Chapter 5

PHYSICAL OCEANOGRAPHY OFF NATAL

Eckart H Schumann
Department of Oceanography
University of Port Elizabeth

GENERAL DESCRIPTION

A description of the origins and structure of the continental shelf off Natal has been given in Chapter 2. The nature of this shelf has a major influence on the ocean dynamics, delineating regions with markedly different characteristics.

Further offshore, the most important large-scale oceanographic feature is undoubtedly the Agulhas Current. It is generally accepted that this classical western boundary current forms off the Northern Natal/Mozambique coast, from a confluence of waters which follow complex paths in the Mozambique Channel and areas south of Madagascar (Lutjeharms, Bang and Duncan, 1981, Saetre and Da Silva, 1984, Gründlingh and Pearce, 1984). It is recognised as one of the world's major currents, and sweeps polewards with the core generally just offshore of the shelf break. As such, the waters on the shelf are affected markedly, and an understanding of this current is necessary before the processes operating on the shelf can be fully understood.

Weather, and particularly the wind, play fundamental roles in an oceanic environment. A description of the situation off Natal has already been given in Chapter 4, and the response of the ocean can be expected to be complex and to depend on a variety of local and remote factors (Gill, 1982).

The amplitude of the barotropic tide varies from about 0.5 m at neap-tides to about 1.75 m at spring-tides, with an indication of an increase with distance northwards. The shelf is too narrow to have a marked influence on this amplitude (Clarke and Battisti, 1981), and tidal currents are generally small compared with those originating in other processes (Schumann and Perrins, 1982). Most analyses place an amphidromic point for the dominant M_2 tide to the south of Africa (e.g

Accad and Pekeris, 1978) with the cotidal lines therefore running nearly parallel to this coast; as a consequence, there is a negligible phase difference between the tides to the north and south of the region.

There are a large number of rivers and estuaries along this stretch of coast. In most cases the discharge of fresh water into the sea tends to be very sporadic, and the influence of this water is local. As a consequence the overall effect is small, as far as the vertical density structures and currents are concerned. Occasionally after heavy rains silt-laden floodwaters penetrate several kilometres out to sea, but such situations are generally short-lived. Nonetheless, in summer waters with slightly lower salinity values are found, and silt can be detected in the circulation patterns further offshore.

MEASUREMENTS

The vast majority of physical oceanographic measurements off Natal have been made by the Physical Oceanography Division of, first the National Physical Research Laboratory, and then the National Research Institute for Oceanology (NRIO). Consequently the description given here will concentrate on the work carried out by this Division, when it was based in Durban during the years 1960 to 1983.

At the start of the investigations in the early 1960s, measurements were confined to a region within a few kilometres of the Natal coast. Current velocities were estimated using drogues tracked from land stations, as well as with dyes whose movement was tracked by aerial photography. Most of these projects were involved with pollution studies, and tended to be concentrated in the vicinity of Durban. The characteristics of the mean flow at different points along the coast were also established from ship-drift estimates (Harris, 1964).

Later, whalers were hired from an industry that was running down, and equipment was developed for measuring temperature profiles. Salinity was determined from water samples taken at specific depths, while currents were measured relative to the ship; accurate navigation was required for determining absolute currents.

With the acquisition of the RV Meiring Naudé (see Appendix) in 1968,

more extensive and regular measurement programmes were started. Pollution studies continued, and in fact one of the first tasks that the ship had to carry out, in June, 1968, concerned an investigation of the pollution threat from the 46 000 ton tanker, the World Glory, which broke in half north-east of Durban. The regular cruises off Richards Bay in the years 1970 to 1972 were also designed specifically to determine the feasibility of disposal to sea of effluents from the new harbour and from industrial and housing developments. At the same time, measurements of temperature, salinity and occasionally currents were started on a line of stations offshore from Durban, and at a later stage to the south off Port Edward.

A sophisticated computer-controlled data acquisition system was developed for the RV Meiring Naudé (Stavropoulos, 1971; Snyman, 1980); this also allowed rapid processing of the data obtained. An improved version of the NRIO-built hydrosonde was used, and accurate navigation enabled precise values of currents to be obtained. Water samples were obtained for chemical and nutrient analyses (see Chapters 6 and 7).

It was recognised at an early stage that variations in sea-surface temperature (SST) could be used to derive circulation patterns. In particular, the marked thermal gradient at the inshore edge of the Agulhas Current allowed the variability of the current to be monitored. A Barnes airborne radiation thermometer (ART), model PRT 14-313, was used to map these changes in SST from an aircraft flying at a height of 150 m. This system started in the late 1960s, was used for a number of years, and provided a valuable synoptic-scale picture of ocean structures to complement work done by the ship.

Nonetheless, it soon became clear that time series data would greatly improve the understanding of dynamic processes in the shelf region. A start was therefore made in 1972/73 with the purchase of suitable self-recording meters. The reliable and well-proven Aanderaa RCM-4 meter was chosen, and a suitable data-processing procedure established. As a consequence, a shelf dynamics project was started in 1975.

The main thrust of this project occurred during the period April, 1976, to March, 1977, when moorings were maintained for most of the time at four points along the coast, namely off Richards Bay, Durban, Southbroom and Port Edward (see Figure 5.1). These were primarily deployed on rigid stands in about 30 m of water (Schumann, 1981). Later

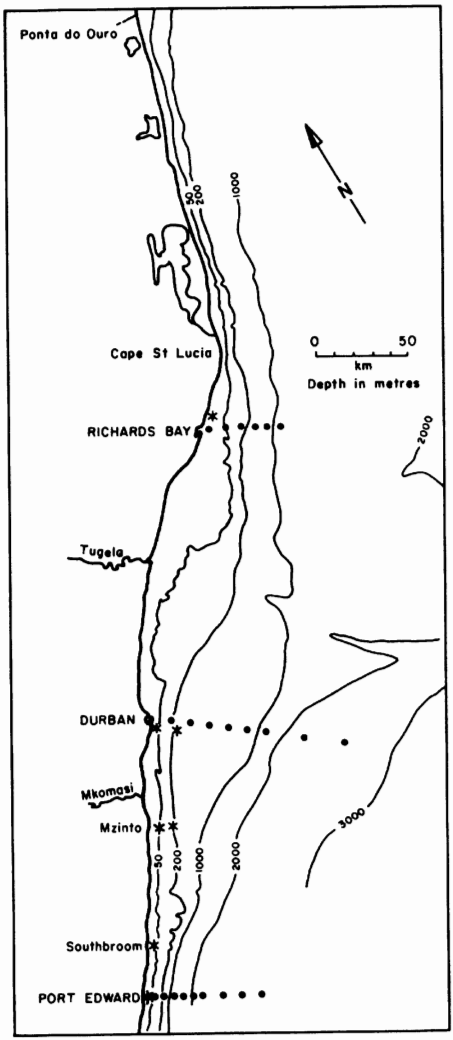

Figure 5.1 Coastal bathymetry and measurement sites off Natal. The lines of dots indicate ship station sites where data were collected regularly; the asterisks show mooring positions reported on in the text.

moorings were deployed in deeper water at specifically selected sites, but were recovered within about two months.

With the acknowledged importance of wind forcing, automatic weather stations were erected at one or two sites to complement the generally unsatisfactory data obtained from Louis Botha airport near Durban (see Chapter 4). None of these stations was maintained for long.

The development of satellite remote-sensing techniques has also been of considerable help in elucidating flow structures. The thermal infrared sensors on board the TIROS and NOAA satellites have given extensive coverage of the ocean areas, while METEOSAT provides pictures more regularly though with much poorer resolution. Images in other spectral bands on LANDSAT and NIMBUS 7 have provided valuable additional information; the fact that South Africa was a member of the Nimbus Experimental Team aided considerably in obtaining these images.

WATER CHARACTERISTICS

The main properties characterizing water type in physical oceanography are temperature and salinity, and many source areas can be identified from so-called TS values. Figure 5.2 shows the distribution of values that can be expected off the Natal coast.

For the shelf areas, only the upper section of the distribution envelope needs to be considered. This shows that these waters generally have a tropical or subtropical origin, with the Agulhas Current system playing an important part in transferring the water to this area. On the other hand, colder, deeper water is occasionally brought onto the shelf by various upwelling mechanisms, particularly off Southern Natal; this is likely to be central water.

Subtropical surface water (STSW) is characterized by a relatively high salinity (greater than 35.5×10^{-3}), caused by greater evaporation. Moreover, it is clear that there are also marked seasonal changes in the upper reaches of the ocean, shown here by the mid-summer envelope. Higher temperatures are due to the increase in summer insolation, with lower salinities due to increased rainfall and outflow from large rivers such as the Zambesi and Limpopo.

Figure 5.3 shows the variabilities in temperature and salinity in

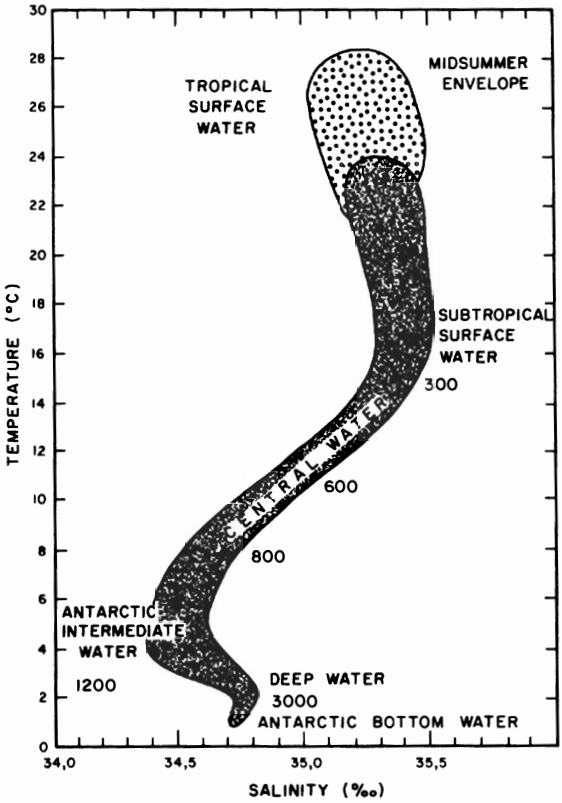

Figure 5.2 A temperature/salinity distribution of values measured off the southeast coast of Southern Africa. Water types are given, along with approximate depths (in m) where such water is commonly found (from Schumann and Orren, 1980).

the water column over a period of about 2 years on the inner and outer shelf off Richards Bay. These sections were chosen to demonstrate the difference between conditions on the shelf and those further offshore on the inner boundary of the Agulhas Current.

The seasonal variability is clearly evident. In the shallower, inshore regions there is about a 4°C temperature change from summer to

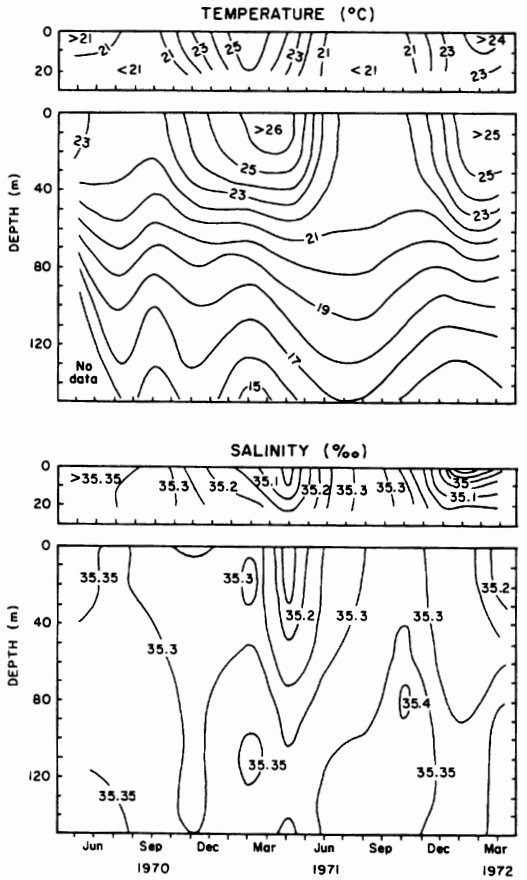

Figure 5.3 Time sections of monthly mean temperatures and salinities off Richards Bay over the two years 1970 to 1972. The shallow, upper sections refer to the inner shelf and the deeper sections to the outer shelf (adapted from Pearce, 1977a)

winter, with maximum temperatures of about 25°C in February. There is also a fairly uniform vertical temperature structure, indicating a well-mixed regime. The most apparent seasonal variation in salinity comes from the relatively fresh water in the upper reaches in late

summer, probably as a result of river outflow.

Further offshore there is also about a 4°C temperature change from summer to winter in the upper 50 m of the water column, with maximum temperatures greater than 26°C; deeper down, this seasonal variation is not evident. There is no clear indication of a marked thermocline at any stage, with a regular decrease in temperature with increasing depth. The lowest temperature at 150 m was less than 15°C, and it is of note that this occurred in summer. Salinity variations are not as conspicuous, although there is evidence of water of lower salinity in the upper reaches in late summer.

Analysing the same data, Pearce (1978) found an annual temperature range of 4.8°C, with the inshore water being some 1.4°C cooler than that at the shelf break. He also postulated that water in the 40 to 60 m layer at the shelf break moves shorewards along the appropriate sigma-t surface in a mild but continuous upwelling process.

Whereas the mean seasonal temperature variation along the Natal coast can therefore be expected to be about 5°C, marked changes can occur on a much shorter time scale. Figure 5.4 shows time series of temperature data taken at moorings deployed at three different sites. The seasonal variation displayed in Figure 5.3 is again evident, while there is also no clear longshore trend. However, the abrupt changes which occurred on a day-to-day time scale in many cases exceeded the seasonal variation. These short-term fluctuations can be up to 8°C or 9°C, and are probably caused by the colder deeper water also shown in Figure 5.3 moving up or down the shelf slope and over the measuring site.

THE AGULHAS CURRENT

After its formation in the north, the poleward-flowing Agulhas Current influences the coastal ocean along the whole Natal coast. Its characteristics have been best monitored in the south, and these results will be used to identify aspects to be expected over the whole region. Differences along sections of the coast can be surmised from the measurements available.

Pearce (1977a,b) analysed data from measurements made in the upper 500 m of the Current off Durban, and Figure 5.5 shows mean profiles and

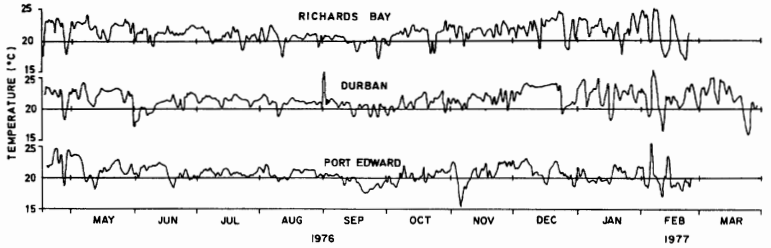

Figure 5.4 Time series of temperatures measured 3 m above the sea bed in about 30 m of water, off Richards Bay, Durban and Port Edward (from Schumann, 1981, JGR, 86 copyright by the American Geophysical Union).

sections from about 45 completed lines of such stations in all seasons. Here the core of the Current lies at a distance of between 40 km and 60 km offshore, with an intense cyclonic shear region on the inshore side, while speeds on the offshore boundary tail off far more gradually.

Sea-surface temperature profiles correlate well with the current speeds, showing the warmer water associated with the Agulhas Current. On the other hand, there is no consistent salinity change on the inshore boundary, with a gradual increase offshore being evident. If the "edges" of the current are defined as the 0.4 m/s isotachs, Bang and Pearce (1978) found the mean width of the Current to be about 100 km.

The subsurface temperature and salinity structures are typical of western-boundary currents, with the slopes of the isotherms and isohalines reaching maxima at the Current core. An intrusion of high-salinity STSW can also be detected at a depth of 150 m to 200 m offshore of this core. Closer inshore, the slopes of the isotherms and isohalines change, and this is associated with a current reversal.

Using data mainly from sections off Port Edward, Gründlingh (1980) found a volume transport for the Agulhas Current of around 70 x 10^6 m^3/s, extrapolated over the total depth and width. This value is comparable to those obtained for the Gulf Stream (Knauss, 1969) and the Kuroshio Current (Taft, 1972), and confirms that the Agulhas Current is one of the major currents of the world's oceans. No distinct seasonal variation was found in the volume flow, and a more

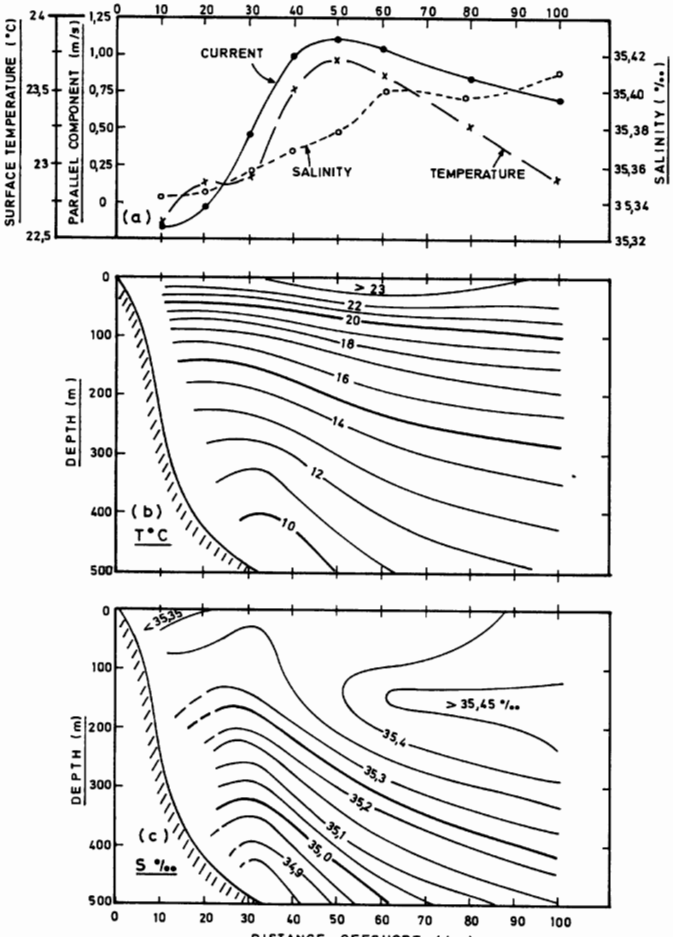

Figure 5.5 Profiles and sections measured on the line of stations off Durban. In (a) are shown the surface profiles of mean temperature, salinity and 0-to-100 m depth-averaged longshore current component, while (b) and (c) depict temperature and salinity, respectively (from Pearce, 1977a).

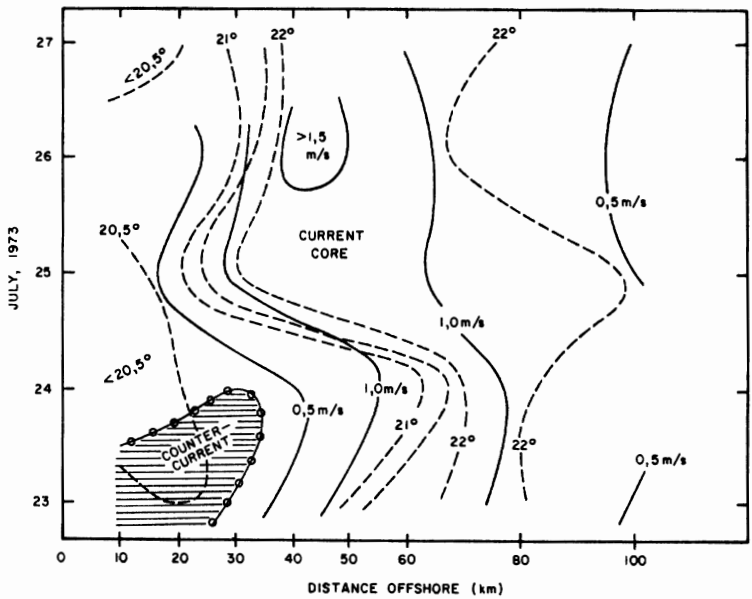

Figure 5.6 A "space-time" map of sea surface temperatures (dashed) and longshore current component during five days of a cruise in July, 1973. The shaded area represents a northeastward counterflow (from Pearce, 1977b).

recent analysis of current speeds (Pearce and Gründlingh, 1982) has confirmed this conclusion, within the limits imposed by the data available.

In fact, it has been found that the daily variability in the Current is such as to mask any seasonal variability that may be present. Figure 5.6 shows the changes measured over a period of 5 days on the Durban line of stations, and demonstrates that the current core can change its position by 30 km and more from day to day. Ostensibly such changes are associated with meanders, and Gründlingh (1974) postulated that these could be initiated by atmospheric forcing.

As mentioned before, it is likely that bottom topography plays an important part in the structure and flow of the Agulhas Current. Off

northern Natal there is a well-formed shelf break, and the few measurements available indicate that the Current usually flows just offshore of this break. South of Cape St Lucia a gentle bight in the coastline causes the Current to move offshore, while the terrace-like topography off Durban affects the structure below about 500 m. To the south the shelf narrows considerably, and observations show an increase in Current speed relative to Durban, with the core situated within about 10 km of the shore off Port Edward. Gill and Schumann (1979) modelled these changes in terms of topographic control of the Current flow.

These features are shown in the sea surface temperatures depicted in Figure 5.7. The Agulhas Current boundary is clearly evident from the strong horizontal temperature gradient, with the apparent onset of a meander south of Cape St Lucia. There is a dramatic growth in the meander off Durban, with a strong onshore tendency off Mzinto and indications of a recirculation flow. Further south off Port Edward the Current has apparently become re-established. A mean sea surface temperature figure obtained by Pearce (1977b) in 14 ART flights, shows a distinct 'kink' in the isotherms off Durban. It is therefore apparent that the meander in Figure 5.7 bears a specific relationship to its position over the bottom topography.

A further feature which has been observed in satellite imagery of this area is the so-called "Natal pulse". These pulses consist of large deflections of the core of the Agulhas Current from its mean position, originating off Natal and growing with distance downstream to beyond Port Elizabeth (Lutjeharms, 1981; Gründlingh, 1979).

THE NATAL SHELF

The current-meter moorings maintained at Richards Bay, Durban, Southbroom and Port Edward during 1976 and 1977 were intended to investigate longshore coherence scales. However, the analysis of subtidal fluctuations carried out by Schumann (1981) essentially showed a lack of coherence between conditions at the sites selected, and the existence of distinct coastal regimes. It was postulated that these different regimes occurred as a result of changes in bottom topography

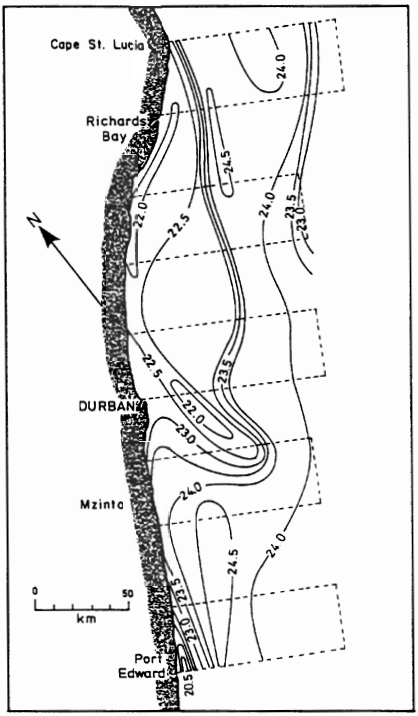

Figure 5.7 Sea surface temperatures from an ART flight on 30 November, 1967. Temperatures are given in degrees Celsius, while the aircraft flight pattern is also shown (from Schumann, 1982).

and also by the varying influence of the Agulhas Current at different sections of the coast.

Four broad regimes are identified, and will be discussed separately. It must be clearly understood that such a subdivision is by no means absolute, but that it merely serves to identify areas with generally different dynamic characteristics. There are no clearly defined boundaries and, indeed, if more comprehensive data were available different subdivisions might be made.

The Northern Region

This is roughly the region north of Cape St Lucia, that is the coast of Maputaland, where the shelf is narrower than 10 km in places (Figure 5.1). Virtually no inshore measurements are available for this region, but it can be surmised that the Agulhas Current will have a dominant influence, particularly where it flows close to the shelf break.

North of Cape St Lucia maximum speeds of about 1.5 m/s have been measured in the Current. There does not appear to be such a distinct thermal gradient on the inshore boundary as there is further south, which perhaps indicates that the Current is still in its formative stages. The slight change in the direction of the coastline leading to the bay at Maputo and the major coastal inflexion northeastwards (Figure 1.1), means that the main flow of the Agulhas Current may also lie further offshore. Satellite imagery has revealed the existence of an eddy situated offshore of Maputo, also depicted in the analysis by Saetre and Da Silva (1984). It is therefore probable that the shelf regions in the far north are not as strongly under the influence of the Agulhas Current as they are further south.

These conclusions are also supported by Harris (1964, 1978), in analyses of data of ship-drift from positions about 2 km offshore. Thus it was found that the percentage of northeastward currents increased to the north. However, northeastward current speeds tended to be less than 0.25 m/s (0.5 knots), while those of southwestward currents generally exceeded 0.5 m/s (1 knot).

The Central Shelf

South of Cape St Lucia the shelf becomes wider, mainly due to a gentle bight in the coastline, and the main stream of the Agulhas Current also diverges from the coast. The widest part of the Natal shelf is off the Tugela River, where the shelf break is about 45 km offshore. It is this wider shelf region which stretches southwards to the start of the terrace-like structure north of Durban that will be discussed here.

Results from the hydrographic measurements made off Richards Bay show the marked effect of the Current at the shelf break and beyond (Pearce,

1977a). The results obtained from the mooring closer inshore and just to the north of Richards Bay (Figure 5.1), indicate the shelf-like characteristics that can be expected further away from the influence of the Current. Thus it is apparent that there are two processes operating: first, in the several-day period range the current fluctuations lie parallel to the coastline, and second, the effect of the Agulhas Current is evident in the longer-term current progression southwestwards along the line of the deeper contours (Schumann, 1981).

In seeking an explanation for the shorter-term fluctuations, the wind was the obvious choice. Figure 5.8 shows time series of wind and current vectors for a portion of the time for which current data are available. It is clear that there is a very close correspondence, and coherency and phase spectra between the longshore wind and longshore and offshore currents confirm this conclusion (Schumann, 1981). A markedly linear relationship was found between phase and frequency, giving a time lag of about 18 hours at all frequencies between the onset of the wind and the response of the currents; this is within the inertial period of about 25 hours. Previously, Bang and Pearce (1978) had identified current fluctuations in the 4- to 6-day period range, but ascribed this to an association with atmospheric pressure lows.

In his analysis of the hydrographic measurements off Richards Bay, Pearce (1977a) found that there was no major seasonal pattern in the behaviour of shelf currents. Any such pattern was probably obscured by the high short-term variability caused by the wind-driven currents inshore, and by the meandering of the Agulhas Current at the shelf break. As mentioned before, the mean flow structures indicated that the cross-shelf flow appeared to be onshore in the lower half of the water column, with an offshore compensatory flow in the upper layer; this was ascribed to **Ekman veering in the bottom boundary layer of the Agulhas Current.**

Pearce (1977a) also found sporadic instances of localised upwelling, typically within about 10 km of the coast and some 20 km in alongshore extent. Surface temperature dropped by **about 1°C and higher levels of nutrients were found in such cases (Chapter 6). Such events were shortlived, however, and seldom lasted much longer than one day.**

Very few measurements are available on the wider shelf to the south, and it must be assumed that many of the characteristics of the inner

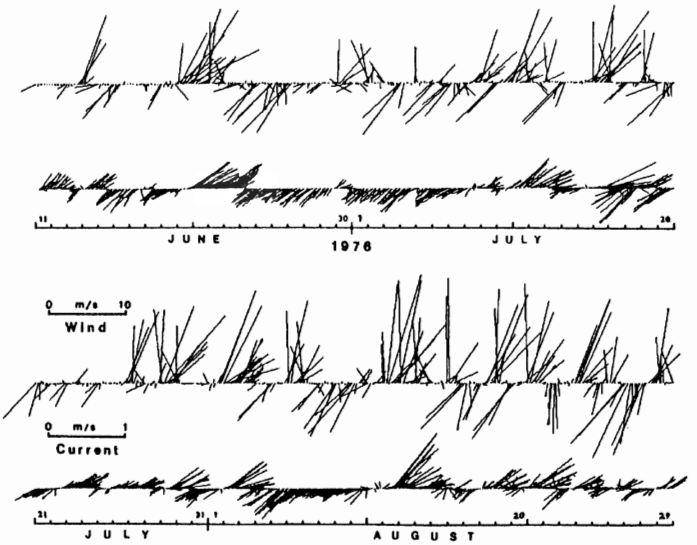

Figure 5.8 Vector time series of winds and currents measured at Louis Botha airport near Durban and Richards Bay, respectively. Filtered, 3-hourly values have been used, and the 80 days of data have been broken into two sections with the wind vectors at the top in each case. North is at the top of the page, while wind and current scales are also given (from Schumann, 1981, JGR, 86, copyright by the American Geophysical Union).

shelf off Richards Bay also apply here. The analysis of ship drift data by Harris (1964) confirms the variability of the currents in the area, with an almost equal percentage of northeastward and southwestward currents. There is an indication of a higher percentage of northeastward currents in the south, although the limited number of measurements available precludes any definite conclusions to be drawn in this regard.

A further source of information on current patterns is satellite imagery. Figure 5.9 shows an enhanced LANDSAT MSS band 4 image, in which the absorption of radiation by particulate-free ocean water is minimal and penetration can be 10 m or more. Clear water is shown as black, while water containing suspended particulate matter (river-borne sediment, industrial effluent, plankton, etc.) is shown in various

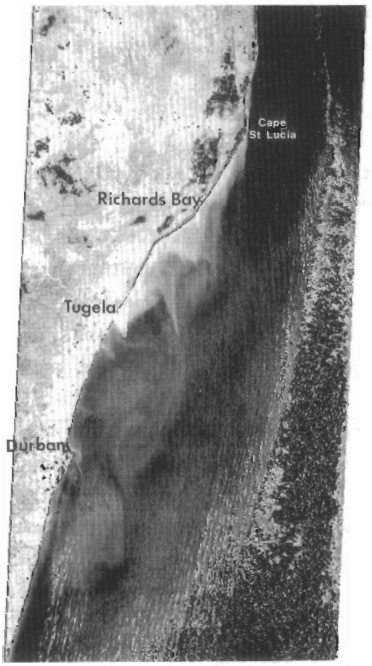

Figure 5.9 A computer-enhanced picture of the LANDSAT-1 multispectral scanner band 4 (0.5 to 0.6 μm) image acquired on 29 January, 1973 (from Malan and Schumann, 1979).

shades of grey, depending on the concentration and depth of the suspended matter. Rainfall reports at the time indicate that there would have been substantial discharges from the major rivers in the area in the days preceding the image.

The distribution of particulate matter in the water reveals a complex pattern of flow over the Natal shelf. The "average" circulation situation described by Pearce et al. (1979) is supported, with the existence of eddies or similar features with a variety of scales. The most persistent feature is the cyclonic eddy immediately offshore and to the north of Durban, while to the north-east of the Tugela are southward-extending plumes with an indication of the presence of a

smaller eddy. Closer to the coast there are smaller-scale features, probably associated with the varying current regime.

The Durban Shelf

This is a region extending from an ill-defined area to the north of Durban, to a point south of Mzinto where the shelf is narrower. It may be thought of as a transition region between the wind-dominated shelf to the north, and the Agulhas Current dominated shelf to the south. However, there appear to be some very specific characteristics which serve to identify this as more than a transition region, while there is also little long-term coherence with the other two regions (Schumann, 1981).

Figure 5.10 shows current vectors measured on the inner stations of the lines off Durban and Port Edward. One of the main results to emerge is the inherent variability of the currents off Durban. The trend from a generally northeastward flow at the innermost station to a southwestward flow at about 50 km offshore is evident, although even at this latter site very slack current conditions were encountered at times.

With the Agulhas Current flowing southwestward further offshore, a source for the northeastward inshore flow probably has to be sought in a recirculation of waters on the inshore boundary of the Current. Such a flow pattern is indicated in Figure 5.7, and is given strong support by simultaneous current meter results from moorings off Durban, Mzinto and Port Edward (Schumann, 1982).

These results reveal a predominantly northeastward flow off Durban, though with the occurrence of fairly regular current reversals. Off Port Edward the flow is strongly southwestward, but with an onshore flow over the whole water column (195 m) off Mzinto. The consistent nature of this flow is the best evidence to date of the fairly permanent nature of the recirculation of the inshore waters of the Current. The temperature records also support this recirculation concept, in that the temperatures measured at the upper meter at Mzinto, and those measured at the inner mooring off Durban generally remained within about 0.5°C of each other over the whole 51-day recording period.

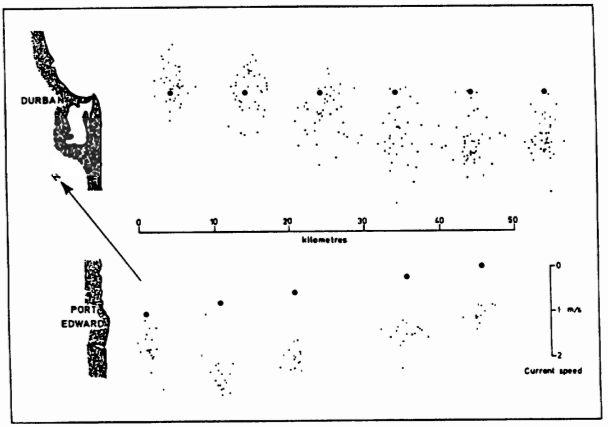

Figure 5.10 Current measurements made on the line of stations off Durban and Port Edward. Each dot represents the head of a current vector averaged over the upper 100 m with respect to the associated station position, represented by the bigger dots (from Schumann, 1982)

The nature of the current fluctuations is also of interest. Figure 5.11 shows current and temperature records taken on another occasion over a period of about 34 days off Durban and Mzinto. The essentially barotropic current structures are apparent, with the variations over the whole water column taking place simultaneously at both sites off Durban.

Wind and air pressure records also reveal little correlation, and it is therefore likely that the cause of such current fluctuations lies in the Agulhas Current variability and changes in the recirculation flow.

The temperature records show that the measurements at the deeper site off Durban were essentially taken below the thermocline. At the other two shallower sites the temperature changes are much more dramatic, indicative again of colder bottom water reaching the measurement site at times. At Mzinto the current speeds were much lower than off Durban with a greater variability being evident. However, of particular note is the close correlation between the temperature variations and the current fluctuations at Durban and Mzinto. Thus with a northeastward

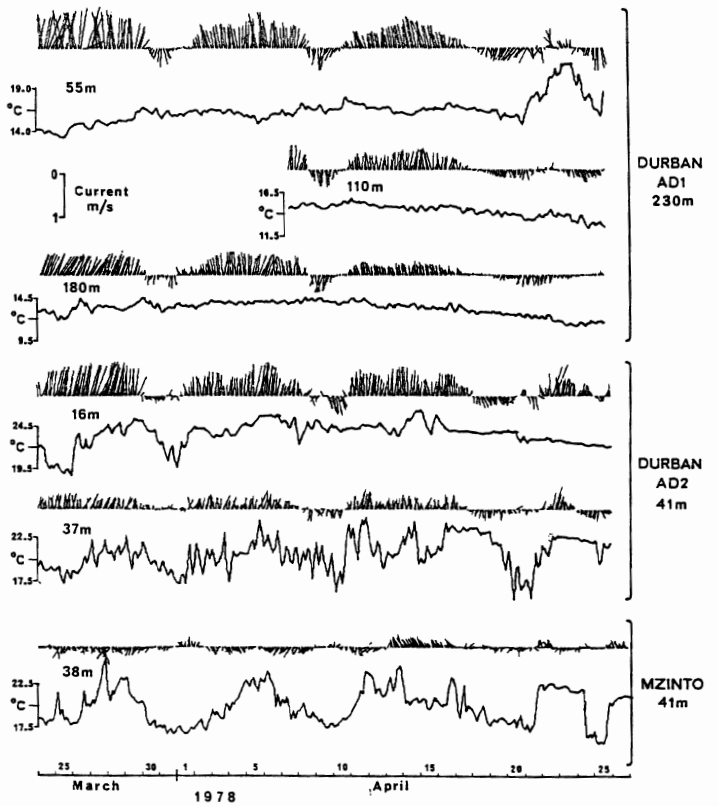

Figure 5.11 Current and temperature time series from moorings off Durban and Mzinto during 1978. The total depth at each mooring is given, as well as the depth of the individual meters. The orientation of the coastline is at 38°T, here parallel to the page margin (from Schumann, 1982)

flow the temperature reached a maximum of about 22.5°C, while a southwestward flow accompanied a drop of around 5°C. The correspondence in terms of actual values and variations in the bottom two temperature records also confirm the existence of connections between the two sites.

On two occasions drogued buoys were released and followed for a period of about 36 hours (Schumann, 1982, with acknowledgement to R. A Carter). One, starting from a position about 20 km offshore, followed roughly the pattern indicated by the gyre offshore of Durban, shown in Figure 5.10, and this may be the northward tendency of the recirculation flow. On the other hand, the second buoy released 10 km offshore first went southwards before turning northwards.

Closer inshore the break in the coastline formed by the Bluff at Durban is apparently responsible for causing a southward flow close to the coast in the small bight. This was shown up by early drogue measurements, and has been ascribed to an anticyclonic gyre formed inshore of the main northward flow (Pearce, 1977a). The rest of the Natal coastline is relatively straight, and it is unlikely that there are other substantial local topographically-related flows.

A number of drogue measurements were also made in the early 1960s. within 5 km of the coast off the Mkomasi river. While the currents recorded were generally very variable, it is clear that on occasion the influence of the Agulhas Current was felt strongly, with southwestward flows exceeding 1 m/s.

The Southern Region

This is a region becoming increasingly under the influence of the Agulhas Current. This is evident from the current vectors depicted in Figure 5.10, which show that current speeds exceeding 1 m/s often occur within 10 km of the coast. Sections offshore of Port Edward show the Current core, with steeply sloping isopycnals, just offshore of the shelf break.

Figure 5.12 shows progressive vector diagrams (PVDs) from meters deployed at roughly the same distances offshore at Southbroom and Port Edward (Figure 5.1). The strong southwestward flow is evident, but it is also markedly stronger at the latter site; this can probably be ascribed to the still narrowing shelf and to the consequent onshore movement of the Current to the south.

Nonetheless, it is also clear that current reversals do occur on occasion, and it is likely that these are associated with variations in the Agulhas Current itself. A coherency analysis between currents

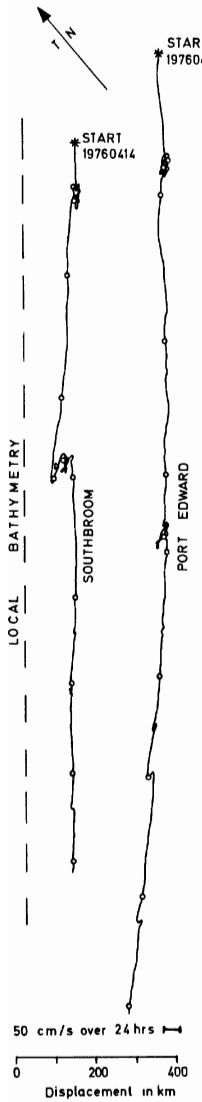

Figure 5.12 Progressive vector diagrams (PVDs) of current measurements covering some 110 days, taken in about 30 m depth at Port Edward and Southbroom. The starting days are given by an asterisk, with an open circle every 10 days. The orientation of the bathymetry and coastline are also shown.

and the longshore winds showed that local wind forcing plays a relatively minor role in this area (Schumann, 1981).

The strong currents on the shelf mean that substantial bottom boundary layer effects can be expected. A recent analysis by Schumann (1986) in 49 m water depth showed that the turbulent flow associated with this layer extended over the whole water column. Ekman veering in excess of 15° was found, and this serves to bring colder, deeper water onto the shelf. Such upwelling does indeed occur along this coast, and Figure 5.7 gives an indication of this off Port Edward. More substantial upwelling is common further south, but it is not clear which mechanism is responsible: either Ekman veering in the bottom boundary layer, or perhaps the topographic mechanism described by Gill and Schumann (1979).

DISCUSSION

With the acknowledged economic and social importance of the coastal oceans of the world, considerable effort has been expended in efforts to understand the processes operating there. However, it is clear from the outset that there can be marked differences between coastal regions. The geographic setting plays an important part, with notable variations between the east and west coasts of the continents.

The orientation of the coastline, latitude, the extent of shelf area and disposition of neighbouring land masses are additional complicating features, quite apart from differing weather patterns. In order to assess the relevance of the results for the Natal coast in relation to those from other regions, it is therefore necessary to identify similar components.

The dominant feature is the western boundary current, which immediately identifies an east coast environment. Such corresponding currents occur off the east coasts of Japan, Australia, and North and South America. Of these, by far the most investigations have been made off the southeast United States, where the Gulf Stream flows polewards adjacent to the shelf.

The South Atlantic Bight (SAB) region, extending over about 9° of latitude, has points of similarity with the Natal coast. However, the shelf there is wider, varying from about 50 km to 120 km, with the shelf break occurring at about the 75 m contour. On this shallow shelf, Atkinson *et al.* (1983) identified three depth-dependent zones: 0-20 m, 21-40 m and 41-60 m. The inner shelf responds quickly to atmospheric conditions, and temperatures in summer exceed 28°C; salinity is also affected markedly by river outflow. At the outer shelf most of the variability is due to Gulf Stream frontal effects which occur at periods of 2 days to 2 weeks (Lee *et al.* 1981), but which are more akin to the eddies observed in the Agulhas Current east of the Agulhas Bank (Lutjeharms, 1981) than to the meanders observed off Natal.

Lee and Atkinson (1983) analysed the low-frequency variability over the SAB shelf using results from an extensive set of moorings. They found that along-shelf current fluctuations at the 40 m isobath were highly coherent with the along-shelf wind and coastal sea level at

periods of 3 to 4 days and 10 to 12 days. These current fluctuations were in phase over the whole length of shelf, indicating a non-propagating barotropic response to wind-driven sea level fluctuations. At the shelf edge Gulf Stream features were observed to propagate northwards at speeds of 0.5 to 0.7 m/s, producing fluctuations of currents and temperatures on the shelf with along-shelf coherence scales of 100 km. These results have aspects which are similar to those obtained on the Natal coast, but it is obvious that the SAB does not have the same along-shelf variability.

Coastal trapped waves have also been found to play an important part in the dynamics of many coastal regions (Le Blond and Mysak, 1978). Lee and Atkinson (1983) did not observe such southward propagating waves in the SAB, although Schott and Düing (1976) found significant evidence for the propagation of trapped waves further south in the Florida Straits.

Schumann (1983) analysed available data but found no clear evidence for the existence of coastal trapped waves off the southeast coast of Southern Africa. This was probably due in part to the use of data from the differing regimes off Natal, although further south conditions may be more favourable. Nonetheless, he also described an event propagating northwards at about 3.4 m/s between Port Edward and Richards Bay; the temperature record in Figure 5.4 shows this signal during April, 1976. It is of interest to note that Brooks and Mooers (1977) found that the coherence between sea level stations decreased rapidly when moving north of the Florida Straits into a widening shelf region. As off Natal, this would also seem to imply that the differing shelf structure and Gulf Stream inhibited the propagation of shelf waves.

The situation is different off the east coast of Australia. There the East Australian Current (EAC) separates from the coast at about 31°S or 32°S, and flows eastwards into the Pacific Ocean (see e.g. Cresswell et al. 1983). Complex eddies result, but the EAC does not have the same effect on the dynamics of the coastal shelf as does the Agulhas Current off Natal. Hamon (1976) also established that coastal trapped waves were a regular wind-forced feature of the East Australian coast.

The bimodal structure of the Kuroshio (Taft, 1972) and the shelf and

island structure off Japan point to a complex dynamical region. Nonetheless, Shoji (1961) was able to follow the progression of what was later discovered to be a shelf wave along the Japanese east coast.

Off South America the Brazil Current flows southwards nearly parallel to the edge of the continental shelf between 32°S and 38°S, before turning southeastwards towards deeper water (Legeckis and Gordon, 1982). Further south a confluence occurs with the northward-flowing Falklands (Malvinas) Current. Conditions on the continental shelf areas are poorly understood at present.

It is clear that, while all these east coast regions have some similarities, there are specific characteristics which serve to identify each one uniquely. The region discussed here, namely, the coastal ocean off Natal, is also only one part of the south-east coast of Southern Africa, dominated by the flow of the Agulhas Current.
In conclusion, some satellite images are shown to highlight features discussed earlier. Figure 5.13 is an example of what might be termed the "average" situation; both the thermal infrared band and a processed level 2 image giving subsurface radiances are shown.

The main stream of the Agulhas Current is seen to diverge from the coast south of Cape St Lucia, and then to move inshore again south of Durban with some indication of meandering. Various features are evident on the Natal shelf, highlighted by the presence of total suspended solids of terrigenous biological and non-biological origin (such as silt, clay and other types of sediment). A plume extending out from the Tugela River is clearly evident, with substantial rainfall reported inland about a week earlier. Walters and Schumann (1985) have investigated the detection of silt utilising the NIMBUS-7 coastal zone colour scanner, with other examples along this coast.

On the other hand, Figure 5.14 shows what can only be described as an anomalous situation. Images of sea surface temperature taken on consecutive days reveal a large cyclonic eddy extending well into the region where the Agulhas Current can normally be expected. No additional, concurrent measurements are available, so that it is not clear where the flow of the Agulhas Current was at that time. However, the flow patterns seem to indicate that during such an event waters from the Natal shelf may be entrained into the deeper ocean. As mentioned earlier, such major perturbations on the flow have been

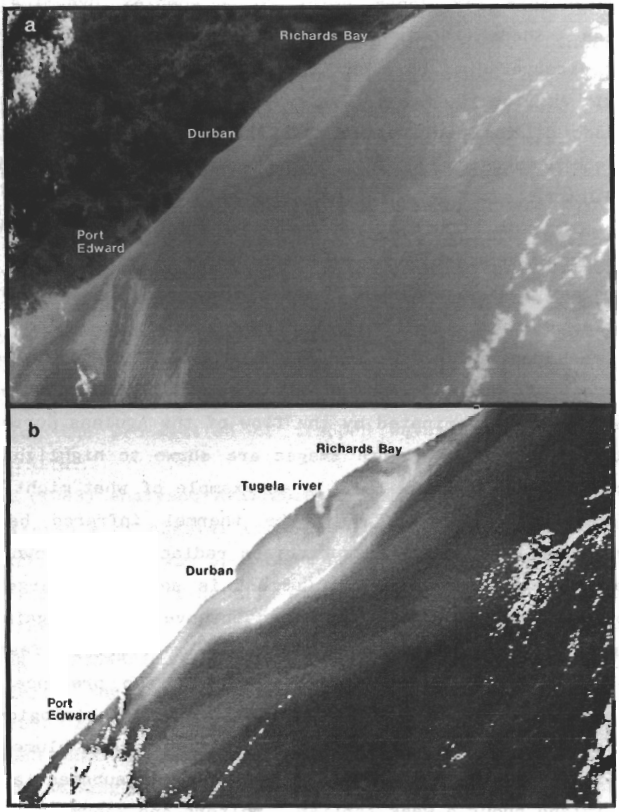

Figure 5.13 Data from the NIMBUS-7 Coastal Zone Colour Scanner acquired on 11 March, 1979. The upper picture (a) shows the channel 6 thermal infrared (11.5 m) image, while below is shown the level 2 image depicting subsurface radiances (with acknowledgement to NASA and the Nimbus Experimental team).

observed from time to time, and Gründlingh and Pearce (1984) also describe the large cyclonic vortex which almost brought oil spilled from the stricken tanker World Glory onto the coast.

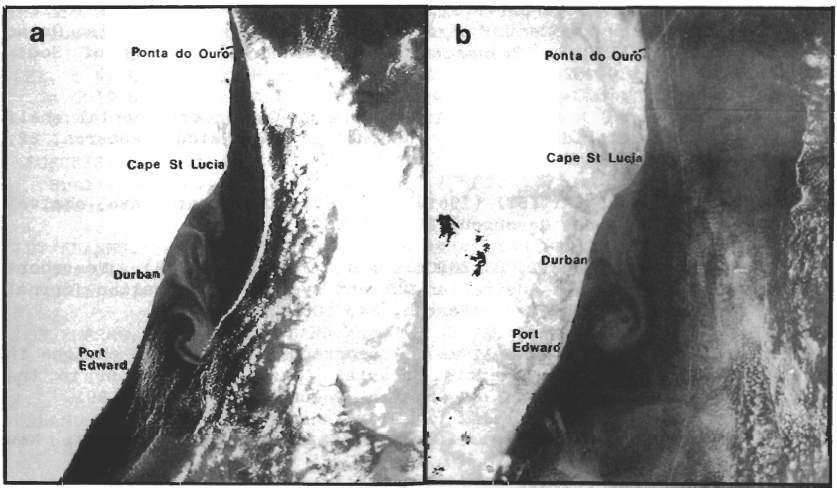

Figure 5.14 Infrared images taken on 21 and 22 April, 1983 (a and b respectively), by the NOAA-7 satellite (with acknowledgement to NOAA).

Acknowledgements

Much of the work was completed while the author was employed by the National Research Institute for Oceanology, and the contribution made by that Institute, and the use of facilities is gratefully acknowledged. In particular, the develpments in data collection and processing made by the late Chris Snyman added substantially to the success of the various programmes.

REFERENCES

ACCAD, Y and C P PEKERIS (1978). Solution of the tidal equations for the M_2 and S_2 tides in the world oceans from a knowledge of the tidal potential alone. **Philosophical Transactions of the Royal Society,** London, Ser. A290, 235-266.

ATKINSON, L P, T N LEE, J O BLANTON and W S CHANDLER (1983). Climatology of the southeastern United States continental shelf waters. **Journal of Geophysical Research,** 88, 4705-4718.

BANG, N D and A F PEARCE (1978). Physical Oceanography. In: Ecology

of the Agulhas Current region: an assessment of biological responses to environmental parameters in the south-west Indian Ocean (Ed: AEF HEYDORN) **Transactions of the Royal Society of South Africa,** 43, 156-162.

BROOKS, D A and C N K MOOERS (1977). Wind-forced continental shelf waves in the Florida Current. **Journal of Geophysical Research,** 82, 2569-2576.

CLARKE, A J and D S BATTISTI (1981). The effect of continental shelves on tides. **Deep-Sea Research,** 28, 665-682.

CRESSWELL, G R, C ELLYETT, R LEGECKIS and A F PEARCE (1983). Nearshore features of the East Australian Current system. **Australian Journal of Marine and Freshwater Research,** 34, 105-114.

GILL, A E and E H SCHUMANN (1979). Topographically induced changes in the structure of an inertial coastal jet: application to the Agulhas Current. **Journal of Physical Oceanography,** 9, 975-991.

GILL, A E (1982). **Atmosphere-Ocean Dynamics.** Academic Press, New York.

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

GRÜNDLINGH, M L (1979). Observations of a large meander in the Agulhas Current. **Journal of Geophysical Research,** 84, 3776-3778.

GRÜNDLINGH, M L (1980). On the volume transport of the Agulhas Current. **Deep-Sea Research,** 27, 557-563.

GRÜNDLINGH, M L and A F PEARCE (1984). Large vortices in the northern Agulhas Current. **Deep-Sea Research,** 31, 1149-1156.

HAMON, B V (1976). Generation of shelf waves on the East Australian coast by wind stress. **Mémoires Société Royale des Sciences de Liége,** 6e série. 10, 359-367.

HARRIS, T F W (1964). Notes on Natal coastal waters. **South African Journal of Science,** 60, 237-241.

HARRIS, T F W (1978). Review of coastal currents in Southern African waters. **South African National Scientific Programmes Report No. 30,** CSIR, 103 pp.

KNAUSS, J A (1969). A note on the transport of the Gulf Stream. **Deep-Sea Research,** 16, 117-123.

LE BLOND, P H and L A MYSAK (1978). **Waves in the ocean,** Elsevier, New York, 602 pp.

LEE, T N and L P ATKINSON (1983). Low-frequency current and temperature variability from Gulf Stream frontal eddies and

atmospheric forcing along the southeast US outer continental shelf. **Journal of Geophysical Research,** 88, 4541-4568.

LEE, T N, L P ATKINSON and R LEGECKIS (1981). Detailed observations of a Gulf Stream frontal eddy on the Georgian continental shelf, April 1977. **Deep-Sea Research,** 28, 347-378.

LEGECKIS, R and A L GORDON (1982). Satellite observations of the Brazil and Falkland currents - 1975 to 1976 and 1978. **Deep-Sea Research,** 29, 375-401.

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 C P DUNCAN (1981). Characteristics of the currents east and south of Madagascar. **Deep-Sea Research,** 28,879-899.

MALAN, O G and E H SCHUMANN (1979). Natal shelf circulation revealed by LANDSAT imagery. **South African Journal of Science,** 75, 136-137.

PEARCE, A F (1977a). The shelf circulation off the east coast of South Africa. **CSIR Research Report No 361.**

PEARCE, A F (1977b). Some features of the upper 500 m of the Agulhas Current. **Journal of Marine Research,** 35, 731-753.

PEARCE, A F (1978). Seasonal variations of temperature and salinity on the northern Natal continental shelf. **South African Geographical Journal,** 60, 135-143.

PEARCE, A F, E H SCHUMANN and G S H LUNDIE (1979). Features of the shelf circulation off the Natal coast. **South African Journal of Science,** 74, 328-331.

PEARCE, A F and M L GRÜNDLINGH (1982). Is there a seasonal variation in the Agulhas Current? **Journal of Marine Research,** 40, 177-184.

SAETRE, R and A J DA SILVA (1984). The circulation of the Mozambique channel. **Deep-Sea Research,** 31, 485-508.

SHOJI (1961). On the variations of the daily mean sea levels along the Japanese islands. **Journal of the Oceanographical Society of Japan,** 17, 141-152.

SCHOTT, F and W DUING (1976). Continental shelf waves in the Florida Straits. **Journal of Physical Oceanography,** 6, 451-460.

SCHUMANN, E H (1981). Low frequency fluctuations off the Natal coast. **Journal of Geophysical Research,** 86, 6499-6508.

SCHUMANN, E H (1982). Inshore circulation of the Agulhas Current off Natal. **Journal of Marine Research,** 40, 43-55.

SCHUMANN, E H (1983). Long-period coastal trapped waves off the southeast coast of Southern Africa. **Continental Shelf Research,** 2, 97-107.

SCHUMANN, E H (1986). The bottom boundary layer inshore of the Agulhas Current off Natal in August, 1975. **South African Journal of Marine Research**, 4, 93-102.

SCHUMANN, E H and M J ORREN (1980). The physico-chemical characteristics of the south-west Indian ocean in relation to Maputaland. In: **Studies on the ecology of Maputaland** (Eds: M N BRUTON and K H COOPER). Rhodes University and the Natal Branch of the Wildlife Society of Southern Africa. 8-11.

SCHUMANN, E H and L-A PERRINS (1982). Tidal and inertial currents around South Africa. **Proceedings of the Eighteeenth Coastal Engineering Conference.** ASCE/Cape Town, South Africa, 2562-2580.

SNYMAN, C G (1980). **An oceanographic data acquisition system using a digital computer.** M.Sc. Thesis, University of Natal, 153 pp.

STAVROPOULOS, C C (1971). Data acquisition on the RV Meiring Naudé. **Electronics and Instrumentation,** May 1981, 11-15.

TAFT, B (1972). Characteristics of the flow of the Kuroshio south of Japan. In: **Kuroshio, Physical aspects of the Japan current** (Eds: STOMMEL and K YOSHIDA), Chapter 6, 164-216, University of Washington Press, Seattle.

WALTERS, N M and E H SCHUMANN (1985). Detection of silt in coastal waters by NIMBUS CZCS. In: **The South African ocean colour and upwelling experiment.** (Ed: L V SHANNON) Sea Fisheries Research Institute, 219-225.