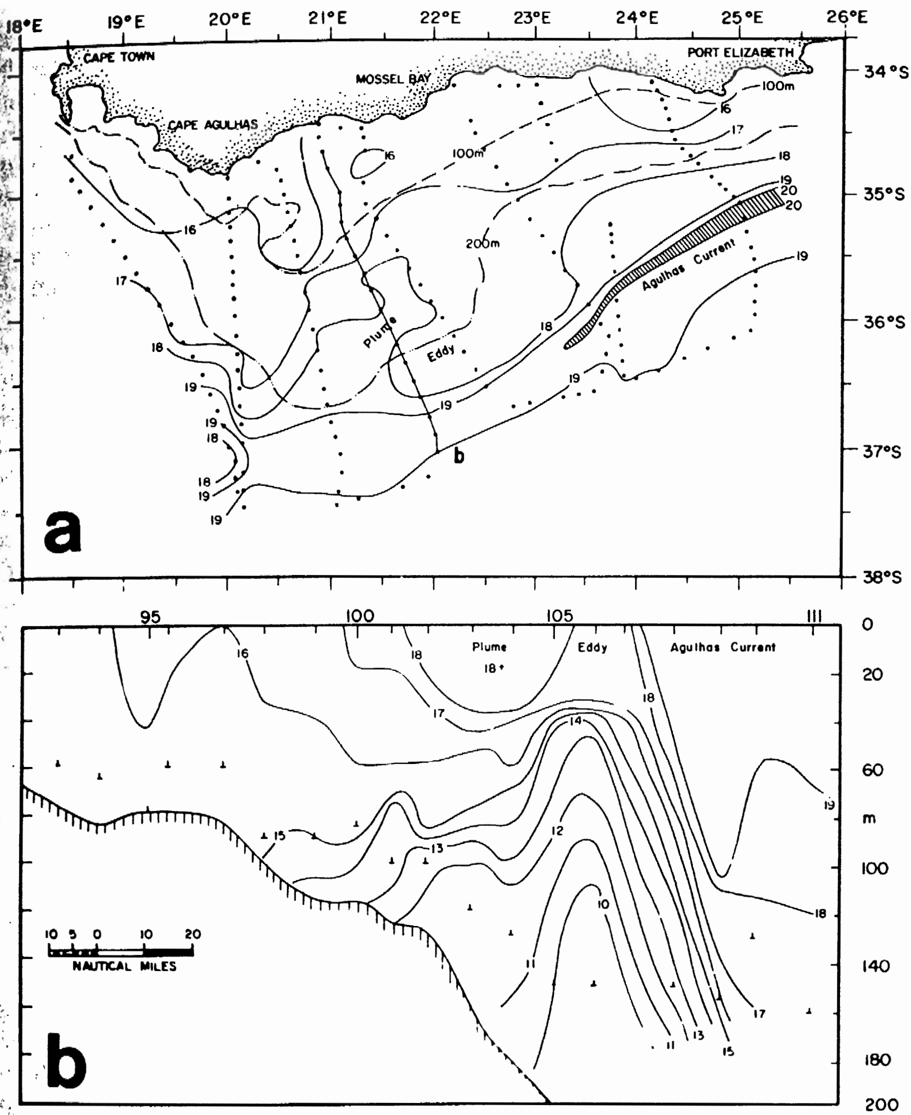

Fig. 3. (a) Distribution of temperature at the sea surface over the Agulhas Bank in September 1968. Otherwise as in Fig. 2a. (b) Temperature section across a border eddy south of Mossel Bay.

High Resolution Radiometer (AVHRR) of this satellite series measures in the 10.5–11.5 μm range. These images were also contrast-enhanced, but not atmospherically corrected or calibrated, with the same justification as stated above.

THERMAL STRUCTURE

The NOAA 9 image presented in Fig. 1 clearly portrays the main current and border features being discussed here. First, it may be noted that upstream of Port Elizabeth the Agulhas Current did not meander noticeably and no border features to speak of were evident. Downstream of Port Elizabeth meanders on the current border increased in amplitude in the downstream direction culminating in amplitudes of roughly about 200 km. A trailing plume of warm water was associated with each shoreward meander of the current. Those plumes associated with meanders just past the southern tip of the Agulhas Bank (see Fig. 2) drifted off in a northwesterly direction into the southeast Atlantic Ocean as warm Agulhas filaments (Catzel and Lutjeharms, 1987; Lutjeharms and Stockton, 1987). At least one such warm filament was being advected onto the Agulhas Bank. This contrasting drift behaviour for warm filaments for the eastern and western parts of the shelf regime of the Agulhas Bank are supported by the findings of Shannon and Chapman (1983) based on the use of plastic drift cards. In the centre of the Agulhas Bank an extensive area of cold water (Fig. 1) is strongly suggestive of the type of upwelling first described by Walker (1986). Some plumes showed inward curvature, suggesting cyclonic border eddies in the lee of meanders; others trailed straight behind. This image gives a reasonably representative portrayal of the general disposition of features which may be present in this ocean area at any particular time.

It is important to attempt to establish the vertical extent of the features observed here. It has, for instance, been shown that the surface expression of the larger features such as the Agulhas Current and Agulhas Rings are representative of the flow of at least the upper hundreds of meters (Lutjeharms and Gordon, 1987). Other features visible at the sea surface, particularly less extensive ones, have, however, been found to be shallow. Swart and Largier (1987) have presented a temperature section on a cruise line which intersected a warm shear-edge plume. Although quite distinct at the sea surface, it did not extend deeper than 50 m.

The results of the two dedicated cruises address this question. In Fig. 2a the distribution of temperature at 10 m depth is presented. Water warmer than 25°C was considered to represent Agulhas Current core water and has been so indicated. The Agulhas Current did not on this occasion follow the shelf break closely. South of Mossel Bay and southeast of Port Elizabeth warm plumes occurred, the former being much more extensive. The temperature section across the plume off Port Elizabeth (Fig. 2b) clearly shows a small border eddy with a diameter of about 10 nmi just north of the warm surface water representing the Agulhas Current. It is assumed, on the basis of Fig. 2a, that the dimensions of this feature are about the same perpendicular to the section as along it. The warm plume can clearly be seen between Stas 1 and 3. Both features find expression throughout the whole water column to a depth of 120 m, although with decreasing amplitude with depth. The core of the Agulhas Current lay between Stas 5 and 10 (Fig. 2b), best represented here by the slope of the 17°C isotherm. A small perturbation in the middle of the current is unexplained but, based on data from one station only, may have been due to a faulty reading.

The section across what could be considered the core of the border eddy is in Fig. 2c. It has the most closely spaced stations (Fig. 2a) and extends to the edge of the Agulhas Current. The extreme thermocline at Sta. 54 is noticeable, where a gradient of 10°C 10 m^{-1} was observed. The plume of warm water is located at Sta. 65 and was noticeable to the full depth measured, namely 125 m on this station. The warm surface water of the Agulhas Current proper lay seaward of Sta. 71. The depths of the isotherms are ambiguous as far as a cyclonic border eddy is concerned (Stas 65–71). Between the warm plume and the Agulhas Current, isotherms, such as the 17°C isotherm, do shoal but in a very unsymmetric fashion with most of the shoaling occurring just seaward of the warm plume (between Stas 65 and 67). On this occasion the warm plumes associated with shear-edge features were thus quite distinct at the sea surface and extended the full depth of the water column. The border eddies associated with each plume were small, but their effect was also felt to the sea bottom.

The repeat cruise in the spring (Fig. 3a) found temperatures about 5°C lower at the sea surface over most of the area and with much weaker sea surface temperature gradients (cf. Fig. 2a). At the sea surface there was indication of a large plume, but not very distinct. The subsurface information of those sections not shown here (CATZEL and LUTJEHARMS, 1987) indicated weak, but identifiable border eddies north of the landward border of the current. The strongest evidence for a well-developed border eddy was found along the fifth section from the east and is portrayed in Fig. 3b as well as in Fig. 4. The vague plume seen at the sea surface (Fig. 3a) is represented here by 18°C water. Between it and the Agulhas Current, here identified by strong downward slopes in all isotherms, the border eddy is noted by the upwelling of 10°C water to nearly 100 m depth. The only place where water this cold was measured during this cruise was in this particular border eddy. Clearly it extended to the full depth measured here and even to 180 m in other sections not shown. The surface plume, on the other hand, had an extremely weak signature below 40 m (Fig. 4).

These two cruises demonstrate that the border features of the southern Agulhas Current along the Agulhas Bank are very similar to those found in the Gulf Stream system. This very limited sample would seem to indicate that the border eddies and plumes may extend through the full depth of the water column over the shelf, but that in the case of plumes the surface expression might attenuate rapidly with depth. The fact that upwelling takes place within these border eddies (GOSCHEN and SCHUMANN, 1988), i.e. that they are not in geostrophic balance but that deeper water is drawn upwards in

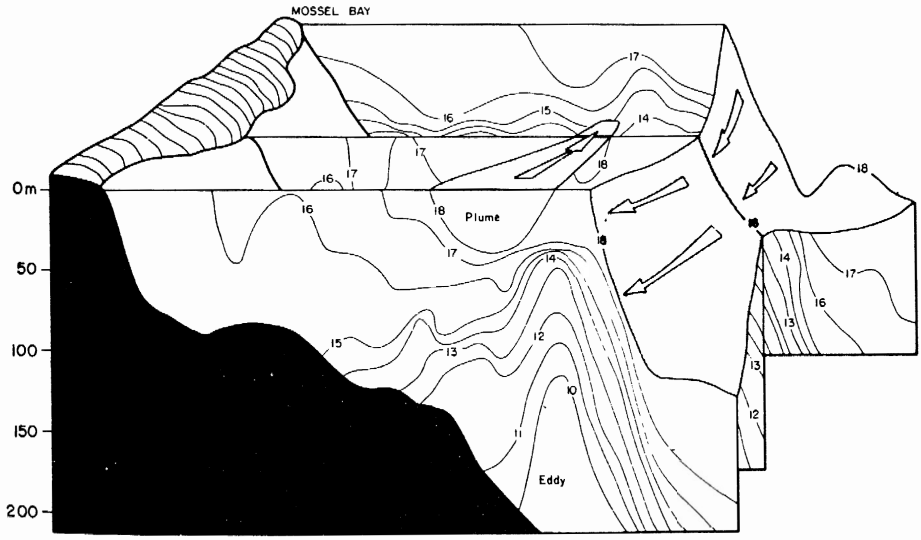

Fig. 4. Disposition of the Agulhas Current, a border eddy and associated plume for the cruise portrayed in Fig. 3.The Agulhas Current is defined as lying outside the 18°C thermal envelope. The plume consists of water warmer than 18°C at the sea surface. Upwelling of cold, deep water in the border eddy is evident.

their centres, suggest that they are driven by the transfer of cyclonic vorticity from the adjacent Agulhas Current. This process is similar, albeit on a smaller scale, to that of lee eddies driven by passing currents, such as those observed in the Natal Bight (MALAN and SCHUMANN, 1979) and the Delagoa Bight (LUTJEHARMS and JORGE DA SILVA, 1988).

PREVALENCE

In Fig. 2a it was noted that the Agulhas Current along the Agulhas Bank did not conform on this occasion to its behaviour further upstream, where it closely follows the edge of the continental shelf. To establish the stochastic path location of the landward border of the Agulhas Current its location was noted for every cloud-poor day over a period of 6 years according to the surface expression visible in METEOSAT imagery (Fig. 5). For the purpose of this analysis plumes, eddies and other border phenomena were ignored and only the north wall of the Agulhas Current proper used. Results of analyses for individual years differed slightly (CATZEL and LUTJEHARMS, 1987), particularly on the two sections covering the furthest downstream part of the current. However, differences were not such as to warrant individual attention here.

A few noteworthy features in the distribution presented in Fig. 5 are evident. First, the most favoured location of the current border relative to the shelf edge, as defined by the 200 m isobath, becomes progressively more diffuse on proceeding downstream. Upstream of Port Elizabeth the current border may be found within 20 km of the 200 m isobath 90% of the time. This is reduced to 28% at the southern tip of the Agulhas Bank. Second, a singular preferred location for the current border is found at all places along the eastern edge of the Agulhas Bank. Third, this singular modal position lies at different

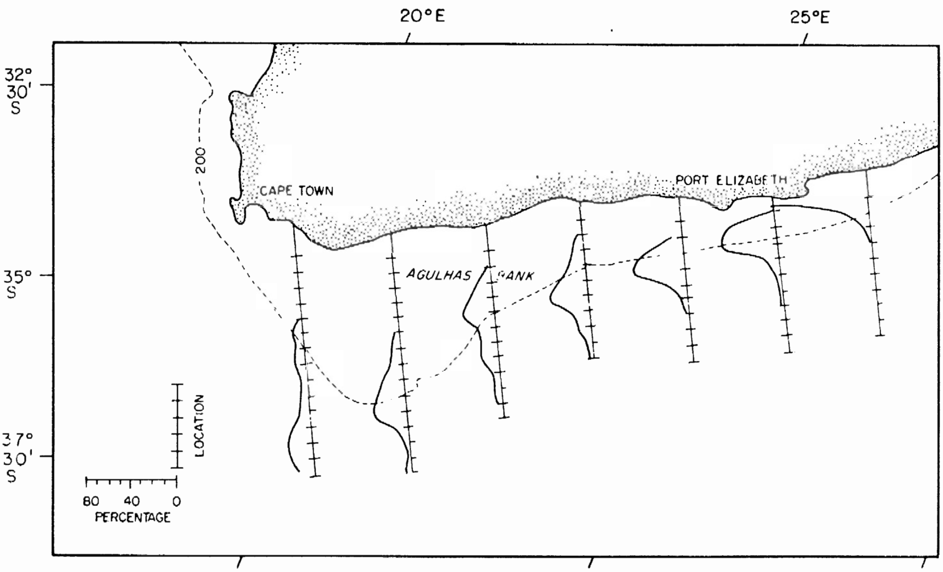

Fig. 5. The percentage location of the northern border of the Agulhas Current for the period 1978–1979 and 1982–1985 in 20 km intervals perpendicular to the coast. The broken line gives the location of the 200 m isobath at the edge of the Agulhas Bank.

positions relative to the 200 m isobath. Upstream of Port Elizabeth it is just inside this isobath, but it shifts progressively further offshore on proceeding downstream. This has also been observed by SCHUMANN and VAN HEERDEN (1988). In the eastern bight of the bank the current edge again lies just inside the 200 m isobath. This pattern is consistent for all individual years analysed (CATZEL and LUTJEHARMS, 1987) and is, therefore, most likely an inherent characteristic of the movement of the Current along the bank.

Having established the average location of the Agulhas Current border it is instructive to determine the prevalence of border features and the number present at any one time. As was clear from an analysis of the results of the two dedicated cruises, surface expressions of plumes are not necessarily strongly related to the intensity of border eddies. Nevertheless the occurrence frequency presented in Fig. 6 indicates that for the years 1984 and 1985 a total absence of any visible shear-edge plumes occurred during only 31% of this period. Shear-edge plumes were considered the most visible expression of the existence of border disturbances and were selected for that reason. The presence of at least one feature was established for 65% of the time, two or more for 36% and more than two features for 17% of the time. Cloud cover partially obstructed a proportion of the images used. The percentages for each category, therefore, are probably underestimates. No data was received, or total cloud cover occurred on only 4% of the days of

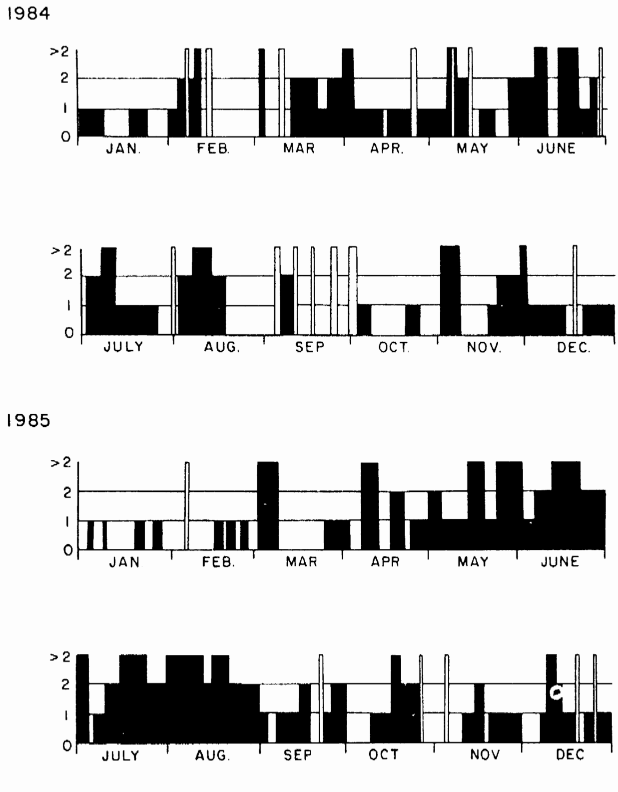

Fig. 6. Prevalence of shear-edge plumes on the Agulhas Current border for the period 1984–1985 according to satellite infra-red imagery. Filled-in parts of the histogram indicate the number of plumes observed each day. Areas of the histogram left blank denote days of extensive cloud cover or the unavailability of images on the particular days.

these two years. These results establish the high occurrence of multiple border features along the eastern Agulhas Bank. Their role on the Agulhas Bank itself depends on their geographic distribution and their penetration of the Bank waters.

GEOGRAPHIC DISTRIBUTION

A further analysis was carried out to study, first of all, the average location and extent of meanders of the Agulhas Current along the Agulhas Bank. The disposition of every single meander observed for the five full years of METEOSAT data was portrayed in the manner shown in the insert in Fig. 7. Downstream of Port Elizabeth it is very difficult to distinguish between the usual but large meanders which have been generated in the area itself and Natal Pulses (GRÜNDLINGH, 1979) which have been generated upstream (LUTJEHARMS and ROBERTS, 1988). In a few cases where cloud cover was sparse over an extended period the downstream movement of a Natal Pulse could be followed and identified as such on reaching the Agulhas Bank. This was only possible in a small number of cases. Because the effects of Natal Pulses would be indistinguishable from other large meanders along the edge of the Bank no further attempt was made to treat them as a separate category. Their inclusion might, however, have an effect on the estimate of meander growth from Port Elizabeth downstream.

Whenever case studies were made of the downstream progression of meanders, their amplitudes were observed to be relatively small off Port Elizabeth and to grow from there (LUTJEHARMS, 1981; CATZEL and LUTJEHARMS, 1987). Natal Pulses would arrive off Port Elizabeth fully fledged and would thus skew the statistics by implying more large

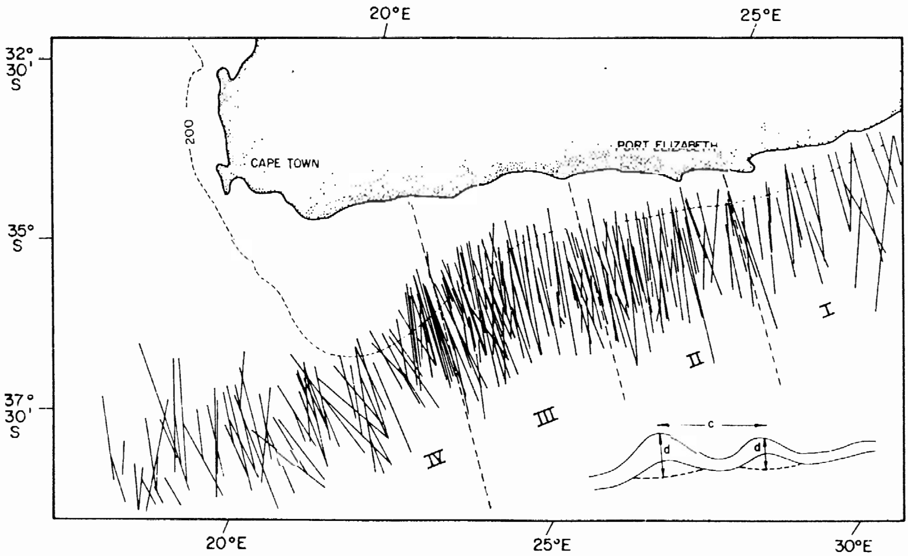

Fig. 7. Distances from crest to trough for all meanders observed along the southern Agulhas Current for the full period under investigation according to infra-red satellite imagery. The lines in the main drawing are a composite of all meander dimensions as illustrated by distance *d* in the insert, the dotted line being an estimate of the instantaneous meander trough. Measured dimensions of *d* and *c* are given in Table 1. The edge of the Agulhas Bank is denoted by the 200 m isobath. Borders of four geographic areas used in Tables 1 and 2 are also shown.

meanders off Port Elizabeth. This seems to be the case in Fig. 7. Splitting up the distance along the bank into four sectors and establishing the average wave amplitudes of Agulhas Current meanders along the Agulhas Bank gave the results shown in Table 1. It is clear that the number of meanders observed in the area between Port Elizabeth and the southern extremity of the Agulhas Bank was highest (Fig. 7, Table 1). Areas upstream and downstream of here were distinctly more sparsely populated. The average amplitude of meanders was about 130 km throughout (with a standard deviation of 37 km).

The geographic distribution of eddies attendant on meanders was established in a similar fashion (see insert in Fig. 8). Establishing the location of each border eddy was to a large degree dependent on the presence of a well-developed plume on each occasion. The results portrayed in Figs 7–9 are therefore not entirely independent. The distribution of border eddies (Fig. 8) has some notable characteristics. Upstream of Port Elizabeth there are hardly any; downstream of the bight in the shelf edge they are geographically widely scattered. Between these two areas eddies seem to be concentrated in two areas, namely in the bight itself and along the rectilinear bit of shelf edge downstream of Port Elizabeth. This geographic pattern is more unambiguous in the distributions for each individual year (CATZEL and LUTJEHARMS, 1987). Perusal of available satellite imagery gives many examples of situations in which border eddies are found just downstream of Port Elizabeth and a large eddy in the eastward-facing bight in the shelf edge, suggesting that the general distribution of Fig. 7 is a generic one. A case in point is the disposition of circulation elements in Fig. 1.

The geographic distribution of shear-edge plumes is very similar (Fig. 9) to that of border eddies as they are closely related. What is important to note here is that the lateral distribution of plumes to the side of the mean location of the current border increases downstream up to a position just short of the southern tip of the Agulhas Bank where the zone of plume occurrence is quite narrow. Downstream of this location plumes are found over a much wider meridional expanse. An analysis of plume dimensions was made using the parameters defined in the insert in Fig. 9. The results are given in Table 2 for each individual year and for the four sectors along the bank described above. The mean width of plumes increased from 27 km upstream and opposite Port Elizabeth (sector I) to 37 km at the tip of the Agulhas Bank and beyond (sector IV). The length of plumes similarly increased from an average of 100 km to a mean of 162 km. The

Table 1. Average distances between crest and trough of Agulhas Current meanders along the Agulhas Bank (in km*). Geographic sectors are defined in Fig. 7*

Sector	I	II	III	IV
Year				
1978	112	118	135	130
1979	124	128	126	112
1982	129	124	135	112
1983	122	118	129	134
1984	151	152	152	142
1985	151	121	135	124
Overall average	131	127	135	126
S.D.	38	33	37	37
No. of observations	38	94	113	71

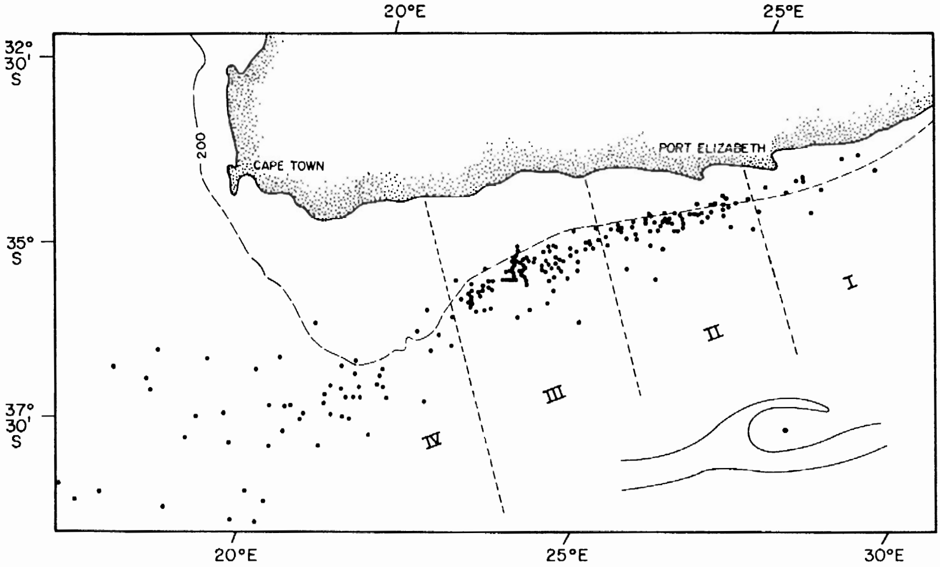

Fig. 8. The geographic location of shear-edge eddies along the Agulhas Current border. Otherwise as in Fig. 6.

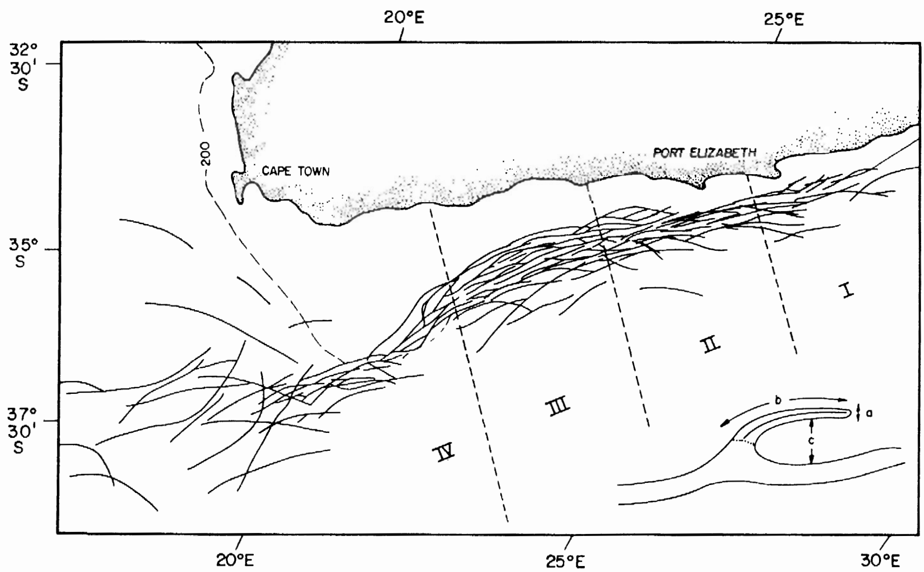

Fig. 9. The geographic location of plumes along the southern Agulhas border. Otherwise as in Fig. 6, except lettering is for Table 2.

Table 2. Average plume dimensions of the Agulhas Current along the Agulhas Bank (*in* km). *Geographic sectors as well as plume dimensions are defined in Fig.* 9

Sector	I			II			III			IV		
	a	b	c	a	b	c	a	b	c	a	b	c
Year												
1978	25	107	20	33	117	23	40	165	38	40	150	53
1979	29	87	30	35	131	25	37	157	31	30	161	34
1982	–	–	–	28	134	25	35	177	37	37	178	41
1983	24	92	29	21	97	10	35	120	22	37	120	31
1984	27	116	18	26	117	21	29	134	33	35	180	74
1985	36	142	45	25	136	29	37	155	40	45	160	60
Overall average	27	100	27	28	122	22	35	152	34	37	162	51
S.D.	13	47	24	13	49	15	16	56	17	20	61	34
No. of observations	15	15	15	47	47	47	78	78	78	44	44	44

diameters of border eddies, as circumscribed by warm plumes (Fig. 9) increase from 27 km off Port Elizabeth to 51 km at the southern tip of the Agulhas Bank. The number of observations on which these statistics are based differ from sector to sector, but are large enough to justify confidence in their representativeness. The tendency for the dimensions of all three plume and eddy parameters to increase on proceeding downstream is found, with few exceptions, in the case of all six of the individual years represented here, even though the number of observations in each year is naturally considerably smaller.

DISCUSSION

Numerous attempts have been made to establish the phase speed of border phenomena on western boundary currents. Vaszquez and Watts (1985) have shown that the most energetic meanders on the Gulf Stream (those with periods between 33 and 50 days) remain coherent for at least 300 km downstream and their phase speeds decrease with distance downstream from about 15 to 7 km day^{-1} over a distance of 550 km. Lee *et al.* (1981), on the other hand, estimated phase speeds of 40 km day^{-1}. In the Agulhas Current Harris *et al.* (1978) and Lutjeharms (1981) obtained values of about 20 km day^{-1}. Gründlingh (1979, 1986) has presented results that are nearly identical. Some of these meanders which were previously reported can now be identified as Natal Pulses. Based on a very limited data set, Lutjeharms and Roberts (1987) have suggested a marked decrease in the phase speed of Natal Pulses when they reach the Agulhas Bank from about 20 to 5 km day^{-1}.

An example of the downstream motion of a meander with attendant plume is shown in Fig. 10. Because of periods of persistent cloudiness, few coherent and long time series examples of moving meanders could be obtained from the data set. In all, 17 series such as that shown in Fig. 10 were analysed. There was no clear indication that a correlation exists between the phase speeds of meanders and distance downstream. Where possible, wavelengths for the meanders were calculated. A statistically non-significant tendency for wavelength shortening downstream exists. Based on 37 measurements an average phase speed of 21 km day^{-1} (S.D. = 15 km day^{-1}) was established. This is comparable with those found by Harris *et al.* (1978), Lutjeharms (1981) and Gründlingh (1979).

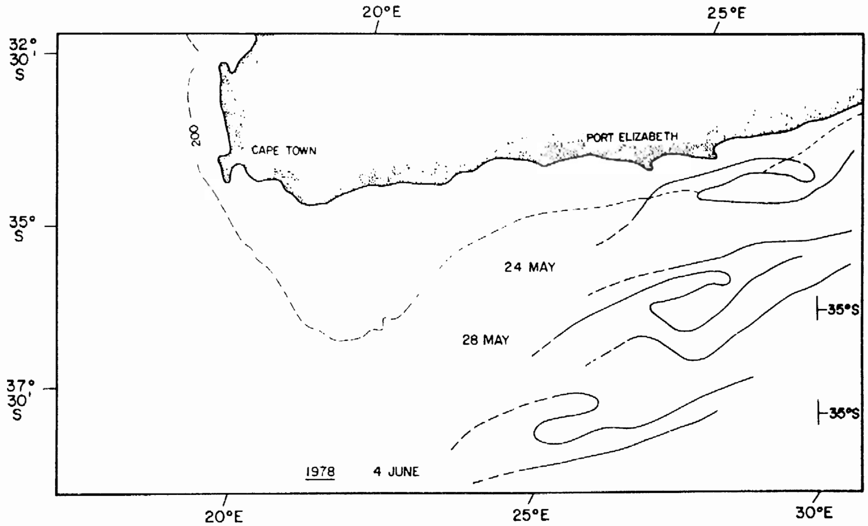

Fig. 10. Location of an Agulhas Current meander with attendant plume on three consecutive days, according to its surface thermal expression in METEOSAT imagery. The outlines of warm water have been offset southward for the last 2 days to separate them. The edge of the Agulhas Bank is denoted by the 200 m isobath.

The periods over which phase shifts were measured lay between 3 and 17 days. Wavelengths of meanders for clearly visible events were 297 km (S.D. = 96 km) compared to between 300 and 360 km found by HARRIS *et al.* (1978).

One of the important reasons for establishing the prevalence, geographic distribution and persistence of border phenomenon of the Current along the Agulhas Bank is the need to know the factors controlling the penetration of warm Agulhas water onto the Agulhas Bank. A striking example of such penetration is presented in Fig. 11. On this occasion warm water of the plume associated with a meander was being dispersed over a wide area forming a significant portion of the Agulhas Bank. Based on the hydrographic results presented above it may be assumed with confidence that such dispersive plumes extend to at least the depth of the thermocline, i.e. 40–80 m depth. Such extensive dispersion could form the major mechanism for maintaining an advectively driven thermocline as suggested by SWART and LARGIER (1987). The extent of this warm water is therefore of importance.

Penetration of warm water onto the Agulhas Bank has been studied by comparing the distance that warm water extends towards the coast from the current proper. This was done for the four sectors defined in Figs 7–9. The results for 3 years are presented in Table 3. It shows quite unambiguously that penetration increases on proceeding downstream. This it did consistently for all 3 years under consideration.

CONCLUSION

The results of this exploratory investigation of border features on the Agulhas Current demonstrates that in contrast to the northern Agulhas Current, shear-edge features of some kind are nearly always present on the inshore border of the Current as it flows past the Agulhas Bank. While the northern Agulhas Current follows the shelf edge quite

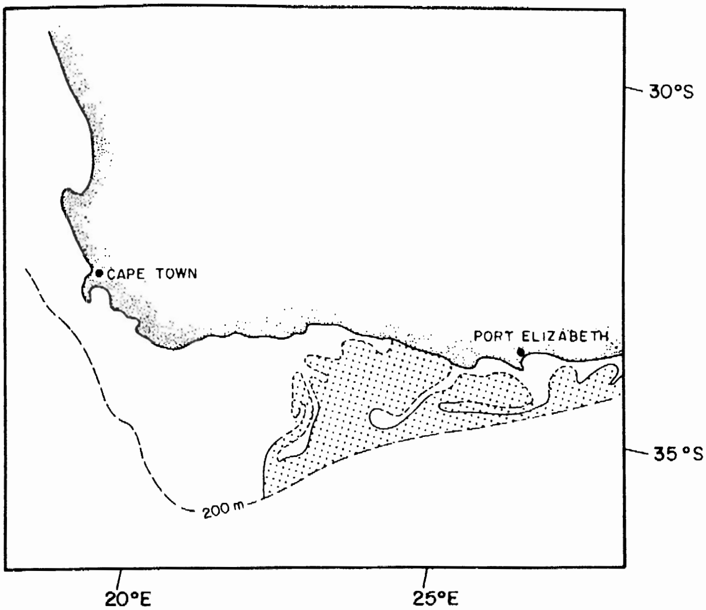

Fig. 11. Advection and dispersal of warm Agulhas Current water onto the Agulhas Bank by way of border plumes. The satellite image is from the AVHRR on board NOAA 7 and for 13 August 1982. Warm water has been darkened in the figure.

Table 3. Average distance of warm water penetration onto the Agulhas Bank from the Agulhas Current (in km)

Area	I	II	III	IV
Year				
1983	37	67	98	127
1984	65	80	110	126
1985	41	81	113	189
Total average	53	76	107	147

closely the mean location of the inshore border of the Current downstream of Port Elizabeth becomes increasingly diffuse. Along the Agulhas Bank the current core lies slightly inshore of the 200 m isobath upstream of Port Elizabeth and in the shelf bight only. The distribution of border eddies is characterized by a concentration just offshore of the 200 m isobath and a dense bi-modal distribution lying between Port Elizabeth and Mossel Bay. The dimensions of plumes associated with current meanders increase downstream. Meanders as well as associated eddies and plumes all seem to go through a mode of minimum occurrence and amplitude at the southern tip of the Agulhas Bank, after which the border features are widely dispersed. A significant reduction in the amplitude of meanders is evident downstream of the Agulhas Bank. No clear geographic variation in wavelength of meanders was apparent. No correlation between the phase speed of different meanders and their distance downstream was evident. Penetration of warm water from the Agulhas Current onto the Agulhas Bank increases downstream.

The geographic configurations of the basins and coastlines which constrain the flow of the three major western boundary currents, the Agulhas Current, the Gulf Stream and the Kuroshio, are so different that close similarities in their dynamic behaviour are probably not to be expected. Whereas the Agulhas Current flows along a narrow shelf for most of its length and shows little sideways meandering (GRÜNDLINGH, 1983) until it reaches the Agulhas Bank, the Gulf Stream exhibits increasing amplitudes in its meanders downstream of the Florida Straits (OLSON *et al.*, 1983). The Charleston Bump, a topographic unevenness in the shelf edge, has been thought to have a triggering effect on Gulf Stream meanders (LEGECKIS, 1979). No such feature exists on the Southern African continental shelf. Meanders of the Kuroshio in general also increase in amplitude downstream, particularly in the Kuroshio extension (KAWAI, 1972). A unique feature of the Kuroshio flow pattern is its bimodality, not found in the other western boundary currents.

Nonetheless, boundary eddies and plumes on the three currents show distinct resemblances. Kuroshio frontal eddies are described (HIRAI, 1985) as consisting of a folded wave pattern with a tongue-like warm filament surrounding a cold core. This description will fit equally well the features observed on the Gulf Stream boundary (e.g. LEE and MAYER, 1977) and the Agulhas Current. Whereas on the Kuroshio the length and width of warm plumes associated with boundary eddies range from 18 to 130 km and from 4 to 28 km, respectively (HIRAI, 1985), dimensions for the same features of the Agulhas Current lie between 100 and 162, and 27 to 34, respectively. For the Gulf Stream the lengths lie between 35 and 200 km (LEE *et al.*, 1981). One may assume that the driving mechanisms of these features are identical, dependent only on the shear parameters of the current boundary and on the continental shelf and shelf edge configuration. For instance, whereas boundary eddies have been observed to spin off the edge of the Gulf Stream and to move independently over the continental shelf, this has not been observed for the Agulhas Current. Perhaps the limited extent of the Agulhas Bank inhibits such separation.

Acknowledgements—Satellite information used for this study was kindly supplied by NOAA/NESS and the SRCS/CSIR at Hartebeeshoek, whom we thank for their willing cooperation. Prof. G. B. Brundrit of the University of Cape Town made helpful comments on the manuscript. The two BT cruises were planned and executed by the late Dr Nils Bang to whose memory we pay tribute.

REFERENCES

BANG N. D. (1972) Logic intensive versus data intensive methods in oceanographic planning, analysis and prediction. In: *Proceedings of "Conference 72"*, Johannesburg, South African Geographical Society, 16 pp.

CARTER R.A., H. F. MCMURRAY and J. L. LARGIER (1987) Thermocline characteristics and phytoplankton dynamics in Agulhas Bank waters. In: *The Benguela and comparable ecosystems*, A. I. L. PAYNE, J. A. GULLAND and K. H. BRINK, editors, *South African Journal of Marine Science*, **5**, 327–336.

CATZEL R. and J. R. E. LUTJEHARMS (1987) Agulhas Current border phenomena along the Agulhas Bank south of Africa. National Research Institute for Oceanology, CSIR Research Report 635, pp. 1–22.

CHEW F. (1981) Shingles, spin-off eddies and an hypothesis. *Deep-Sea Research*, **28**, 379–391.

CHURCHILL J. H., P. C. CORNILLON and G. W. MILKOWSKI (1986) A cyclonic eddy and shelf-slope water exchange associated with Gulf Stream warm-core rings. *Journal of Geophysical Research*, **91**, 9615–9623.

EAGLE G. and M. J. ORREN (1985) A seasonal investigation of the nutrients and dissolved oxygen in the water column along two lines of stations south and west of South Africa. National Research Institute for Oceanology, CSIR Research Report 567, 52 pp.

GOSCHEN W. S. and E. H. SCHUMANN (1988) Ocean current and temperature structures in Algoa Bay and beyond in November 1986. *South African Journal of Marine Science*, **7**, 101–116.

GRÜNDLINGH M. L. (1979) Observations of a large meander in the Agulhas Current. *Journal of Geophysical Research*, **84**, 3776–3778.
GRÜNDLINGH M. L. (1983) On the course of the Agulhas Current. *South African Geographical Journal*, **65**, 49–57.
GRÜNDLINGH M. L. (1986) Features of the northern Agulhas Current in spring, 1983. *South African Journal of Science*, **82**, 8–20.
GRÜNDLINGH M. L. and A. F. PEARCE (1982) Is there a seasonal variation in the Agulhas Current? *Journal of Marine Research*, **40**, 177–184.
HARRIS T. F. W., D. VAN FOREEST and R. LEGECKIS (1978) Satellite infra-red images in the Agulhas Current system. *Deep-Sea Research*, **25**, 543–548.
HIRAI M. (1985) Satellite observation of characteristic features of frontal eddies in the vicinity of the Kuroshio Front. *Bulletin of the Tohoku Regional Fisheries Research Laboratory*, **47**, 69–78.
HSUEH Y. and J. J. O'BRIEN (1971) Steady coastal upwelling induced by an along-shore current. *Journal of Physical Oceanography*, **1**, 180–186.
KAWAI H. (1972) Hydrography of the Kuroshio Extension. In: *Kuroshio, its physical aspects*, University of Tokyo Press, pp. 235–352.
LARGIER J. L. and V. P. SWART (1987) East–west variation in thermocline breakdown on the Agulhas Bank. In: *The Benguela and comparable ecosystems*, A. I. L. PAYNE, J. A. GULLAND and K. H. BRINK, editors, *South African Journal of Marine Science*, **5**, 263–272.
LEGECKIS R. V. (1979) Satellite observations of the influence of bottom topography on the seaward deflection of the Gulf Stream off Charleston, South Carolina. *Journal of Physical Oceanography*, **9**, 483–497.
LEE T. N. and D. A. MAYER (1977) Low-frequency variability and spin-off eddies along the shelf off Southeast Florida. *Journal of Marine Research*, **35**, 193–220.
LEE T. N., L. P. ATKINSON and R. LEGECKIS (1981) Observations of a Gulf Stream frontal eddy on the Georgia continental shelf, April 1977. *Deep-Sea Research*, **29**, 347–378.
LUTJEHARMS J. R. E. (1981) Features of the southern Agulhas Current circulation from satellite remote sensing. *South African Journal of Science*, **77**, 231–236.
LUTJEHARMS J. R. E., N. D. BANG and H R. VALENTINE (1981) Die fisiese oseanologie van die Agulhasbank. Deel 1: Vaart 170 van die N.S. *Thomas B. Davie*. National Research Institute for Oceanology, CSIR Research, 386, pp. 1–38.
LUTJEHARMS J. R. E. and H. R. VALENTINE (1983) Die fisiese oseanologie van die Agulhasbank. Deel 2: Vaart 185 van die N.S. *Thomas B. Davie*. National Research Institute for Oceanology, CSIR Research Report 557, pp. 1–15.
LUTJEHARMS J. R. E. and A. L. GORDON (1987) Shedding of an Agulhas ring observed at sea. *Nature*, **325**, 138–140.
LUTJEHARMS J. R. E. and P. L. STOCKTON (1987) Kinematics of the upwelling front off Southern Africa. In: *The Benguela and comparable ecosystems*, A. I. L. PAYNE, J. A. GULLAND and K. H. BRINK, editors, *South African Journal of Marine Science*, **5**, 35–49.
LUTJEHARMS J. R. E. and A. JORGE DA SILVA (1988) The Delagoa Bight eddy. *Deep-Sea Research*, **35**, 619–634.
LUTJEHARMS J. R. E. and H. R. ROBERTS (1988) The Natal Pulse; an extreme transient on the Agulhas Current. *Journal of Geophysical Research*, **93**, 631–645.
MALAN O. G. and E. H. SCHUMANN (1979) Natal shelf circulation features revealed by *LANDSAT* imagery. *South African Journal of Science*, **75**, 136–137.
MAUL G. A., P. W. DE WITT, A. YANAWAY and S. R. BAIG (1978) Geostationary satellite observations of Gulf Stream meanders: infrared measurements and time series analysis. *Journal of Geophysical Research*, **83**, 6123–6135.
OLSON D. B., G. B. BROWN and S. R. EMMERSON (1983) Gulf Stream frontal statistics from Florida Straits to Cape Hatteras derived from satellite and historical data. *Journal of Geophysical Research*, **88**, 4569–4577.
SCHUMANN E. H. and I. L. HEERDEN (1988) Observations of Agulhas Current frontal features south of Africa, October 1983. *Deep-Sea Research*, **35**, 1355–1362.
SCHUMANN E. H., L.-A. PERRINS and I. T. HUNTER (1982) Upwelling along the south coast of the Cape Province, South Africa. *South African Journal of Science*, **78**, 238–242.
SHANNON L. V. and P. CHAPMAN (1983) Suggested mechanism for the chronic pollution by oil of beaches east of Cape Agulhas, South Africa. *South African Journal of Marine Science*, **1**, 231–244.
SWART V. P. and J. L. LARGIER (1987) Thermal structure of Agulhas Bank water. In: *The Benguela and comparable ecosystems*, A. I. L. PAYNE, J. A. GULLAND and K. H. BRINK, editors, *South African Journal of Marine Science*, **5**, 243–253,
VAZQUEZ J. and D. R. WATTS (1985) Observations on the propagation, growth and predictability of Gulf Stream meanders. *Journal of Geophysical Research*, **90**, 7143–7151.
VUKOVICH F. M. and M. W. CRISSMAN (1980) Some aspects of Gulf Stream western boundary eddies from satellite and *in situ* data. *Journal of Physical Oceanography*, **10**, 1792–1813.

WALKER N. D. (1986) Satellite observations of the Agulhas Current and episodic upwelling south of Africa. *Deep-Sea Research*, **33**, 1083–1106.

WATTS D. R. and W. E. JOHNS (1982) Gulf Stream meanders: observations on propagation and growth. *Journal of Geophysical Research*, **87**, 9467–9475.