THE COASTAL OCEANS OF SOUTH-EASTERN AFRICA

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Chapter 20. THE COASTAL OCEANS OF SOUTH-EASTERN AFRICA

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1. Introduction to the region

The coastal ocean off south-eastern Africa is characterised by at least one common, coherent aspect: it forms part of what may be considered to be the greater Agulhas Current circulation and all its components are largely dominated by this current system. In other respects it is very diverse (Schumann, 1998). It extends from the tropics to a region adjacent to the Subantarctic. The shelf regions are very narrow in some distinct parts and quite wide in others (Fig. 20-001). Certain parts of the shelf regions have been studied fairly intensively, while for other regions there is no data or information to speak of. The current extent of knowledge on this coastal ocean region is therefore, relying on the existing data base, very inhomogeneous.

Knowledge on the bathymetry and geology of the region has not changed significantly since a previous review of this kind (Schumann, 1998), so will only be dealt with here where it affects other aspects of the nature of the coastal oceans. The equatorward border of the system lies at the northern mouth to the Mozambique Channel (Fig. 20-001). This is a useful and generic choice and not just one brought about by geographical pragmatism. The major influence of the Indian monsoon system on the dominant ocean currents lies entirely to the north of this border (e.g., Ridderinkhof and de Ruijter, 2003). Numerical model studies (e.g., Maltrud et al., 1998) suggest a residual monsoonal effect on currents in the Mozambique Channel, but direct current observations to date do not support this. By contrast, the poleward border of the region coincides with the termination of the Agulhas Current at the Agulhas Current Retroflection south-west of the southern tip of Africa. The eastern border of the coastal oceans of south-eastern Africa has to include the waters to the east of the island of Madagascar. As is described below, the coastal waters of the east coast of Madagascar are not a distinctly separate system (Cooke et al., 2004) but in many ways form a coherent part of the greater Agulhas Current system. Nevertheless, for organisational purposes the coastal oceans of this system can be separated into four distinctive parts: the shelf regions in the Mozambique Channel, the shelf regions east and south of Madagascar, the shelf inshore of the northern Agulhas Current and, last,

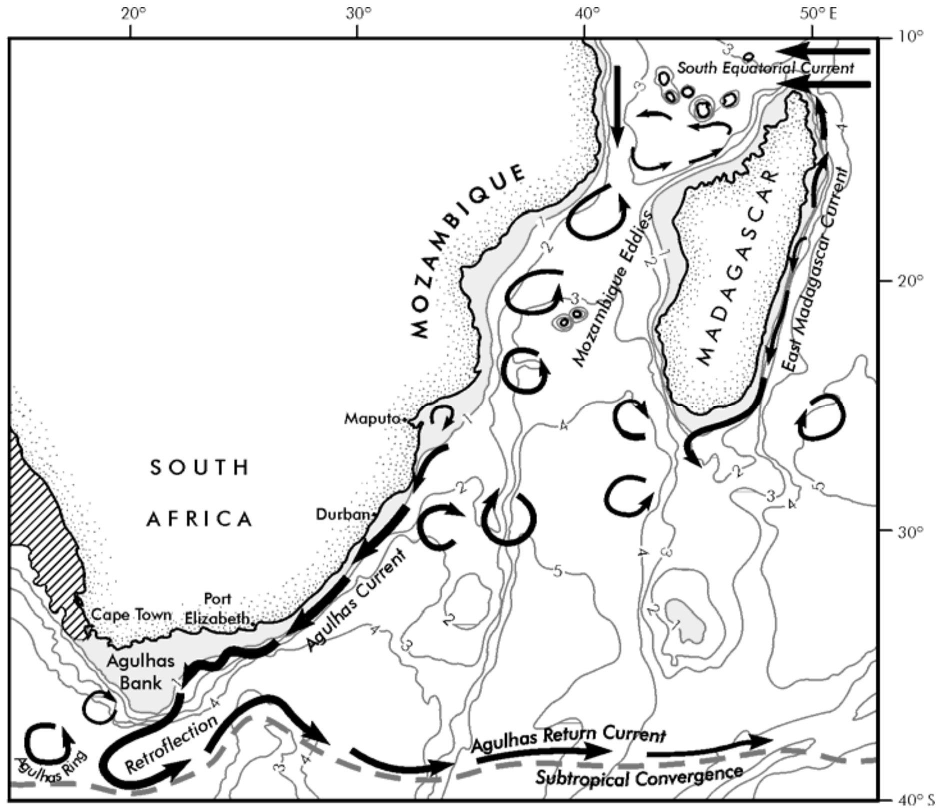

Fig. 20-001 Bathymetry of the South West Indian Ocean in km (after Dingle et al., 1987a and Simpson, 1974) and the major circulation features. Shelf regions shallower than 1 km are shaded; hatching indicates upwelling. Some major place and feature names used in the text are given.

inshore of the southern Agulhas Current. As will be seen, making this geographic distinction between the southern and northern parts of the Agulhas Current is important since the nature of the waters and the circulation on their respective shelves are dissimilar (viz. Fig. 20-001). This comes about as a result of the different behaviour of the edge of the Agulhas Current in these two regions. For an understanding of the characteristics of waters on the continental shelves it is therefore necessary briefly to describe the existing knowledge on the offshore ocean currents of the greater Agulhas Current system.

The Agulhas Current is supplied with water from essentially two different sources: the South Equatorial Current and recirculation in a South-West Indian Ocean subgyre (Stramma and Lutjeharms, 1997; Fig. 20-002). The greater part (40 Sv out of a total 65 Sv in the upper 1 000 m) comes from the subgyre. This configuration of the basin-wide circulation has been thought to be reflected in the behaviour and natural history of marine animals (Heydorn et al., 1978), for example the migrations of leatherback sea turtles (Hughes et al., 1998). The manner in which the South Equatorial Current acts as a source for the Agulhas Current is not entirely clear. It was previously thought that this current bifurcates on reaching the east coast of Madagascar - forming the southern and the northern branches of the East Madagascar Current. The northern branch of this current and the remainder of the South Equatorial Current would then pass the northern tip of Madagascar and move onwards to the east coast of the African

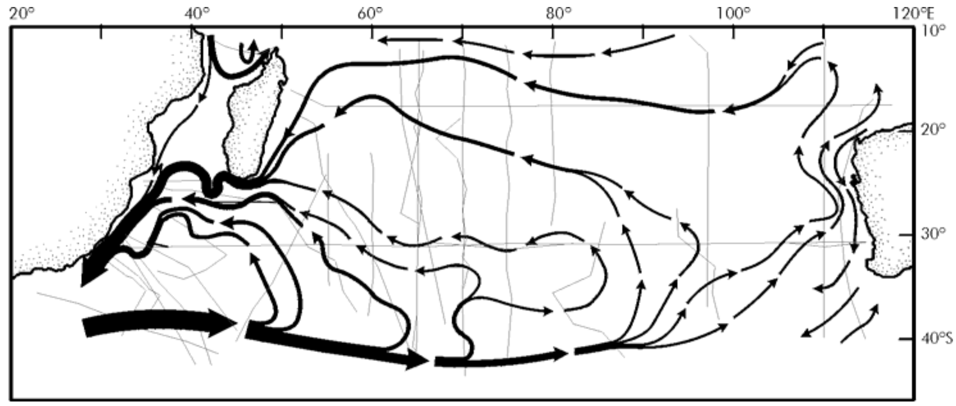

Fig. 20-002 Circulation patterns of the South West Indian Ocean. (After Stramma and Lutjeharms, 1997.) The thickness of the lines denotes the volume flux in the upper 1 500 m. Thin lines indicate lines of historical hydrographic stations on which the portrayal is based. The Agulhas Current along south-eastern Africa is largely supported by recirculation in a South West Indian Ocean subgyre.

continent. Here a similar split would occur with some of the water passing northwards into the Somali Current and the rest southward into the Mozambique Channel as the Mozambique Current.

These two western boundary currents - the southern limb of the East Madagascar Current and the Mozambique Current - would then have a confluence somewhere off South Africa to form the Agulhas Current. This is the classical portrayal of flow in this ocean region (Michaelis, 1923) still found in many textbooks and most atlases and is largely based on analyses of ships' drift (e.g., Sætre, 1985; Lutjeharms et al., 2000b). However, modern observations have shown this depiction to be largely incorrect. The new findings on these currents are of substantial importance for understanding the flow patterns on the adjacent continental shelves.

It has been demonstrated that no coherent, unbroken western boundary current exists in the Mozambique Channel. First adumbrated by using the full set of non-synoptic hydrographic observations (Sætre and Jorge da Silva, 1984) as well as by modelling (Biastoch and Krauß, 1999), modern synoptic observations (De Ruijter et al., 2002) have unequivocally shown that mesoscale eddies are formed at the narrows of the channel and progress from here southward. No continuous current exists. On averaging the motions of the drifting eddies (as happens by plotting the means of many ships' drift observations; e.g., Lutjeharms et al., 2000b) there is the suggestion of a consistent and continuous boundary current, leading to the classical misinterpretation.

These Mozambique eddies drift southward along the shelf edge at speeds of about 5 cm/s and may eventually reach the Agulhas Current (Schouten et al., 2002). They form the major elements of the circulation in the Mozambique Channel. The movement in the rest of the channel seems to be sluggish and quite variable, but there are few observations to support any firm conclusion in this regard, particularly on the eastern side of the channel. Here there is a dearth of modern hydrographic or current meter observations (Lutjeharms, 1977). In contrast to classical portrayals, the Mozambique Channel is therefore now seen as a minor source of water for the Agulhas Current proper (Fig. 20-002), and only in an intermittent manner. The same holds for the East Madagascar Current.

Instead of being a direct tributary to the Agulhas Current, the southern branch of the East Madagascar Current has been noted to retroflect south of Madagascar both in hydrographic data (Lutjeharms et al., 1981a) as well as in satellite remote sensing (Lutjeharms, 1988). This implies that this current, as in the case of the purported Mozambique Current, contributes very little to the Agulhas Current, and if so, only spasmodically. However, the retroflection of the East Madagascar Current has been shown to be a region that generates both cyclonic as well as anti-cyclonic eddies (De Ruijter et al., 2003), carrying away some of the shelf waters in the process. Although these two currents systems – East Madagascar Current and Mozambique eddies - therefore do not form a continuum with the Agulhas Current itself, they do influence its behaviour indirectly and can therefore be considered to constitute an inherent part of the greater Agulhas system.

The Agulhas Current proper is fully constituted somewhere near 28° S, along the east coast of the province of KwaZulu-Natal of South Africa, between Maputo and Durban (Fig. 20-001). Here the continental shelf is narrow and the course of the current very stable. This is true for the whole of what might be considered the northern Agulhas Current (Gründlingh, 1983) extending downstream as far as Port Elizabeth, at the eastern end of the broad shelf region south of Africa known as the Agulhas Bank (Fig. 20-001). The coincidence of a narrow shelf and a very stable juxtapositioned current is not fortuitous; De Ruijter et al. (1999a) have demonstrated that the continental slope plays an important role in stabilising the trajectory of the current. The only part of the shelf that does not comply with these stabilising requirements lies just upstream of Durban, the Natal Bight. At this coastal offset the shelf is anomalously wide and the continental slope considerably gentler than at other locations adjacent to the north Agulhas Current. Perturbations on the current path that occur here will grow, move downstream and have considerable effects on the subsequent behaviour of the current (Van Leeuwen et al., 2000). This intermittent meander on the Agulhas Current (Lutjeharms and Roberts, 1988) is called the Natal Pulse and has a considerable effect on the circulation of the adjoining shelf region. When the waters in the Agulhas Current reach the Agulhas Bank, the nature of the current changes dramatically.

From the latitude of Port Elizabeth it is know as the southern Agulhas Current and, in contrast to the northern Agulhas Current, a range of meanders are formed on its shoreward side (Lutjeharms et al., 1989a). These meanders cause shear edge eddies and attendant plumes that move with the current and influence the upper waters of the shelf in this region. The average trajectory of the current follows the shelf edge, thus lying farther and farther from the coastline (viz. Fig. 20-001), until the tip of the Agulhas Bank is passed. In the western lee of the shelf this major current generates an intense cyclonic eddy (Penven et al., 2001a) that eventually drifts off into the South Atlantic Ocean. The current itself continues south-westward into the South Atlantic until it retroflects.

The Agulhas Retroflection is a region exhibiting some of the highest levels of mesoscale variability in the world ocean (Lutjeharms and van Ballegooyen, 1988; Garzoli et al., 1996). This is due to the manner in which the retroflection loop occludes, intermittently forming large Agulhas rings (Lutjeharms and Gordon, 1987) that then drift off into the South Atlantic (Duncombe Rae, 1991; Duncombe Rae et al., 1996; Schouten et al., 2000). It has been suggested (Duncombe Rae et al., 1992) that these rings may interact with the coastal upwelling on South Africa's west coast, but analyses of the tracks of such rings (e.g., Schouten et al., 2000) indicates that such interaction must be a rare exception. Most rings spend some time in the vicinity of where they have originally been shed (Boebel et al., 2003), losing a substantial part of their characteristic heat and salt (Arhan et al., 1999) and having their water masses exchanged with other rings (Fine et al., 1988) and with Agulhas cyclones (Lutjeharms et al., 2003b). There is some evidence that Agulhas rings may often be found next to the western edge of the Agulhas Bank (Lutjeharms and Valentine, 1988) and may play a role in carrying surface water directly from the Agulhas Current northward past the western edge of the bank (Lutjeharms and Cooper, 1996).

On moving away from their source region, Agulhas rings tend to move further away from the African coast (Byrne et al., 1995; Schouten et al., 2000). Comprehensive reviews of what is currently known about the inter-ocean exchange that takes place here can be found in Lutjeharms (1996) and in De Ruijter et al. (1999b). That part of the flow not involved in ring formation, the Agulhas Return Current (Lutjeharms and Ansorge, 2001), moves water eastward along the Subtropical Convergence. These deep-sea components of the greater Agulhas system therefore no longer have a direct influence on the shelf regions. They, as well as the Agulhas Current proper, may have an indirect effect via their influence on the atmosphere and on biota.

The Agulhas Current has a marked, visible effect on the overlying atmosphere through the creation of cumulus clouds (Lutjeharms et al., 1986b), especially along its southern part and at the Agulhas Retroflection where the heat and moisture loss to the atmosphere is substantial (Mey et al., 1990). In these regions, under the right conditions, the thermodynamic considerations adequately account for the formation of cumulus clouds (Lee-Thorp et al., 1998, 1999). The uptake of moisture in the marine boundary layer (e.g., Jury and Walker, 1988) can have a marked effect on the moisture of the adjacent coastal zone and in consequence on the intensities of local storms and thus on rainfall (Rouault et al., 2002). Increasing rainfall may in turn be felt in the salinity, water column stratification and colour of the adjacent shelf waters. Jury et al. (1993) have in fact shown that the distance of the Agulhas Current offshore has a noticeable effect on the coastal rainfall. Under different climate change scenarios, the behaviour of the Agulhas Current may change significantly and the effect on coastal and shelf rainfall may change in concert (Lutjeharms and de Ruijter, 1996).

The Agulhas Current not only has a direct effect on rainfall over the adjacent coast and shelf, it also has an effect on regional atmospheric circulation patterns (Reason, 2001) and thus on rainfall over much wider areas. An increase in sea surface temperature of 2 ˚C at the Agulhas Retroflection (Crimp et al., 1998) can substantially affect the atmospheric circulation over the whole southern African subcontinent. An increase in sea surface temperature over the South Indian Ocean will statistically lead to an increase in rainfall over regions that form the drainage regions for some of the main rivers of the South African east coast (Walker, 1990). The effect of increased runoff on different shelf seas may be very uneven. An investigation of the shelf waters in the Natal Bight shortly after a major rainfall event (Lutjeharms et al., 2000c) suggests that it might be relatively insignificant here and restricted to a small area just offshore of the mouth of the river. Along the Mozambican coast it may, by contrast, affect the surface salinities of substantial parts of the shelf (Sætre and de Paula e Silva, 1979).

To summarise: the south-western Indian Ocean may be considered to be that part of the South Indian Ocean that is not directly influenced by the monsoonally driven ocean currents. The shelf regions of this particular region are largely dominated by what may be considered to be the greater Agulhas Current system. Along the east coast of Madagascar and the east coast of South Africa this consists of well-developed western boundary currents. Along the east coast of Mozambique it consists of a series of eddies drifting poleward and along the west coast of Madagascar it may be a sluggish flow with no distinct pattern or temporal behaviour. Too few observations are available to characterise the latter unambiguously. This is also true of the behaviour of shelf waters in many other parts of the Mozambique Channel.

2. Mozambique Channel

A proper understanding of the nature of the waters over the shelves of the Mozambique Channel is constrained by the large degree of ignorance on the water movement in the adjacent deep sea. As noted above, historically the flow here has been visualised as consisting of an intense western boundary current along the east coast of Mozambique. Although this has now been shown to be incorrect (e.g., Ridderinkhof et al., 2001), the average drift patterns at the sea surface (e.g., Sætre, 1985) nevertheless indicate a strong movement poleward along the eastern shelf of Mozambique (Fig. 20-004) whereas elsewhere in the channel the average flow is small and its direction indistinct. The variability of the flow is very high in the western side of the channel, but low in the eastern side. This variability is evident in analyses of ships' drift (Lutjeharms et al., 2000b), altimetric observations (e.g., Lutjeharms et al., 2000d) and in modelling of the region (e.g., Biastoch and Krauß, 1999). These results – both strong currents at the shelf edge and high variability – of course all agree with the concept of a train of eddies moving poleward through the channel. Knowledge on the deep sea circulation that may affect the shelves is even more lacking on the eastern side of the channel.

Ships' drift observations, altimetry and even the few hydrographic observations give no unambiguous indication of the movement of water here. In general speeds are low and to the north in the ships' drift observations (Sætre, 1985; Lutjeharms et al., 2000b) whereas modelling results (e.g., Biastoch et al., 1999) indicate an average flow to the south. Interpretations from the very few hydrographic data (e.g., Menaché, 1963; Sætre and Jorge da Silva, 1984; Donguy and Piton, 1991) have included a northward flow as well as a southward flow. The only known direct observations indicated a weak northward (Martin et al., 1965) and a weak southward flow (Piton and Poulain, 1974). Satellite observations have indicated the presence of cyclonic eddies off the shelf edge at the south-western coast of Madagascar that draw coastal water, rich in chlorophyll-*a*, seaward (Quartly and Srokosz, 2004). What does stand out in all appropriate data is that the intensity of current variability on the eastern side of the channel is considerably lower than on the western side.

2.1 General water mass characteristics in the channel

The temperature-salinity characteristics of the waters in the Mozambique Channel are shown in Fig. 20-003. This figure is based on relatively old hydrographic data, but homogeneously covers a greater part of the channel than more modern data. It demonstrates that the salinities of waters in the upper layers lie in a band between

35.00 and 35.40, with a few outliers, mostly as fresher water. These particular outliers may be due to river runoff. At 18˚ C there are two different water masses, identifiable

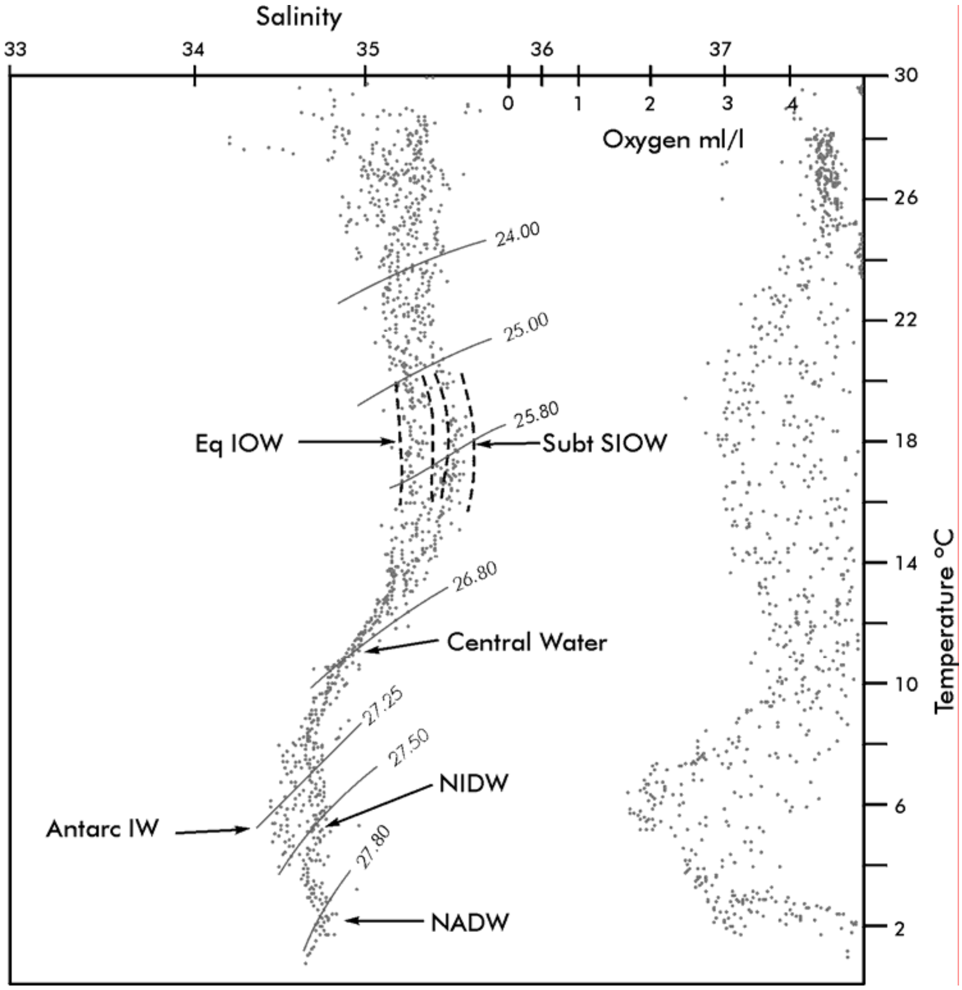

Fig. 20-003 The temperature-salinity and temperature-oxygen characteristics of the water masses in the Mozambique Channel. (After Lutjeharms, 1991.) Sigma-t isolines have been added on the T-S scattergram. Water types that are evident are Equatorial Indian Ocean Water (Eq IOW), Subtropical South Indian Ocean Water (Subt SIOW), Central Water, Antarctic Intermediate Water (Antarc IW), North Indian Deep Water (NIDW) and North Atlantic Deep Water (NADW).

by distinct salinities. They are Equatorial and Subtropical Indian Ocean Water respectively and are found in different parts of the channel on different occasions. No durable delimitation for the distribution of either is to be found (Sætre and Jorge da Silva, 1984), although Equatorial Indian Ocean Water (also called Tropical Surface Water) is found largely in the northern part of the channel. Since waters to a depth of 900 m are know to upwell onto the Mozambican shelf (e.g., Lutjeharms and Jorge da Silva, 1988) one can expect to find water types down to the less saline water of the Central Water (viz. Fig. 20-003) in some coastal regions, but most of the waters on shallow shelves would come from waters in more superficial layers.

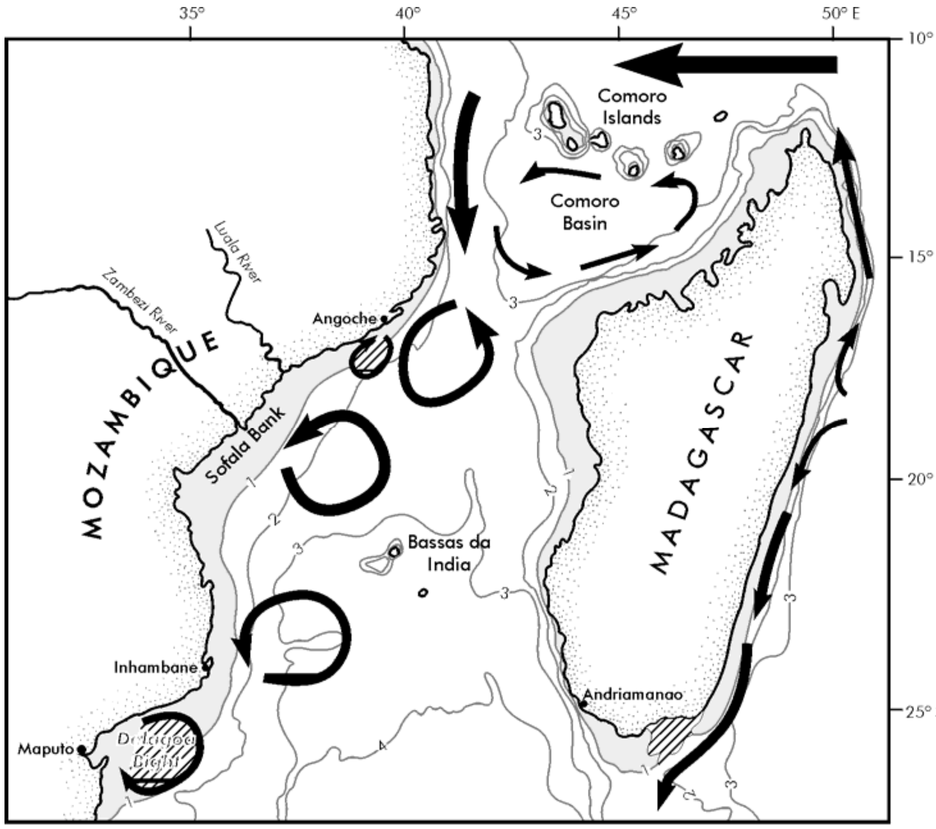

Fig. 20-004 Bathymetry of the Mozambique Channel and the continental shelf off Madagascar in km (after Simpson, 1974) with the major circulatory features. Shaded areas are shallower than 1 km; hatched areas denote upwelling. Names of places and features mentioned in the text are given.

2.2 Effects of shelf morphology

The general bottom morphology of the shelves in the Mozambique Channel is shown in Fig. 20-004. The shelf is narrow on the western side of the narrows of the channel at about 16° S, but wide on the eastern side. They are fairly narrow on both sides of the channel at its southern mouth. The rest of the Mozambican shelf is wide, while that off Madagascar is narrower. Just south of the mouth of the channel there is an extensive offset in the coastline just off the Mozambican capital of Maputo, the Delagoa Bight. There is also an offset south of Angoche (Fig. 20-004). The shelves around the numerous islands, particularly the Comores in the northern mount of the channel, are narrow. These shapes of the shelf edge have a decided effect on the coastal water movement.

One of the consequences of the changes in direction of the coastline is in the formation of coastal lee eddies. An example of such a feature can be seen off the town of Angoche (Fig. 20-005). Here the flow along the greater part of the shelf edge - and probably on the shelf as well - is strongly poleward. At the time it was assumed that this formed part of a continuous Mozambique Current (Nehring, 1984); currently the consensus is that this most probably was part of the edge of an anti-cyclonic eddy drifting southward (e.g., De Ruijter et al., 2002). Notwithstanding the ignorance on its

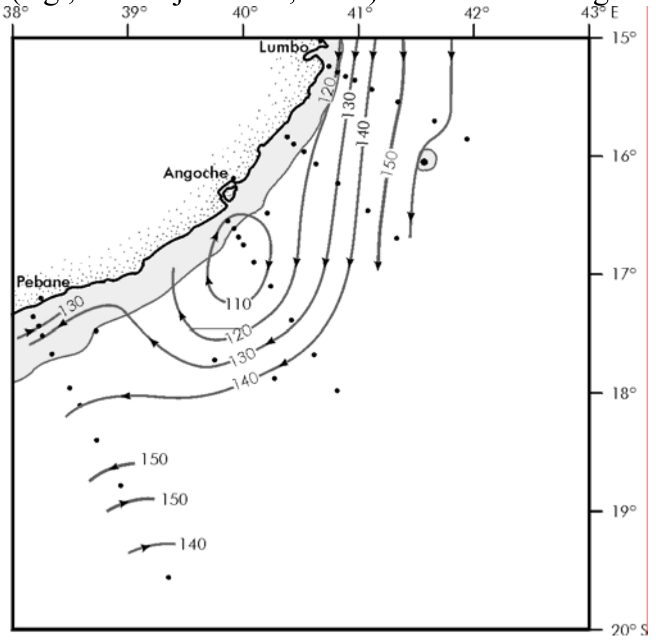

Fig. 20-005 Lee eddy at Angoche along the Mozambican coast (viz. Fig. 20-004). The dynamic topography of the sea surface relative to the 600 dbar level is given in dynamic centimetre, based on a cruise undertaken in 1980. Dots represent station positions. The continental margin shallower than 1 km is shaded. (After Nehring et al., 1987.)

source, the important thing to note is the fact that there was a strong current poleward on this occasion, even though it might have been intermittent. This current overshot the offset in the coast at about 16° S, forming a distinct lee eddy to the south (Fig. 20-005). This eddy had a diameter of about 100 km and deeper water was upwelled in its core (Schemainda and Hagen, 1983). This is shown by an enhanced nutrient content of more than 12 μmol/ℓ nitrate-nitrogen at 75 m depth compared to 2-4 μmol/ℓ in the offshore current at the same depth. A resultant peak in chlorophyll-*a* concentration was also observed in this lee eddy (Nehring et al., 1987). Although no hydrographic stations were carried out on the shelf itself, the implication clearly is that the motion on the adjacent shelf would be equatorward.

The shelf configuration at this presumed lee-eddy is similar to that of the St Lucia and the Port Alfred upwelling cells (Lutjeharms et al., 1989b; Lutjeharms et al., 2000a; Figs 20-001 and 20-016). At all three of these locations a strong current along the shelf edge moves past an offset in the coastline, from a narrow shelf and then past a wider shelf. According to the theory put forward by Gill and Schumann (1979), this should lead to upwelling inshore of the strong current. In the former two cases it does, therefore perhaps also off Angoche at about 16˚ S in the Mozambique Channel. In his analysis of seasonal sea surface temperatures and the depths of isotherms along this coastline, Jorge da Silva (1984a) has shown the prevalence of upwelling at this spot, but only for certain periods of the year. His database for such seasonal analysis was not very large, so that this result can only be considered tentative. If the hypothesis is correct and this upwelling is driven by poleward currents as part of passing eddies, it would be sporadic and not a continuous feature. Nevertheless, this spot represents the highest observed chlorophyll-*a* values along this coastline (Nehring et al., 1987) and may therefore have a decided influence on the ecosystem of this whole shelf region.

If the offshore eddies that form at the narrows (De Ruijter et al., 2002; Ridderinkhof and de Ruijter, 2003; Fig. 20-004) consistently move along the shelf edge it is likely that the waters on the adjacent shelf would experience alternating poleward and equatorward setting currents. This situation is also found on the shelf adjacent to the northern Agulhas Current where the shelf waters move largely in harmony with the current, but on the intermittent passing of a Natal Pulse, reverse and set strongly against the direction of the Agulhas Current (Lutjeharms and Connell, 1989). Quartly and Srokosz (2004) have used satellite observations of ocean colour to demonstrate that passing Mozambique eddies extract water from the neighbouring Mozambican shelf and inject it into the mid-channel region. In this way the exchange of waters between the shelf and the deeper part of the channel will consist of rather frequent episodes, driven from afar. They (Quartly and Srokosz, 2004) have also shown that the passage of eddies past the Delagoa Bight appears to affect the circulation there.

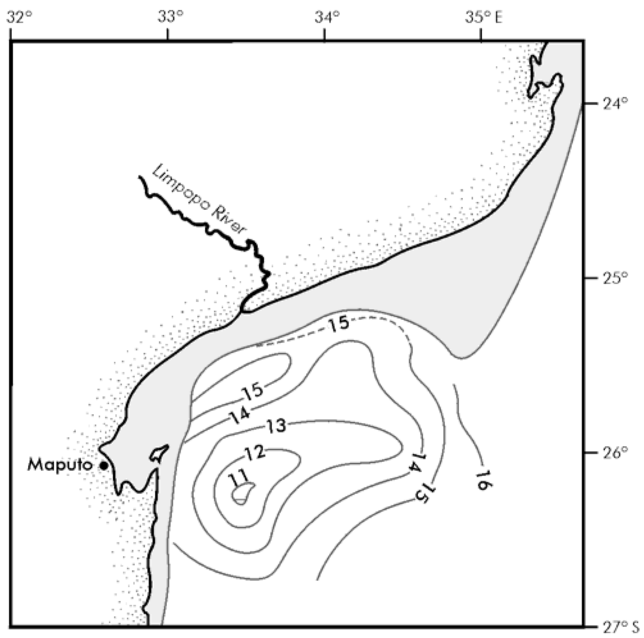

Fig. 20-006 The Delagoa Bight eddy off the city of Maputo in southern Mozambique (viz. Fig. 20-04). Isotherms at 200 m depth show the cold water upwelled in the centre of the eddy, based on a cruise undertaken in 1982. (After Lutjeharms and Jorge da Silva, 1988.) The broken line shows the intersection of the 200 m isobath with the shelf edge; the shelf itself is shaded.

The Delagoa Bight is a large offset in the coastline at the latitude of Maputo (see Fig. 20-004). The flow past here, either as the start of the Agulhas Current or as the landward end of passing, anti-cyclonic Mozambique eddies, is poleward. This passing water generates a cyclonic flow in the bight (Lutjeharms and Jorge da Silva, 1988) and the resultant Delagoa Bight eddy dominates the flow at the shelf here throughout most of the year (Fig. 20-006). Over a period of 23 years it has been observed 11 times in the hydrographic results of research cruises. It has been hypothesised that this recurrent eddy has largely determined the distribution of the sediment base of the Delagoa Bight (Martin, 1981). There is evidence (Gründlingh, 1992a) that these eddies may on occasion escape from the bight and drift into the deep ocean. On this part of the Mozambican shelf the water movement will most probably be totally dominated by this lee-eddy. If the same effects are found here as in lee-eddies in the other offsets in this coastline (e.g., Nehring et al., 1987), it can be assumed that there is considerable vertical movement of water in the lee eddy (Schemainda and Hagen, 1983). Water masses in this eddy have temperature-salinity characteristics implying substantial upwelling in the core of the eddy from depths of at least 900 m. Hence there should be nutrient enrichment of the surface layers and thus increases in the chlorophyll-*a* content. To date this has not been observed, except intermittently at the north-eastern point of the Delagoa Bight (Quartly and Srokosz, 2004). This sporadic increase in primary productivity may be the result of current-induced upwelling as predicted by Gill and Schumann (1979). If driven by passing eddies, such intermittent upwelling would be expected.

The shelf morphology of the eastern part of the Mozambique Channel is different to that of the western part (Fig. 20-004). For the most part the shelf is narrow except at the narrowest part of the channel – at about 17° S – where the eastern shelf is widest. As mentioned before, the flow along this eastern shelf edge is quiescent compared to the western side of the channel (Sætre, 1985; Lutjeharms et al., 2000b) with low speeds and low eddy kinetic energy. The average current direction seems to be equatorward. Nevertheless, there are tentative indications from the distribution of chlorophyll-*a* (Quartly and Srokosz, 2004), as observed from satellite, that cyclonic eddies form along the southern tip of Madagascar and drift into the channel. They seem to draw water off the shelf and inject it into the waters of the central channel.

In summary, the shelf edges of the western part of the Mozambique Channel seem to be influenced mainly by passing Mozambique eddies that have their origin in the narrows of the channel and by secondary effects due to these eddies, namely upwelling at coastal offsets, the generation of lee eddies at shelf offsets and the extraction of shelf waters to mid-channel. It is possible that parts of the eastern shelf of the Mozambique Channel are also influenced by eddies, but the data at hand are inadequate to show this unambiguously. It is evident that such eddies would be considerably more infrequent than and not as intense as those that affect the western shelf of the channel. Besides the direct influence of the currents at the shelf edge, the waters over the shallower parts of the shelf may be substantially influenced by the reigning winds.

2.3 Effect of winds and tides

The meteorological conditions for the Mozambique Channel have been summarised by van Heerden and Taljaard (1998). In austral summer the mean wind direction is uniformly from a south-easterly direction and weak. In winter the average wind direction differs for the southern and the northern part of the channel. The southern part experiences south-easterly winds; the northern part north-westerlies. The northern part thus may be considered to form part of the monsoonal wind system of the Indian Ocean up to 15° S (Sætre and Jorge da Silva, 1982) whereas the southern part does not. The border between these two systems is the Inter Tropical Convergence Zone. Donguy and Piton (1991) have attempted to relate the currents in the channel to the monsoonal winds, but with only a few cruises and short sea level records at their disposal a conclusion of monsoonal seasonality in the currents is probably premature. As mentioned above, the large scale current systems show no evidence of monsoonal influence.

The winds over the shelf regions agree in part with the current direction hypothesised by Sætre and Jorge da Silva (1984). Except for the most southern part of the western shelf – the Delagoa Bight – the winds along this coastline all have a strong equatorward component year round. Sætre and Jorge da Silva (1984) have therefore concluded that the shelf currents here also are in that direction. These inferred current directions are in contrast to ships' drift observations (Sætre, 1985; Lutjeharms et al., 2000b) that show consistent movement poleward over the western shelf region. The winds over the eastern shelf are also largely northward, but vary with season.

During summer the shelf waters of the Mozambique Channel may also be affected by passing tropical cyclones that, as a rule, move poleward through the channel (Van Heerden and Taljaard, 1998). Some, however, make landfall somewhere along the coast of Mozambique. The effect of passing cyclones on the water movement over the shelves is dramatic. In situ current observations have shown (H. Ridderinkhof, personal communication) a reversal of current direction to a depth of at least 200 m at the passing of a severe cyclone.

Tides are an important component of water motion in the Mozambique Channel, especially when compared to other parts of the South-West Indian Ocean where tidal ranges are small. There is a gradual increase in tidal range from less than 2 m to the north and to the south of the channel to more than 5 m in its central part. This is the product of a double standing wave system, driven from either end, which develops in the channel (Pugh, 1987). Low lying coastal regions and estuaries, particularly on the Mozambican side, contain extensive areas of salt marshes and mangrove swamps as a result of the tidal motion (G. B. Brundrit, personal communication). Over the wide, shallow parts of the Sofala Bank (viz. Fig. 20-007) strong tidal currents lead to the continuous movement of sand banks and other mobile sedimentary seabed features.

In summary, tidal currents are important in the shallow parts of the shelves, but the usually weak winds have a limited affect on the main water movement over the shelves of the Mozambique Channel, with the exception of passing cyclones whose influence might be short lived.

Apart from the wind regimes, in a region of high rainfall (Van Heerden and Taljaard, 1998) the influence of river runoff on the shelf waters may be important.

2.4 Effect of river runoff

The runoff from the Mozambican land mass varies seasonally, but there also are considerable interannual differences (Jorge da Silva, 1984c). The total runoff from the Zambezi River (viz. Fig. 20-004, 20-007), for example, was 168.9 km^3 for 1977-78; whereas for 1982-83 it was a mere 50.3 km^3. Intermittent tropical cyclones bring event-scale rainfall episodes that may totally dominate the annual rainfall distribution. This naturally also holds for the Madagascar land mass, but runoff records for that country are difficult to obtain. One of the few coastal regions for which accurate observations of the effect of the river runoff on the shelf waters have been made on a number of occasions (Jorge da Silva, 1984c; 1984b) is along the Sofala Bank. It lies between 16˚ and 21˚ S on the western shelf of the channel (Fig. 20-004).

The salinity of surface waters close to the Zambezi River mouth on the Sofala Bank may drop as low as 20.00 (Sætre and de Paula e Silva, 1979) at a time when water at the shelf edge may be 35.4 (viz. Fig. 20-007). This river water may be severely discoloured, giving a Secchi disc depth of less than 2 m (Jorge da Silva, 1984b). The

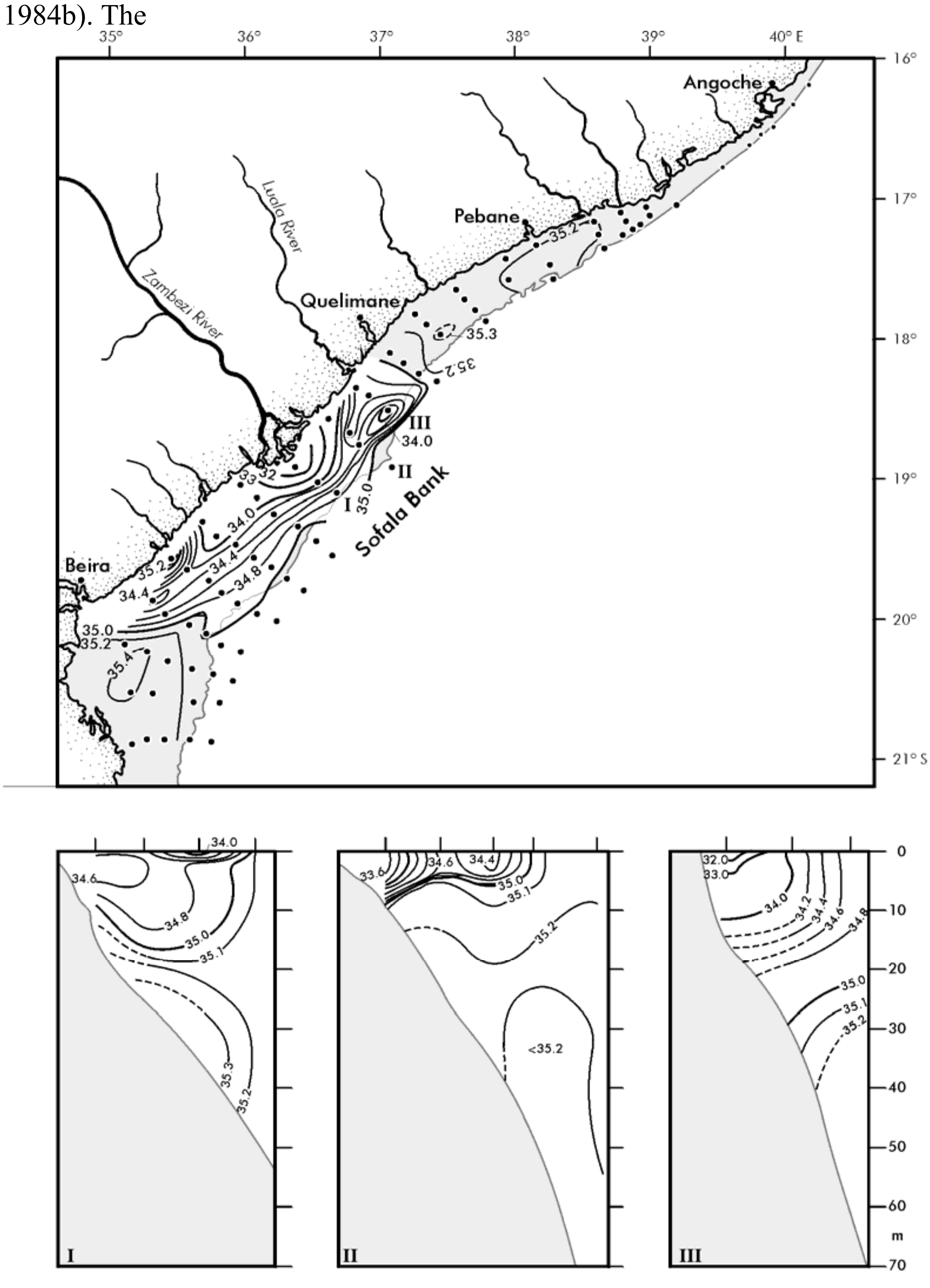

Fig. 20-007 Surface salinities on the Sofala Bank - the wide, shallow shelf off central Mozambique - based on a cruise of 1982. (After Jorge da Silva, 1984c.) For general location see Fig. 20-004. Dots show station positions. Locations of station sections in the bottom panels are shown by roman numerals in the upper panel. The shelf shallower than 50 m is shaded. Fresher water (< 35.0) extended to a depth of 15 m directly off the Zambezi River mouth; to 30 m off the Luala

River mouth. Note the high salinity values south of the city of Beira, due to marsh runoff.

plume of muddy water can be quite extensive (Sidorn et al., 2001) and has been thought to play a major role in the natural history of local biota, such as shrimp. The fresher water may extend over the shelf to a distance of 50 km offshore. It may be confined to the top 15 m of the water column, or it may extend to the full depth of the shelf (Fig. 20-007), presumably dependent on the density differences between the river and shelf waters as well as the concurrent wind action. Plumes of fresh river water have been observed to extend both equatorward as well as poleward from most rivers here. No clear pattern of movement is therefore immediately evident. Sætre and de Paula e Silva (1979) have shown that the greater part of the Sofala Bank is affected by fresher surface water.

The chlorophyll-*a* distribution as well as the primary productivity on the Sofala Bank seems to be largely controlled by the effluent from rivers. These carry loads of nutrients (Jorge da Silva, 1984c) that, as mentioned above, may penetrate half-way across the shelf. The chlorophyll-*a* distributions exhibit very analogous patterns. That these distributions occur with a high frequency can be seen by the organic matter content of the surface sediments on this part of the shelf. It is highest directly off the Zambezi River mouth and in a narrow strip adjacent to the coast to either side of this river mouth. Some small pelagic fish seem to concentrate in these waters (Jorge da Silva, 1984c). Otherwise pelagic fish on the Sofala Bank seem chiefly to frequent strips parallel to the coast, most extending along the whole coastline (Brinca et al., 1981).

One may quite reasonably expect the observed effects of fresh water runoff on the Sofala Bank to hold for the rest of the shelf regions of the Mozambique Channel as well, where there are fewer measurements of this kind. The salinity of shelf waters along most of Mozambique varies seasonally with the river outflow, with the lowest salinities found in February (Sætre and de Paula e Silva, 1979). Apart from the expected seasonality, results for the Sofala Bank show great inter-annual variability and one could assume that this holds for all the other Mozambican shelf regions as well. The freshening of the shelf waters off Mozambique by river run-off seems ubiquitous.

There is at least one clear exception. At the southern extremity of the Sofala Bank, between 20˚ to 21˚ 30' S (viz. Fig. 20-007), there is a large expanse of coastline that is subject to inundation by seawater. The subsequent runoff from this region can be extremely salty. Salinity values in excess of 36 are not uncommon (e.g., Jorge da Silva, 1984c). During September of 1982 surface values of 37.2 were observed near the coast (Brinca et al., 1983). The influence of this saline water has been observed a distance of 100 km offshore and throughout the shallow water column of 50 m.

2.5 Characteristics of the western shelf

To recapitulate, the water mass characteristics of the shelf waters on the western shelf of the Mozambique Channel have been presented by Jorge da Silva et al. (1981), Jorge da Silva (1984a), Lutjeharms and Jorge da Silva (1988) and Sætre and Jorge da Silva (1982). Except for regions and times where river run-off plays a major role, the water masses over the shelf are identical to those offshore (viz. Fig. 20-003) at the same depths. This means that the subsurface salinity maximum of Subtropical Surface

Water (at depths of 150 – 300 m) is much more pronounced in the southern part of the channel than farther north. In the Delagoa Bight eddy, at the southernmost extremity of the shelf (Lutjeharms and Jorge da Silva, 1988), there is hardly any evidence of Tropical Surface Water left. The exchange of water masses between the shelf and the deep ocean seems to vary considerably. The passage of Mozambique eddies may play a key role here. At parts of the western shelf where the shelf is very narrow (viz. Fig. 20-004) and the current at the shelf edge strong, such as at the narrows of the channel (Angoche; Sætre, 1985) and just north of the Delagoa Bight (Inhambane; viz. Fig. 20-004; Lutjeharms et al., 2000b), one may expect that the shelf edge currents may have a more decided effect, whereas along the Sofala Bank where the shelf is widest (Fig. 20-004), this effect would be substantially less.

Sætre and Jorge da Silva (1982; 1984) have carried out the most detailed analyses of water masses on this shelf to date. They have claimed that the circulation patterns of the shelf waters can be visualised by the temperature distribution at 150 m depth. This leads to a different pattern for the hydrographic results of each research cruise for the region. A set of cyclonic eddies of various shapes and sizes are evident. Based on these data one may therefore safely assume that the waters and the circulation on this shelf region are very variable. What effect does this have on the ecosystem of this shelf region?

Surveys of organisms and in particular of fish resources have been made on the western shelf region of the Mozambique Channel (Nehring, 1984; Nehring et al., 1987; Sætre and de Paula e Silva, 1979; Jorge da Silva, 1984a), but particularly on the Sofala Bank (Brinca et al., 1981; Jorge da Silva, 1984c). The values of column chlorophyll-*a* concentration are relatively low over most of the outer parts of the shelf, somewhat higher at the shelf edge (Sætre and de Paula e Silva, 1979). Over inner parts it can rise to 98 mg/m^2 (Nehring et al., 1987). The exception, mentioned above, are the observations in the upwelling cell off Angoche where values of 600 mg/m^2 have been observed. The distribution of zooplankton biomass in the upper 30 m of the water column shows a similar general distribution with low values of 20-40 mg/m^3 over most outer parts of the shelf with higher values, up to 160 mg/m^3 at inner stations. The exception is for the region directly poleward of the Angoche upwelling cell where observations of 320 mg/m^3 have been made. No evidence for such major increases in either phytoplankton or zooplankton have to date been found in the Delagoa Bight eddy. Even though Nehring et al. (1987) have shown that the primary productivity at inshore stations on the shelf was double that of stations farther offshore, there were considerable differences between stations close to each other on the shelf. Large degrees of spatial and temporal variability can therefore be assumed.

An analysis of the seasonal distribution of the depth of the 20° and the 23° C isotherms has shown that large parts of the outer shelf would in principle be suitable for yellowfin tuna fisheries, whereas the skipjack tuna are most likely to be found off Angoche and Maputo, i.e. at the sites of upwelling induced by lee eddies (Fig. 20-008). The distribution of fish; demersal, small pelagic, larger pelagic, mesopelagic as well as that of crustaceans has been summarised by Sætre and de Paula e Silva (1979). In most cases where more than one survey cruise was carried out there was a considerable difference between the cruise observations and this was usually considered to be due to seasonality in the distribution of organisms. It may have been due to irregular temporal changes of shorter duration.

In short, the circulation on the Mozambican shelf is very variable in both space and time and may be influenced by offshore currents only where the shelf is narrow. Runoff from land plays a key role, but exhibits both seasonal and inter-annual variations. The biogeography exhibits the same variability. Although the interpretation of the circulation patterns as well as the biogeography of this western shelf of the Mozambique Channel is constrained by limited data, this is even more the case for the eastern shelf.

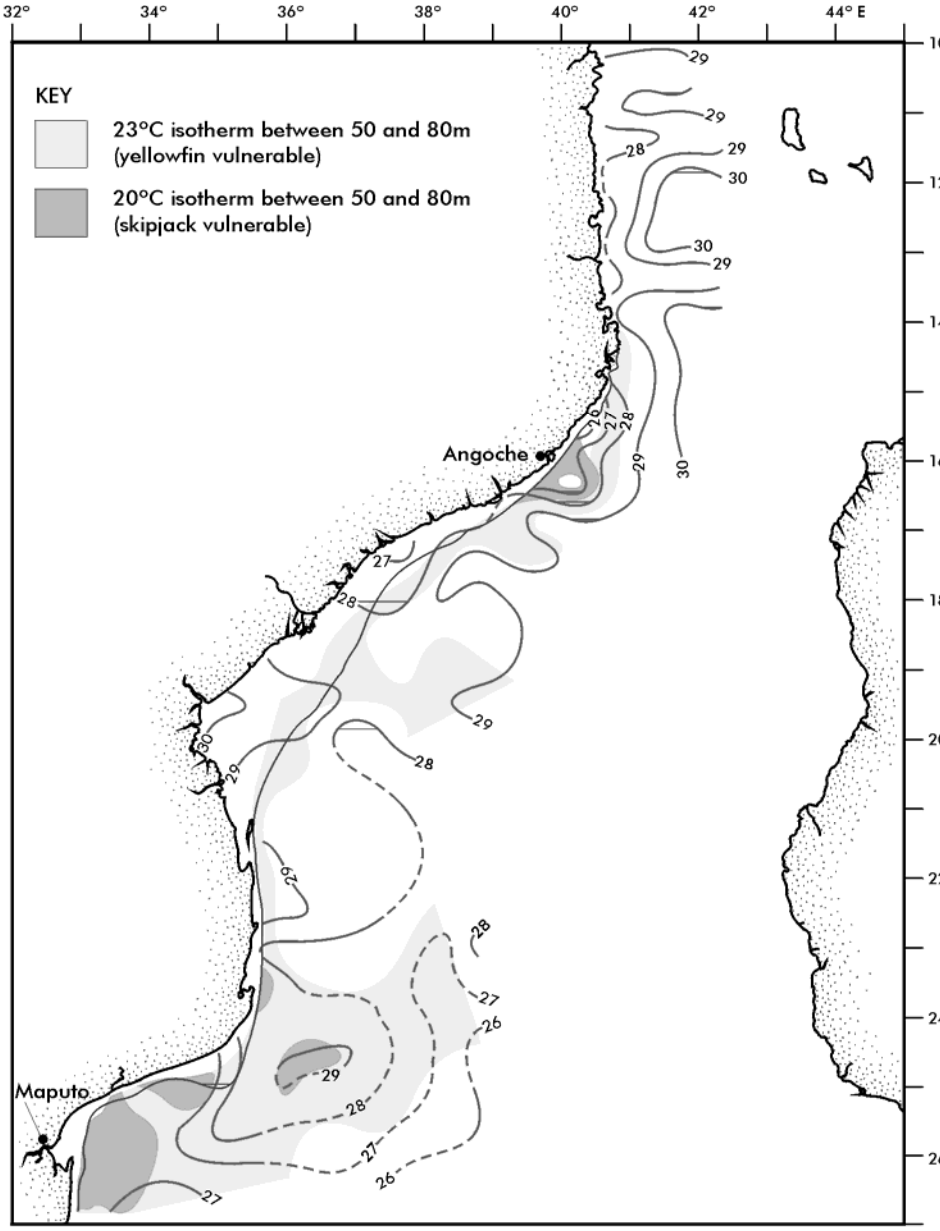

Fig. 20-008 Tuna vulnerability to catching by surface gear on the Mozambican shelf, superimposed on average sea surface temperatures during the period January to March. (After Jorge da Silva, 1984a.) The 50 m isobath is shown. Note the increased concentration in the lee eddies off Angoche and in the Delagoa Bight off Maputo.

2.6 Characteristics of the eastern shelf

The eastern shelf of the Mozambique Channel can – using information currently available - be divided into three specific regions: the very south where the shelf is more or less zonal, the very north, where the shelf forms part of the Comoro Basin (viz. Fig. 20-004) and, third, the meridional shelf in between.

The Comoro Basin lies directly south of the South Equatorial Current (Piton and Poulain, 1974). Between it and the narrows of the channel an anti-cyclonic gyre is formed that seems relatively stable (Donguy and Piton, 1991). The surface currents of which the gyre consists are not strong (Sætre, 1985) except near the African coast where mean speeds in excess of 0.5 m/s are to be found (Lutjeharms et al., 2000b). The variability on the African side is high. The currents over the eastern shelf in the Comoro Basin are weak but in general in an equatorward direction. This rather inadequate portrayal is nonetheless supported by direct measurements (Piton and Poulain, 1974; Martin et al., 1965) as well as by a variety of models (e.g., Biastoch and Krauß, 1999; Asplin et al., 2004; Sætre, 1985).

The water types on the shelf are dominated here by Tropical Surface Water with a salinity range from 34.3 to 35.2 (Donguy and Piton, 1969). There is no evidence to date that Subtropical Surface Water with greater salinity is found on the shelf, although in principle it is entirely possible since this water mass is found at about 200 m depth in the region. Surface temperatures exceed 26˚ C throughout the year, except in the months of August and September. Highest temperatures (> 29˚) are found in April; lowest (25˚ to 26˚ C) in August. Surface salinities are lowest (34.4) in March; highest in the period September to November (>35.10). Recent observations on this

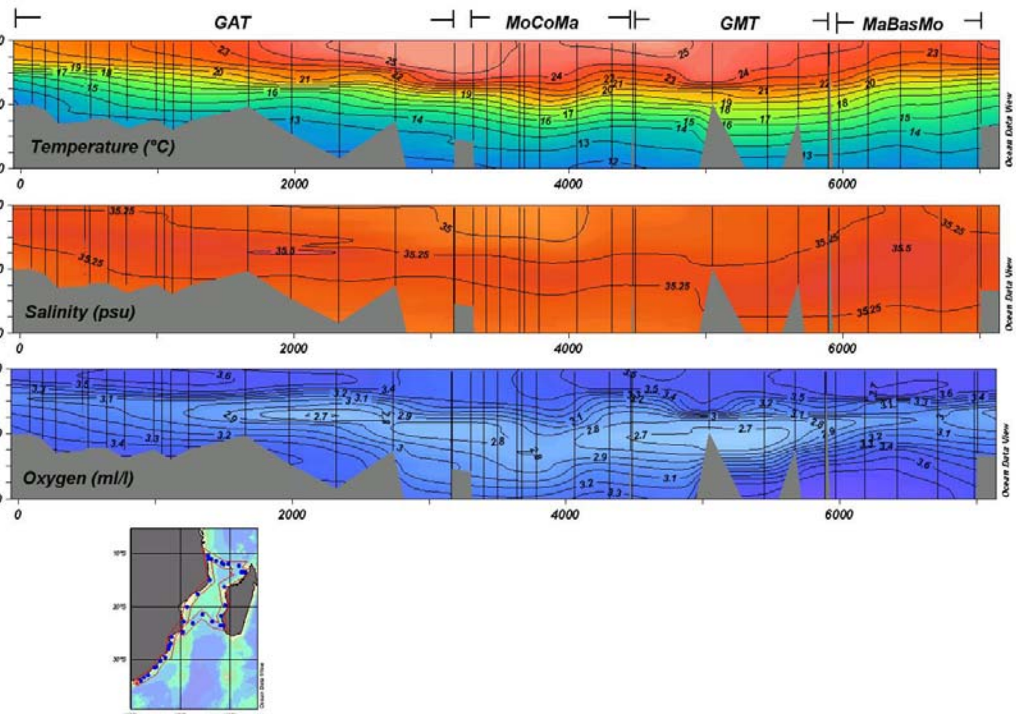

Fig. 20-009 Hydrographic characteristics of shelf waters along the east coast of South Africa and the continental shelves in the Mozambique Channel. (With special permission of M. Roberts.) GAT is the section from Port Elizabeth in the south along the east coast of South Africa and of Mozambique; MoCoMa represents the zonal section from the coast of Mozambique to the west coast of Madagascar via the Comores; GMT a poleward section along the west coast of

Madagascar and MaBasMo a zigzag section from the southern point of Madagascar to the island of Bassas da India and on to Maputo on the east coast of Mozambique.

shelf region (Roberts, personal communication) shows that the water column consists of a warm mixed layer to a depth of about 80 m with the seasonal thermocline extending to 250 m. Salinities in the centre of the Comoro Gyre are slightly elevated above those found on the adjacent shelves. An oxygen minimum lies at 200 – 300 m depth and is less strongly developed in the centre of the gyre. The hydrography of the middle part of the western shelf of Madagascar is not much different.

Here, according to the only observations to be found (Roberts, personal communication) the warm mixed layer extends to 150 m, with a uniform salinity between 35 and 35.25 (Fig. 20-009). Particularly noteworthy is the oxygen minimum layer found between 150 and 250 m that is strongly developed here, more so than anywhere else on the shelves of the region. How representative these observations are remains unknown. The little that is known about the currents along the shelf edge (e.g., Sætre, 1985; Lutjeharms et al., 2000b) here, suggest that they are very weak and will most probably have very little influence on the movement of the waters on the shelf itself. As mentioned before, satellite imagery, particularly of ocean colour (Quartly and Srokosz, 2004), shows that cyclonic eddies along this coastline may on occasion draw off substantial amounts of shelf water and with it chlorophyll-*a* into the deeper parts of the channel. The origin of these eddies, between 200 to 300 km in diameter, is uncertain. De Ruijter et al. (2003) have shown that cyclones can be formed at the termination of the southern East Madagascar Current and these could

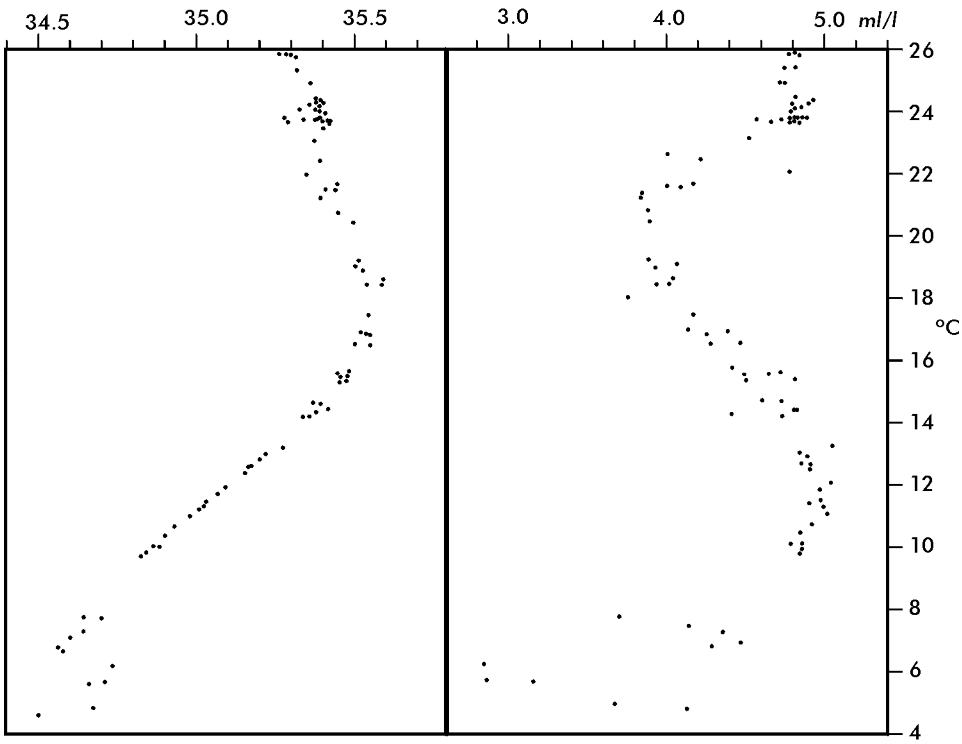

Fig. 20-010 The temperature/salinity (left panel) and the temperature/dissolved oxygen characteristics for the shelf waters south of Madagascar. (After

Anonymous, 1983.) The line of stations on which this was based was taken to the south-west of Andriamanao (viz. Fig. 20-04).

conceivably drift into the Mozambique Channel along the shelf edge. Although a number of hydrographic interpretations (e.g., Sætre and Jorge da Silva, 1984; Donguy and Piton, 1991) imply a southward setting current along this shelf, direct measurements (Martin et al., 1965) and ships' drift observations (Lutjeharms et al., 2000b) indicate otherwise. Cyclonic eddies could therefore be advected equatorward along this coast.

The third and last component of the eastern shelf of Madagascar is the southern part. The movement of the shelf waters here may be more dynamic, since it could conceivably be affected by the southern limb of the East Madagascar Current (viz. Fig. 20-004). This would most likely be true largely for the eastern part of this shelf region (Lutjeharms et al., 2000b). Hydrographic observations on the shelf show the normal temperature/salinity characteristics to be expected (Fig. 20-010). Surface temperatures (in June) were 24 ˚C and surface salinities 35.3. (The higher temperatures shown in the scatter diagram of Fig. 20-010 represent temperatures farther offshore.) Both Tropical and Subtropical Surface Waters are evident in the temperature/salinity values. The Tropical Surface Water extended from the surface to about 100 m depth. The Subtropical Surface Water below that extended to about 250 m. A well-developed subsurface oxygen minimum was found at a depth of 80 to 200 m.

The surface salinities and temperatures all suggest an upwelling regime on this southern shelf. During the first extensive cruise over this shelf (June 1983; Anonymous, 1983) the temperatures at the coast were 2 ˚C lower than further offshore. The salinities were up to 35.6, indicating upwelled Subtropical Surface Water (see Fig. 20-010). Ocean colour also shows signs of enhanced chlorophyll-*a* values along this coastal segment (Quartly and Srokosz, 2004) and that these may be drawn off the shelf in plumes. The presumed upwelling is concentrated in an upwelling cell on the south-eastern corner of Madagascar (Lutjeharms and Machu, 2000; DiMarco et al., 2000) where enhanced concentrations of chlorophyll-*a* and lower temperatures are found most frequently. The question remains if these remotely sensed suggestions of upwelling may not be due to runoff from land.

Hydrographic evidence specifically collected to ascertain the origin of these elevated values of chlorophyll-*a* (Machu et al., 2002) has recently shown unequivocally that there is indeed upwelling at this location. The upwelling does not seem to be strictly related to the wind patterns and it has therefore been hypothesised (Lutjeharms and Machu, 2000) that the driving force for the upwelling is the juxtapositioned East Madagascar Current. This would be comparable to the upwelling at the eastern extremity of the Agulhas Bank (Lutjeharms et al., 2000a; viz. Fig. 20-016) and at the northern extremity of the Natal Bight (Lutjeharms et al., 1989b; viz. Fig. 20-011). However, there is some evidence (Quartly and Srokosz, personal communication) that the chlorophyll-*a* concentration at this location has a distinct seasonal pattern with the highest concentrations found in the austral winter months of July and August, the lowest in December. Major winds at this location are from the east in winter, from the north-east in summer (Sætre, 1985) suggesting winds more favourable for upwelling along the full south coast of Madagascar in winter, at the south-eastern corner in summer. The importance of the wind compared to the current in driving this upwelling therefore remains unresolved.

The biological implications of this upwelling are intriguing, but to date not properly quantified. Apart from the remotely sensed chlorophyll-*a*, surveys of fish stocks (Anonymous, 1983) have shown slightly higher concentrations of demersal fish on the southern shelf than off the adjacent, eastern shelf. Mackerel numbers were higher on the southern shelf, but scad lower. In general fish were found with such a very scattered distribution on this shelf that no firm conclusions can be reached on their biogeography.

In summary, the waters over the shelves of western Madagascar seem fairly unusual, based on the current - very limited - data. Water masses are those found offshore, except for an intensification of the subsurface oxygen minimum, and the currents are most probably weak and variable. The wider, southern shelf exhibits characteristics of upwelling, but this does not seem to have a marked effect on higher trophic levels.

An outline of the characteristics of the shelf waters of the Mozambique Channel as a whole is, as can be seen from the above descriptions, largely a function of the amount of available data and their quality. The broad Mozambican shelf is characterised by substantial terrestrial influence from runoff both from rivers and salt marshes. Lee eddies at Angoche and in the Delagoa Bight may play an important, but local role. The effect of Mozambique eddies intermittently passing by the shelf edge is not known. Water masses over the northern shelves are predominantly Tropical Surface Water, those to the south Subtropical Surface Water. This seems true for the western as well as the eastern shelves of the Mozambique Channel. About the latter very little is known, except that it is relatively broad.

The shelf to the east of Madagascar is by contrast much narrower and the offshore circulation totally different.

3. Region east of Madagascar

Not only is the shelf narrow here, but the continental slope is precipitous (viz. Fig. 20-004). Along the shelf flows a small, but intense western boundary current, the East Madagascar Current (e.g., Lutjeharms et al., 1981a). Swallow et al. (1988) have observed a speed in the southern limb of this current of 0.66 m/s, at a latitude of 23 ˚S, about 50 km from the coast, with a standard deviation of only 12 cm/s. The speeds in the northern branch of this current (Schott et al., 1988) are not much different. The separation point between the northern part, flowing equatorward, and the southern part, flowing poleward, is estimated to lie between 17 and 18 ˚S (e.g., Lutjeharms et al., 2000b; viz. Fig. 20-004). This may vary with season as the wind patterns shift northward along this coastline in the austral winter (Van Heerden and Taljaard, 1998). No direct observations have been made to date, but one may assume that the waters over the shelf move in concert with the strong offshore currents.

As can be expected, the temperature/salinity relationships of the waters on this part of the shelf are indistinguishable (Anonymous, 1983) from those found on the shelf south of Madagascar (Fig. 20-010).

Little is known about the biological productivity of the region. Fish distributions are scattered with a decrease in pelagic as well as demersal fish as one moves equatorward. Catches of sharks and rays increase on going northward along this coast (Anonymous, 1983).

In summary, all that is known with a certain degree of certainty about the shelf seas east and south of Madagascar is the presence of the East Madagascar Current at the shelf edge and the likelihood of persistent upwelling south-east of the island. The interaction between these or the influence of the current on the shelf circulation remains unknown due to an extreme paucity of observations.

Compared to the lack of data and knowledge about this particular part of the shelf seas of the South-West Indian Ocean, the region inshore of the northern Agulhas Current is very much better studied and understood.

4. Northern Agulhas regime

The northern Agulhas Current is defined as that part of the current extending from the southern mouth of the Mozambique Channel downstream to the eastern edge of the Agulhas Bank (viz. Fig. 20-001). This component of the current flows past a shelf that may be considered to consist of two categories. For the greater part the shelf is narrow and the continental slope has a steep gradient. The only exception is a part of the shelf along the province of KwaZulu-Natal known as the Natal Bight. Here the shelf is considerably wider and the slope much broader and with a gentler gradient (Fig. 20-011). As will be seen below, this shelf morphology has some remarkable effects on the offshore currents.

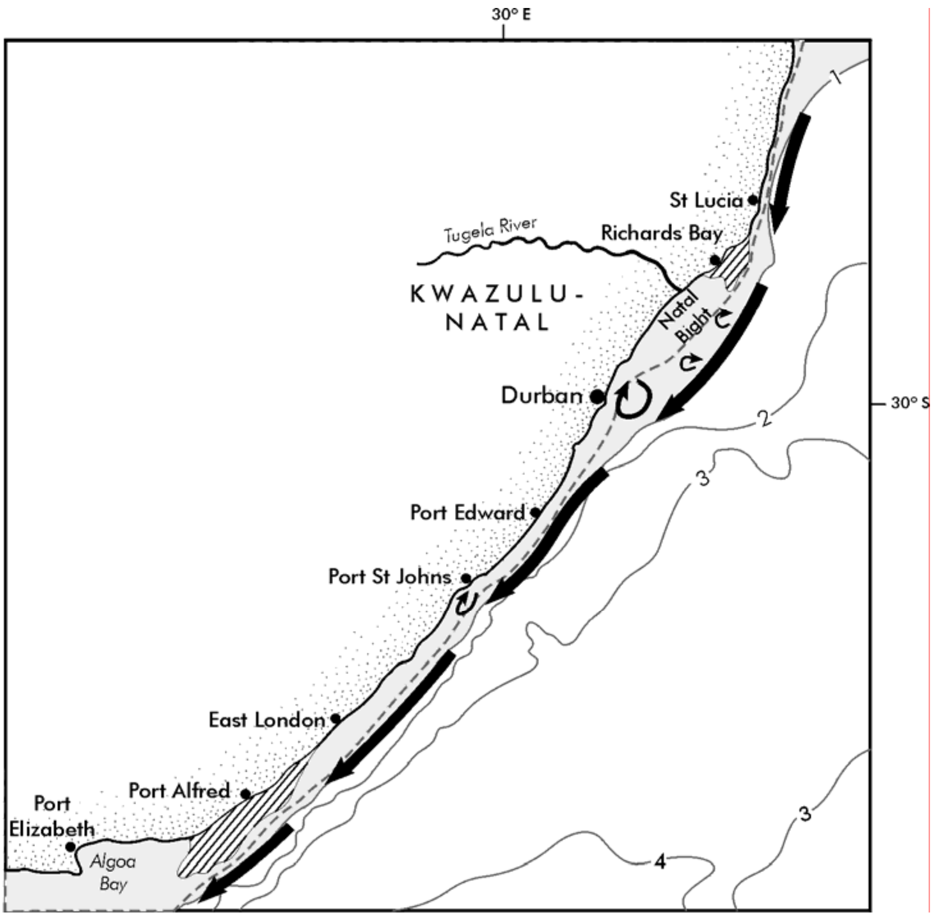

Fig. 20-011 The bathymetry of the continental shelf along the northern Agulhas Current. (After Simpson, 1974.) The continental shelf area is shaded. The 200 m isobath is shown as a broken line. Hatched areas denote upwelling. Place names and circulatory features are mentioned in the text.

The core of the northern Agulhas Current follows the shelf edge very closely almost all of the time (Tripp, 1967) meandering less than 15 km to either side (Gründlingh, 1983). For a western boundary current this is quite unusual, but it has important consequences for the circulation on the adjacent shelf. As can be expected, in its very surface layers the behaviour of the current is not as stable (Pearce, 1977a) with changes in speed occurring from day to day and the penetration of surface water of the current onto the shelf taking place at irregular intervals. In some cases short-term current reversals at the edge of the current have been observed (Gründlingh, 1974; Schumann, 1981; Pearce et al., 1978), possibly due to shear edge eddies or to the effect of the wind. Surface speeds of the inshore edge of the current may exceed 1.5 m/s, salinities may lie between 35.00 and 35.50 and temperatures in summer may exceed 28. In winter these sea surface temperatures drop to less than 21 ˚C (Pearce, 1978). Shallow water near the shelf edge is usually Tropical Surface Water. The characteristic salinity maximum of Subtropical Surface Water is found at a depth of 150 to 250 m at least 60 km offshore (Pearce, 1977a) although this distance may vary on a near-daily basis. One would therefore expect the waters over the adjacent shelves to consist largely of modified Tropical Surface Water, but as it turns out, this is not the case.

This established current disposition is not entirely stable, as mentioned above. During about 15% of the time – and at irregular intervals – the current moves offshore in a sudden, single meander (Gründlingh, 1979). This Natal Pulse (Lutjeharms and Roberts, 1988) moves downstream with the current at a rate of about 20 km/day. Features of this kind have also been observed north of the Natal Bight (Gründlingh and Pearce, 1984; Gründlingh, 1992a), however, all information currently available suggests that it is only meanders that originate at the Natal Bight that consistently progress downstream with the current. Theoretical studies (De Ruijter et al., 1999a) have shown that it is the weak gradient of the shelf at the Natal Bight that will allow baroclinic instability in the Agulhas Current to occur here and to grow once the core of the current has been detached from the sharp slope gradient. The trigger for this meander has been thought to be the adsorption of offshore eddies, the tell-tale signs of which have been seen in many satellite images in the thermal infrared (e.g., Gründlingh, 1986; Lutjeharms and Roberts, 1988). This has recently been proven to be the case (Schouten et al., 2002). It is interesting to note that some marine animals such as leatherback sea turtles carefully use all these circulation features to move about in the ocean (Hughes et al., 1998; Luschi et al., 2003). The question remains what, if any, effects these unusual meanders have on the shelf waters. This will be discussed in a section to follow. It is necessary first to describe the wind regimes over this shelf region.

4.1 Winds along the shelf off south-eastern Africa

Tropical cyclones hardly ever reach this coastline, in contrast to that of Madagascar and Mozambique (Jury and Pathack, 1991). On the infrequent occasions when they do arrive at the coast (e.g., Poolman and Terblanche, 1984), one would expect the shallow waters of the shelves over which they move to be thoroughly mixed. Otherwise the shallow waters, as measured by moored current meters (upper ~20 m), follow the reigning winds closely (Pearce et al., 1978).

Coastal winds for the region have been analysed in detail by Schumann (1989). He has shown that the main wind axis is parallel to the coast. At Durban the wind is 5 times more likely to blow along the shelf than across it, whereas at East London (viz. Fig. 20-011) it is three times more likely. Average wind speeds are about 2.5 m/s at Durban; 3.2 m/s at East London (for 1984). The average wind speeds along the coast and across it were not very different. The north-easterly wind and the south-westerly winds both occur about 50% of the time (Schumann and Martin, 1991), with both showing seasonality in wind speed, the north-easterly winds having slightly greater seasonality. During summer the alongshore component of the wind is considerably higher (Hunter, 1988), particularly farther downstream.

An important additional wind process for the coastal waters is diurnal land and sea breezes. These can exhibit speeds of the same magnitude as those brought about by normal synoptic systems (Hunter, 1988). Hunter (1981) has used offshore wind observations to show that land breezes can here extend at least 60 km seaward. The direction of these winds may have a decided influence on cloud formation, precipitation over the shelf as well as coastal runoff.

As mentioned before, it has been demonstrated that cumulus cloud lines frequently form over the northern Agulhas Current (Lutjeharms et al., 1986b; Lee-Thorp et al., 1998) but mostly when the winds are along-current, from the north-east. During such along-current air motion there is an enormous uptake of moisture from the current (Lee-Thorp et al., 1999; Rouault et al., 2000). About 5 times as much water vapour is transferred to the atmosphere above the current itself than from ambient waters. During on-shore winds this moisture is advected inland and may contribute significantly to moisture convergence and rainfall over the interior of South Africa. In fact, it has been shown that this leads to local intensification of storm systems and the concurrent flood events (Rouault et al., 2002). To what extent this leads to measurable dilutions of coastal waters by river runoff is not known. What is known is that the presence of the Agulhas Current has a consistent effect on coastal rainfall all along its

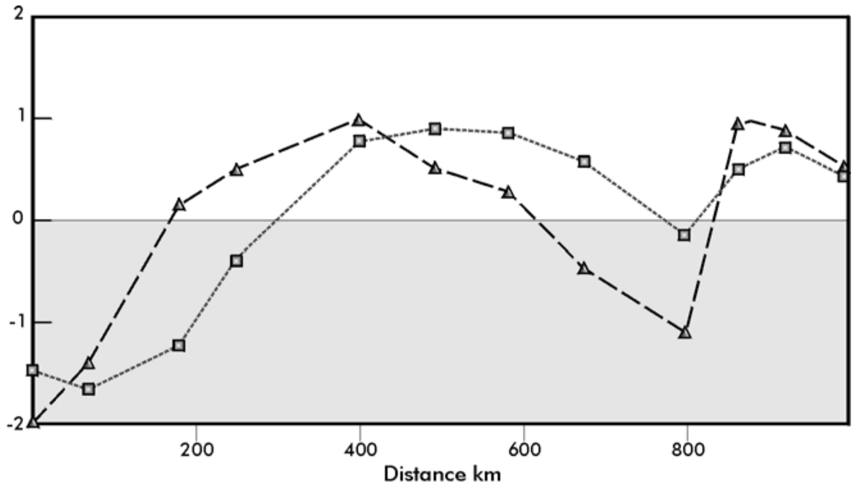

Fig. 20-012 The influence on coastal rainfall of the distance of the core of the Agulhas Current from the coastline. (After Jury et al., 1993.) The abscissa gives the distance upstream from Port Elizabeth (see Fig. 20-011). The solid curve gives the distance from the coast to the core of the Agulhas Current as expressed

by sea surface temperatures. Note that the distance is greater off the Agulhas Bank (0 km) and at the Natal Bight (800 km). The broken line shows the coastal rainfall. Both curves are expressed as standardized departures; that of the distance from the coast having been inverted for comparison.

northern part (Jury et al., 1993; Fig. 20-012). Wherever the current is close to the coast, such as between Durban and Port Elizabeth, the rainfall is enhanced; wherever the current axis diverges from the coastline, such as at the Natal Bight and at the southern part of the Agulhas Current, coastal rainfall is significantly reduced. This is not the only process that makes the Natal Bight an unusual shelf region.

4.2 The Natal Bight

The Natal Bight is formed by a landward offset between Richard's Bay and Durban in an otherwise rather linear coastline (Fig. 20-011). The northern part of the bight is shallower than 50 m; the southern part deeper. There are some well-developed canyons in the bathymetry of the continental slope, but these do not extend onto the shelf, where they have been filled in by sediment (Martin and Flemming, 1988). The major depocentre of the region is the offshelf Tugela Cone (viz. Fig. 20-013), evidence that the Tugela River is the major source of sediment for this shelf region. Sediments over the shelf itself consist largely of sand. The percentage is in excess of 75% over all parts of the Natal Bight shelf except seaward of the Tugela River (Flemming and Hay, 1988) where mud is the dominant sediment type. Gravel patches are found largely, but not exclusively, at the shelf edge where scouring from the Agulhas Current is to be expected. The distribution of sediments (Flemming and Hay, 1988) is particularly instructive here since it gives a clear indication of the integrated movement of the bottom waters where other data may not be available.

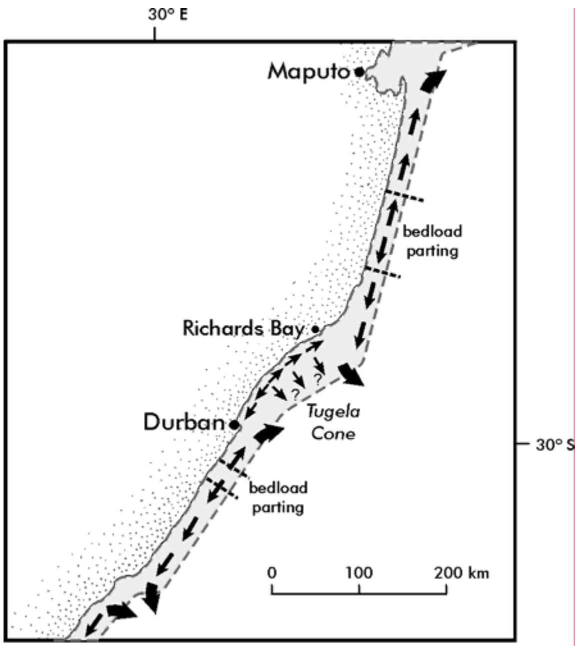

Fig. 20-013 A conceptual model of the bedload movement on the continental shelves adjacent to the northern Agulhas Current. (After Flemming and Hay, 1988.)

The shelf directly equatorward of the Natal Bight has, for instance, seen hardly any hydrographic investigations. However, the general bedload dispersal model suggests that the shelf waters move equatorward here, in clear disagreement with the concept of a straightforward Mozambique-Agulhas Current continuity. A bedload parting is found at about 28 ˚S (Fig. 20-013). Analyses of ships' drift (Harris, 1978) indicate that poleward of this point the currents over the shelf follow the Agulhas Current 75% of the time. This implied movement is consistent along the whole coastline except just downstream of Durban where it again is equatorward. This latter discrepancy may be due to an embedded lee eddy that is a recurring feature of the circulation at this location just south of the Natal Bight (e.g., Anderson et al., 1988; Meyer et al., 2002) and will be discussed in greater detail below.

The submarine bedform distribution is even more instructive. Active submarine dune fields, moving with the current, are found north of the Natal Bight and along the shelf break of the northernmost half of the bight. Along the southern half of the shelf break there is no evidence of the influence of the current, suggesting that it overshoots here (viz. Fig. 20-011), maintaining some distance from the shelf edge and thus not affecting the sediments. It is intriguing that off Durban the movement of the mobile dune field is, by contrast, northward, substantiating the persistence of the lee eddy surmised to occur here (Pearce et al., 1978; Meyer et al., 2002). Flemming and Hay (1988) have inferred a complex shelf circulation from the sediment distributions and the bedforms, consisting of a cyclonic movement over the northern, shallower part of the bight and a dipolar structure of an inner anticyclonic and an outer cyclonic eddy over the southern, deeper parts. What is in fact known about the circulation here?

First, the presence of a persistent upwelling cell at the upstream end of the Natal Bight is the most prominent part of the hydrodynamics of the shelf waters of the Natal Bight and a fundamental key to understanding the ecosystem of this shelf sea. From all other perspectives it may be considered to be a semi-enclosed system. The strong and ever-present Agulhas Current at the shelf edge forms a formidable barrier to exchanges of water and biota with the open ocean. At the northern end of the bight, between Richard's Bay and Cape St Lucia, the shelf widens as the current sweeps poleward. This bathymetric arrangement is believed to lead to topographically induced upwelling (Gill and Schumann, 1979), as it does elsewhere along the trajectory of the Agulhas Current.

In this general region sea surface temperatures are about 26 ˚C in the summer months, peaking in February (Pearce, 1978) and dropping to about 21 ˚C in August. Observations of sea surface temperature in the region (Gründlingh, 1974; Gründlingh and Pearce, 1990) have shown that off Richard's Bay the temperatures are always a few degrees lower. As could be expected, the water here is largely Tropical Surface Water with only the occasional presence of Subtropical Surface Water (Pearce, 1978). Others (Lutjeharms et al., 2000c) have shown that the purest Subtropical Surface Waters is found on the shelf edge off Richard's Bay and St Lucia. This sporadic presence of Subtropical Surface Water on the shelf, otherwise found at depths of 150 m or more offshore (Pearce, 1977b), is highly suggestive. Subsequent investigations using satellite images (Lutjeharms et al., 1989b) and a dedicated hydrographic cruise (Lutjeharms et al., 2000c; Meyer et al., 2002) have demonstrated unequivocally that this is indeed a persistent upwelling cell.

Lower temperatures are observed here more or less continuously, although the areal extent of the surface expression may vary considerably. This surface expression seems to have no clear seasonal pattern, neither is it clearly related to potential upwelling inducing winds (Lutjeharms et al., 1989b). Pearce (1978) has shown that evidence of 16 ˚C water (Subtropical Surface Water, viz. 20.3) at depths of 125 m, sometimes less than 100 m depth, on the shelf is intermittent, with no clear pattern. It can therefore be accepted that this upwelling is not wind-driven. The effect of this upwelling can be observed at the sea surface along the inner edge of the Agulhas Current as far downstream as Durban as the colder surface water is dragged southward as a cool filament (Lutjeharms et al., 1989b). Further evidence for the nature of this upwelling cell comes from nutrient distributions (Carter and d'Aubrey, 1988; Meyer et al., 2002; Fig. 20-014). It shows that the influence of the upwelling cell extends over a sizeable part of the bight. Carter and d'Aubrey (1988) have given historical nutrient values all over the bight and state that there is no clear seasonal pattern in the occurrence of nutrients. Vertical sections show clearly (Lutjeharms et al., 2000c) that this nutrient-rich water is upwelled at the St Lucia upwelling cell and from there moves over the floor of the bight southwards. Further evidence for the effect of this upwelling cell comes from biological observations.

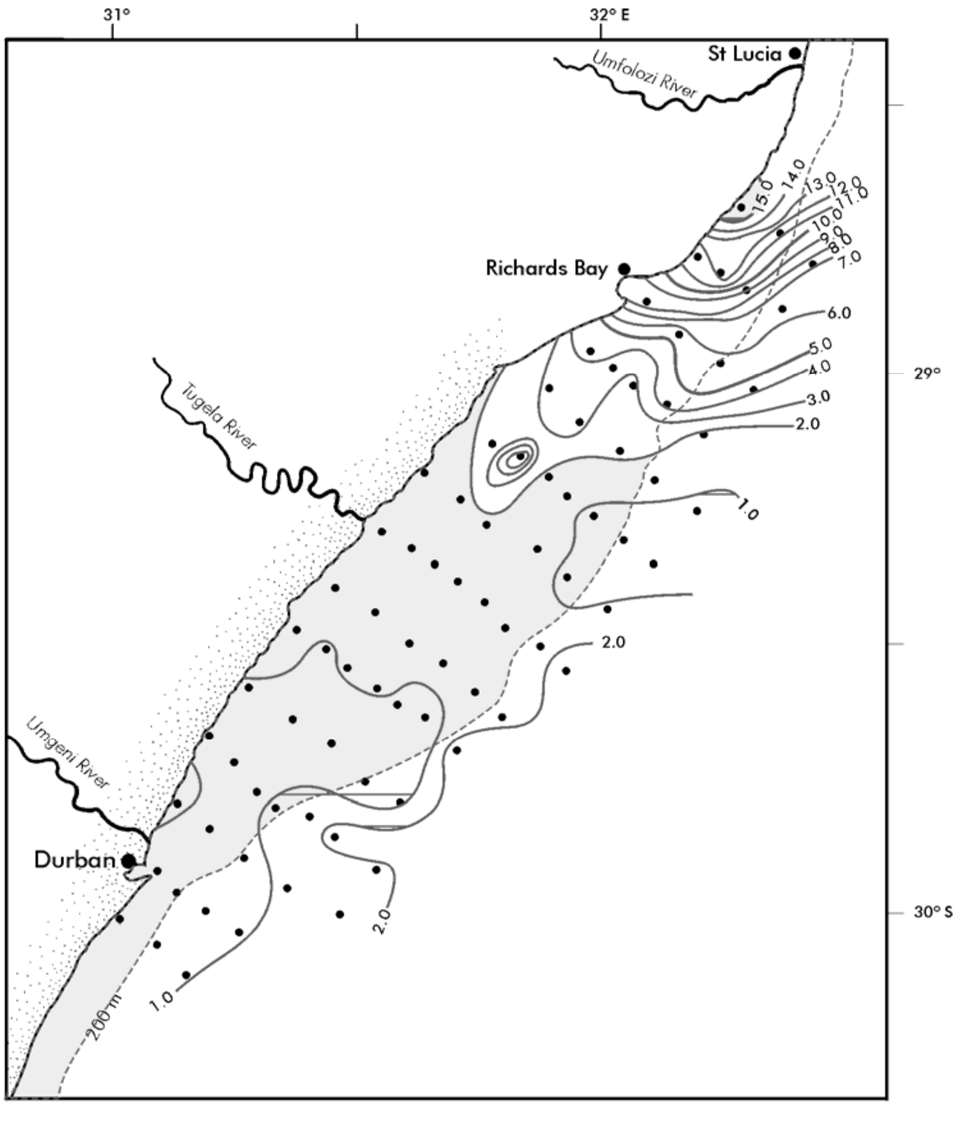

Fig. 20-014 Distribution of dissolved nitrate at 10 m depth over the Natal Bight during July 1989. (After Meyer et al., 2002.) Dots represent station positions.

The shelf shallower than 200 m has been shaded. The presence of an active upwelling cell equatorward of Richard's Bay is evident.

The distribution of chlorophyll-*a* exhibits a very similar pattern to that of the nutrients (e.g., Meyer et al., 2002), with the enhanced values slightly lower very close to the coast, implying an active upwelling process taking place during the observations. Oliff (1973; as quoted by Carter and Schleyer, 1988) has shown how the phytoplankton production reacts almost instantaneously to an upwelling event at Richard's Bay. Reviews of the plankton, zooplankton as well as the benthic species found in the Natal Bight have been given by Carter and Schleyer (1988) and by McClurg (1988) respectively. These studies were based on information that was geographically very inhomogeneous, since they had to depend on an eclectic set of previous collections not designed uniformly to cover the shelf as a whole. From these scattered observations it is impossible to infer the extent of the biological influence of the St Lucia upwelling cell over the Natal Bight shelf, particularly over the southern part.

The waters of the poleward part of the Natal Bight are by contrast unspectacular and fit well into the ranges, both physical and biological, to be expected at these latitudes. The nutrients are low (Carter and d'Aubrey, 1988; Meyer et al., 2002), coming from Tropical Surface Waters. The nutrient concentrations are 1.01 – 1.86 µmol/ℓ (nitrate), 0.48 – 0.72 µmol/ℓ (phosphate) and 3.50 – 4.69 µmol/ℓ (silicate) at 10 m depth. The values on this part of the shelf do not exhibit great differences from those found in the surface waters of the Agulhas Current. The exception is to be found close to the Tugela River mouth (viz. Fig. 20-011) where values of all nutrients are higher during floods and chlorophyll-*a* values are enhanced (Carter and Schleyer, 1988). This is reflected in greater densities of fish larvae at such times (Beckley and van Ballegooyen, 1992). When this outflow was directly observed during such a flood event, the indications were that most of the outflow occurred at a depth of 30 m and extended at least 25 km offshore. Salinities and temperatures over the shelf otherwise closely follow those of the Agulhas Current itself, also its seasonal cycle.

The circulation in the southern part of the bight is much harder to establish. Remote sensing has suggested a cyclonic eddy (Malan and Schumann, 1979) and this has been considered the main element in many conceptual portrayals ever since (e.g., Pearce, 1977b, Gründlingh and Pearce, 1990; Schumann, 1987; Harris, 1978). Observations show (Pearce, 1977b) that close to the coast the currents only follow the Agulhas Current 50% of the time. Ship's drift close inshore (1.6 km) is also about equally divided between poleward and equatorward drift (Harris, 1964; Pearce et al., 1978), agreeing with wind frequencies. The closer to the current, the greater the tendency is to follow its direction closely (Harris, 1978). The only quasi-synoptic hydrographic survey of the bight as a whole (Lutjeharms et al., 2000c) gives no indication of a consistent circulation. There are indications that the location of the edge of the Agulhas Current may show greater shifts in location along the edge of this particular part of the shelf than farther up- or downstream (Gründlingh and Pearce, 1990) and that shear edge eddies may play an important role on occasions (e.g., Lutjeharms and Roberts, 1988; their Fig. 10b). Putting it all together, Pearce et al. (1978) have concluded, on the basis of an eclectic set of observation, that "at any one time a succession of eddies of a variety of scales (are) generated by shear processes or meteorological forcing probably exists in the (Natal Bight)" and this is as good a summary of what is currently known as data will allow. Directly south of the bight, adjacent to the city of Durban (Fig. 20-011), the situation seems much simpler.

As mentioned above, a number of investigators (e.g., Pearce et al., 1978; Schumann, 1982; Anderson et al., 1988; Lutjeharms et al., 2000c and Meyer et al., 2002) have pointed out the presence of a cyclonic eddy directly off Durban, in the lee of the broader shelf that forms the Natal Bight. Currents measured off Durban do show a dominant north-eastward component (Fig. 20-015). Ship's drift close inshore (1.6 km) is – similar to further north on the shelf – about equally divided between poleward and equatorward drift (Harris, 1964; Pearce et al., 1978), which agrees with wind frequencies. Drifters have shown the same bi-polar tendency. Results presented by Tripp (1967) are also in agreement, showing that the current sets north-eastwards only about 50% of the time, with speeds of between 0.25 to 0.51 m/s. Current observations for a period of a month (Schumann, 1988b), as well as over shorter periods (Gründlingh and Pearce, 1984), indicate frequent current reversals here. There is therefore abundant evidence that this eddy does not seem to be present all the time. Current reversals at its location are measured over the full depth, indicating the

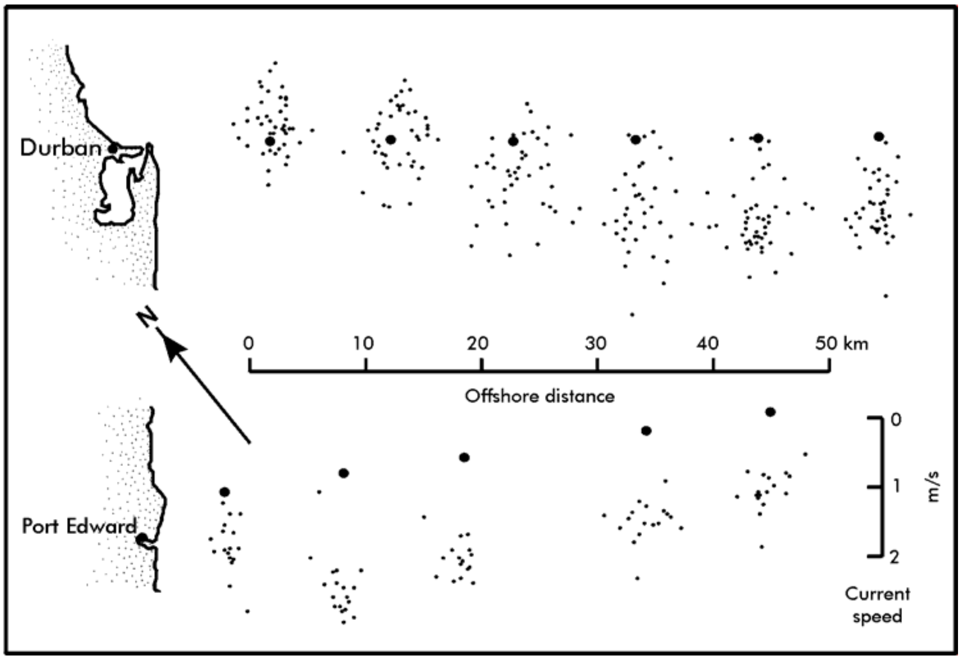

Fig. 20-015 Current observations off Durban and Port Edward. (According to Schumann, 1982.) For the location of these two places, see Fig. 20-011. The large dot indicates the location of the observations; the small dots the tips of current arrows from the station location. These arrow points show speed and direction integrated over the top 100 m of the water column. Each dot represents one spot measurement.

barotropicity of this eddy. The main driving force of the shelf circulation at this location is most probably the Agulhas Current and not the wind (Schumann, 1981). It is clear from hydrographic observations that there is considerable upwelling in this eddy, bringing nutrient rich water closer to the surface, but this also occurs in a very spasmodic way.

When there is no eddy present there may be a mixed layer to a depth of 50 m with a maximum gradient in nitrate-nitrogen lying below 100 m. With an eddy present this nutricline can be lifted to about 40 m (Carter and d'Aubrey, 1988) with a concurrent drop in surface temperatures. This surface cooling has also been observed in satellite thermal infrared observations (Lutjeharms and Connell, 1989). Average values of nitrates in the Durban eddy have been measured around 3.33 µmol/ℓ, but maximum values have reached 16.79 µmol/ℓ, demonstrating the effect of the eddy's presence at times. These higher values in nutrients do not seem to be reflected in higher chlorophyll-*a* values. There is evidence of higher zooplankton biomass here, but only intermittently. Phytoplankton production rates are below 1 gC/m^2/ day (Burchall, 1968). There has been a greater density of fish larvae off Durban on occasion (Beckley and van Ballegooyen, 1992), but not consistently (Beckley and Hewitson, 1994). A hydrographic cruise covering the whole Natal Bight has clearly demonstrated (Lutjeharms et al., 2000c; Meyer et al., 2002) the vertical structure of this eddy compared to the waters over the rest of the shelf. The upwelling of nutrient-rich water did not enhance chlorophyll-*a* values on that occasion either.

In summary, a cyclonic lee eddy is a recurrent, but not ever-present part of the circulation on the shelf directly off Durban, but seems to have hardly any local biological impact, perhaps because it is not enduring. There is evidence that this cyclonic eddy and its nutrient contents form the core to incipient Natal Pulses (Lutjeharms and Roberts, 1988).

When a Natal Pulse forms, due to an offshore eddy or otherwise, it seems to carry the Durban lee eddy with it (Lutjeharms et al., 2003b) all the way to the southern tip of the continent, intensifying the cyclonic motion in the eddy in its downstream journey. This would imply that inshore currents from Durban downstream would experience a sudden, but short-lived, reversal. As mentioned before, such a reversal has actually been observed (Lutjeharms and Connell, 1989) and directly related to a passing Natal Pulse. This incorporation of the Durban eddy in Natal Pulses also means that a part of the shelf fauna of the Natal Bight will intermittently be carried away. The effect of such a mechanism on the shelf biota is not known. Most local fish seem to spawn in Cape waters downstream and migrate upstream in July and November (Garratt, 1988). Only geelbek (*Atractoscion aequidens*) and seventy-four (*Polysteganus undulosis*) appear to spawn off the east coast of southern Africa. A small proportion of the fish caught off Natal are present throughout the year, most are distinctly seasonal, being either summer or winter species (Van der Elst, 1988). The most dramatic of the upstream migrations is that of the pilchard *Sardinops ocellata*, that takes place close inshore and is therefore very noticeable. No correlation with the passing of Natal Pulses in any of these fish migrations has to date been established.

4.3 Between Durban and the Agulhas Bank

Downstream of Durban the bathymetry changes dramatically (Fig. 20-011). Here the shelf is narrow and without any indentations to speak of. This configuration of the continental border has a controlling influence on the behaviour of the Agulhas Current. The current closely follows the edge of the shelf (Gründlingh, 1983) and the currents on the shelf move largely in sympathy (Fig. 20-015). Current speeds up to 1 m/s have been measured to 10 km off the coast. The currents at the shelf edge are, on average, about 0.5 m/s just downstream of Durban (based on ships' drift; Tripp, 1967), but increase steadily till they are 2.16 m/s off Port Elizabeth. Current speeds inshore are much lower and vary in a seemingly random manner from 0.38 to 0.77 m/s. At Port St Johns there is a minor coastal offset (viz. Fig. 20-011) and this seems to cause a higher frequency of counter currents (Harris, 1964), up to 40% of the time (Tripp, 1967). Observed currents at Port Edward (Fig. 20-015) are with the Agulhas Current, but somewhat reduced in speed. The strong currents are reflected in the sand transport and bedform patterns along this whole shelf edge. Substantial underwater sand dunes are formed (Flemming, 1978, 1980, 1981) and this whole dune field is mobilised to move downstream with the current. It has been surmised that at certain locations where canyons cut into the shelf they act as sediment traps, carrying sediment off the shelf.

Surface drifts over this shelf region, as measured by drifters (Anderson et al., 1988), are parallel to the current, but in both alongshore directions, suggesting that they are driven largely by the wind. Movement at greater depths is with the current (Schumann, 1982; 1987) except during very strong south-westerly winds when the shelf currents may briefly change direction. The latter is also reflected in observations of ships' drift (Pearce et al., 1978), although the incidence of current reversal is much reduced here compared to the movement in the Natal Bight, demonstrating the greater influence of the juxtapositioned Agulhas Current. From a direct comparison of current meter data and concurrent wind records it has been shown (Schumann, 1981) that the correlation between these signals is smaller than expected. Many current reversals therefore seem likely to be due to the passing of a Natal Pulse. However, there are other possible low frequency fluctuations in the currents on the shelf on this coast.

Schumann (1981; with Perrins, 1982) has analysed current records for signs of tidal and inertial signals. He found limited inertial motion; the energy spectrum being dominated by much longer periods that were assumed to be associated with variations in the Agulhas Current. Schumann (1986), in an investigation of the bottom boundary layer along this coastline, has furthermore demonstrated that in 50 m of shelf water Ekman veering took place over the lower 35 m. This would cause some upwelling of deeper water, possibly enhancing biological productivity.

Observations of the vertical distribution of nutrients do indeed show higher nutrient levels at depth (Carter and d'Aubrey, 1988) and over the deeper parts of the shelf. In general shelf waters were poor in nutrients (nitrate: 2.48 μmol/ℓ mean; 15.80 μmol/ℓ maximum) as is to be expected where surface waters of the Agulhas Current dominate. No observations have to date been made during the passage of a Natal Pulse and its imbedded Durban eddy. Conceivably such an event could cause a sudden, but short-lived elevation of nutrient concentrations. The effect of such pulses on the productivity along this stretch of shelf remains unknown. Observations of zooplankton (Carter, 1977) indicate higher biomass at the edge of the Agulhas Current here than upstream. Ichthyoplankton observations (Beckley and van Ballegooyen, 1992) reveal the same, but with great variability in space and time.

To recapitulate: the influence of the northern Agulhas Current on the shelf circulation seems to start only at about 28˚ S. The circulation in the wider shelf region of the Natal Bight is principally influenced by the passing current in the creation of an upwelling cell at St Lucia. By inserting nutrients into shelf waters this cell may have a controlling influence on the ecology of the whole Natal Bight. At the southern end of the bight the current drives a persistent lee eddy off Durban. The movement of waters on the narrow shelf south of Durban are for the most part parallel to the Agulhas Current. With the possible exception of what happens during the passage of a Natal Pulse, the circulation on this particular shelf region consequently seems uncomplicated, with low productivity and biological activity. The exception seems to be at Port Alfred, at the eastern tip of the Agulhas Bank.

5. Southern Agulhas regime

The Agulhas Bank forms the triangular continental shelf south of Africa (Fig. 20-016). It lies between Port Elizabeth in the east and Cape Town in the west. It is about 250 km at its widest. A shallow part, the Alphard Rise, where the shelf is widest (viz. Fig. 20-016), constitutes the border between the western and the eastern Agulhas Bank that, as a result of this partition, have distinctly different characteristics. This is exemplified by the contrasting sedimentary nature of the eastern and western Agulhas Bank.

The sediments on the eastern bank are dominated by shelly fragments whereas there are mainly foraminiferal oozes on the western bank (Rogers and Bremner, 1991). The organic matter content of the eastern Agulhas Bank sediments lies between 0.0 and 3.9 % (per unit mass) compared to 4.0 to 11.9 % on the western Agulhas Bank This places the western bank squarely in the province of the Benguela upwelling system

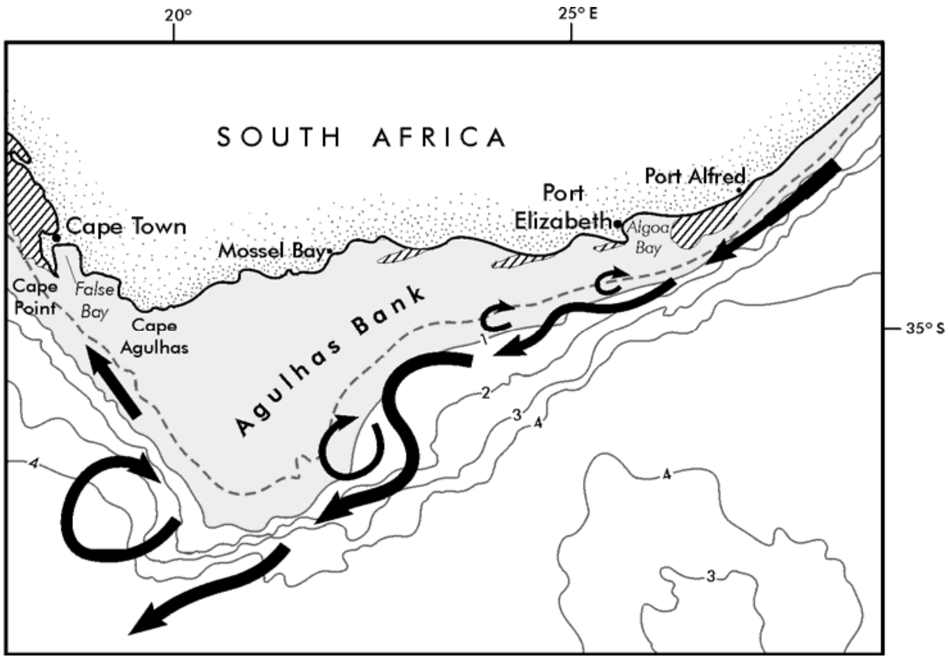

Fig. 20-016 Bathymetry of the continental shelf off the south coast of South Africa in km (after Simpson, 1974; Dingle et al., 1987a) and its major circulatory elements. This covers the southern Agulhas Current regime. Areas shallower than 1 km are shaded. The broken line denotes the edge of the continental shelf as defined by the 200 m isobath. Upwelling is shown by hatching. Place and feature names used in the text are given here.

(Dingle et al., 1987b) A further reason for this difference is the contrasting characteristics of the offshelf currents on either side.

On the eastern side the warm waters of the intense southern Agulhas Current follow the shelf edge (Fig. 20-016), but much less closely than upstream. The current starts to meander near Port Elizabeth and these meanders grow in amplitude downstream (Lutjeharms et al., 1989a). The meanders come with cyclonic shear edge eddies and attendant warm plumes. These plumes in general are shallow features, but may eventually spread their warm water over large parts of the adjacent shelf. By contrast, on the western side of the Agulhas Bank the sluggish Benguela Current carries cold water equatorward, but this is complicated by the presence of a lee eddy directly to the east of the Agulhas Bank (Penven et al., 2001a), the recurrent passage of Agulhas rings (Lutjeharms and Valentine, 1988; Boebel et al., 2003) and the intermittent advection of warm Agulhas surface water in the form of Agulhas filaments (Lutjeharms and Cooper, 1996). However, this shelf region is wide and the inner parts may be less affected by the offshore currents than by winds.

5.1 Wind regimes south of Africa

As is the case along the east coast, the winds along the south coast are mainly parallel to the coastline, more so at Port Elizabeth than in the central part of the south coast (Schumann, 1989). The ratio of offshore/onshore to coast-parallel winds is also lower along the south coast to that of Port Elizabeth where the winds are more strongly oriented parallel to the coast. North-easterly winds show the greatest seasonality with a greater than 40% occurrence frequency in austral summer, dropping to 25% in winter (Schumann and Martin, 1991). Average speeds for north-easterly winds at Port Elizabeth are greater than 4 m/s in summer, but only 1.5 m/s in winter. South-westerly winds show an inverse seasonal occurrence compared to north-easterly winds, but the wind speeds always lie around 4 m/s. Based on ships' reports, Jury (1994) has shown that on the eastern Agulhas Bank the most frequent and the strongest winds are from the east in summer and from the west in winter. Winds are significantly weaker over the southern parts of the shelf compared to closer to the coast. These winds and their directions naturally are part and parcel of the global ENSO and other perturbations (e.g., Schumann, 1992). Little work has to date been carried out to pin down these relationships.

A significant proportion of these winds come about as a consequence of coastal lows. These are formed as a result of the topography of southern Africa (Gill, 1977), most often associated with cold fronts that move from west to east (Hunter, 1987). The coastal lows move along the south coast with periods of 2 to 5 days and propagation speeds of 14 to 20 m/s. Analyses of the climatological variability of the major axis winds along the coast of the Agulhas Bank (Schumann et al., 1991) has therefore shown a distinct spectral peak at 6 days.

Over the western Agulhas Bank the wind patterns are significantly different to those on the eastern bank. At Cape Town the most seasonal wind is the south-easterly wind with an 80% occurrence frequency in summer and a 40% frequency in winter. Average speeds in summer are in excess of 5 m/s; only 1.5 m/s in winter. By contrast the north-westerly winds are only slightly more prevalent in winter and maintain average speeds of about 3 m/s.

Wind strength is increased over the Agulhas Current itself. The loss of heat from the Agulhas Current to the atmosphere is about 200 W/m^2 higher than that of ambient water masses (Rouault et al., 2000). During along-current winds an atmospheric moisture and thermal front develops at the inshore edge of the current off Port Alfred, where the current passes a distinct upwelling cell.

5.2 The Port Alfred upwelling cell

As mentioned before, if the theoretical portrayal of Gill and Schumann (1979) holds, wherever a western boundary current moves from a narrow shelf past a wider shelf a degree of upwelling should be experienced. This has been observed south of Madagascar, at the northern corner of the Natal Bight and even in the Kuroshio system (Lutjeharms et al., 1993). It would therefore be expected to occur also where the Agulhas Current starts flowing along the Agulhas Bank and there it has indeed been observed (Lutjeharms et al., 2000a).

Thermal infra red imagery from satellite shows that this upwelling has its centre off Port Alfred (viz. Fig. 20-016), but that cold water inshore of the Agulhas Current may extend up to a maximum of 300 km upstream. On average it is about 30 km wide and extends 180 km along the edge of the current (Fig. 20-017). Water masses in the upper 200 m of the Agulhas Current are Subtropical Surface Water with the occasional pulse of Tropical Surface Water, mostly at the landward side (Gordon et al., 1987). During those times that the upwelling is evident at the sea surface the water in the upwelling cell is all South Indian Central Water (Lutjeharms et al., 2000a). This implies that it is upwelled onto the shelf from offshore waters deeper than 400 m and this has been confirmed by hydrographic observations in the region (Goshen and Schumann, 1988; their Fig. 8). Nutrient values in the upwelling cell can exceed, for example, 20 µmol/ℓ

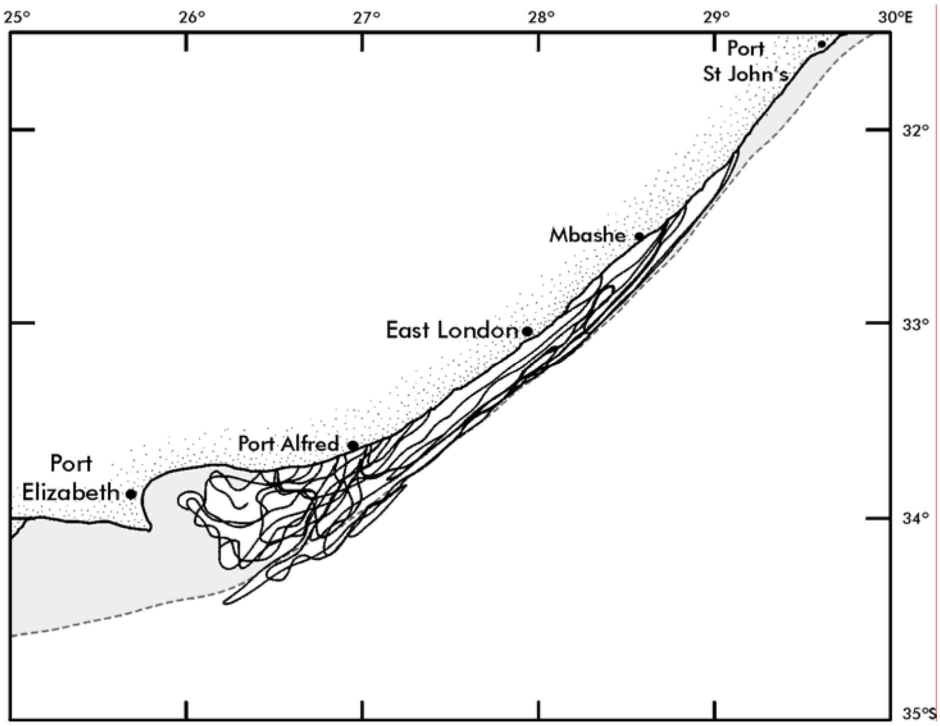

Fig. 20-017 An ensemble of outlines of cold water of the Port Alfred upwelling cell inshore of the Agulhas Current, using the 17 ˚C isotherm as an indicator. (As given by Lutjeharms et al., 2000a.) The 200 m isobath is shown as a dotted line and the shelf inshore of this isobath shaded.

at 100 m, whereas they are less than 5 µmol/ℓ on the adjacent shelf. This upwelling cell may furthermore have considerable implications for the Agulhas Bank as a whole.

First, it forms one of what may be considered to be the three main physical/chemical provinces of the bank. The others are the greater part of the shelf and the coastal upwelling regime of the western Agulhas Bank (Lutjeharms et al., 1996). These provinces are well-defined, considering the poor and inhomogeneous distribution of hydrographic stations available. Second, from this upwelling cell water colder than 10 ˚C moves over the bottom of the Agulhas Bank (Lutjeharms and Meyer, 2004). The seasonal thermoclines over the bank are unusually intense. It is believed that this is partially due to the continual input of cold water along the bottom. It has previously been surmised that this cold water is upwelled inshore of the Agulhas Current along the eastern edge of the bank (Chapman and Largier, 1989). To date little direct evidence for this has been found. In fact, almost all hydrographic sections across the bank show the water colder than 10 ˚C near the shelf edge only in the vicinity of Port Alfred. If this upwelling cell plays such a crucial role in the stratification of the whole Agulhas Bank, how permanent is it?

Regrettably, there are no data to address this important question. Surface observations show that it is present almost 50% of the time (Lutjeharms et al., 2000a), but this surface outcropping may be largely wind dependent, as has been observed at sea (Rouault et al., 1995). With the limited hydrographic data available, the presence of upwelled water at depth seems considerably more enduring. If this upwelling cell is so persistent, how does it affect the distribution of primary productivity and biota at higher trophic levels?

A chlorophyll-*a* maximum zone extends from the vicinity of Port Alfred roughly along the 100 m isobath across the eastern Agulhas Bank (Probyn et al., 1994). This “upwelling ridge” has primary production rates of 104 mg/m^2/h, whereas the shelf near Port Alfred boasts values of 888 mg/m^2/h. Values at the shelf break are 231 mg/m^2/h. In this respect it is interesting that ocean colour observations from satellite (Lutjeharms and Walters, 1985) show slightly enhanced values along the whole landward edge of the Agulhas Current. By contrast the zooplankton biomass is low near Port Alfred (Verheye et al., 1994), increasing westward. Spawning of chokka squid, as detected by eggs trawled, show a distinct concentration at Port Alfred, with a downstream decrease across the shelf, downstream (Augustyn et al., 1994). About predators much less is known (Smale et al., 1994). The size distribution of fish varies noticeably across the Agulhas Bank (Japp et al., 1994), the larger fish being found on the eastern Agulhas Bank, some species densities higher at the horizontal thermal gradients associated with the shelf edge (Barange, 1994). The biological influence of the Port Alfred upwelling cell therefore seems indirect, particularly via the inflow of bottom water over the eastern Agulhas Bank.

5.3 The eastern Agulhas Bank

Much has been made of the ridge of cold water (< 10 ˚C) that overlies the 100 m isobath over much of the eastern Agulhas Bank (e.g., Boyd and Shillington, 1994; Verheye et al., 1994; Probyn et al., 1994). This ridge is evident in temperature sections across the bank; at times it crops out, producing areas of cold water at the sea surface (e.g., Walker, 1986; Swart and Largier, 1987) over the bank. The location of this ridge corresponds with the distribution of a number of copepod development stages (Largier and Swart, 1987), medium size chokka squid (Augustyn et al., 1994) and a subsurface chlorophyll-*a* maximum at the nutricline (Probyn et al., 1994). It has been proposed (Lutjeharms and Meyer, 2004) that this ridge of cold, nutrient-rich water originates in

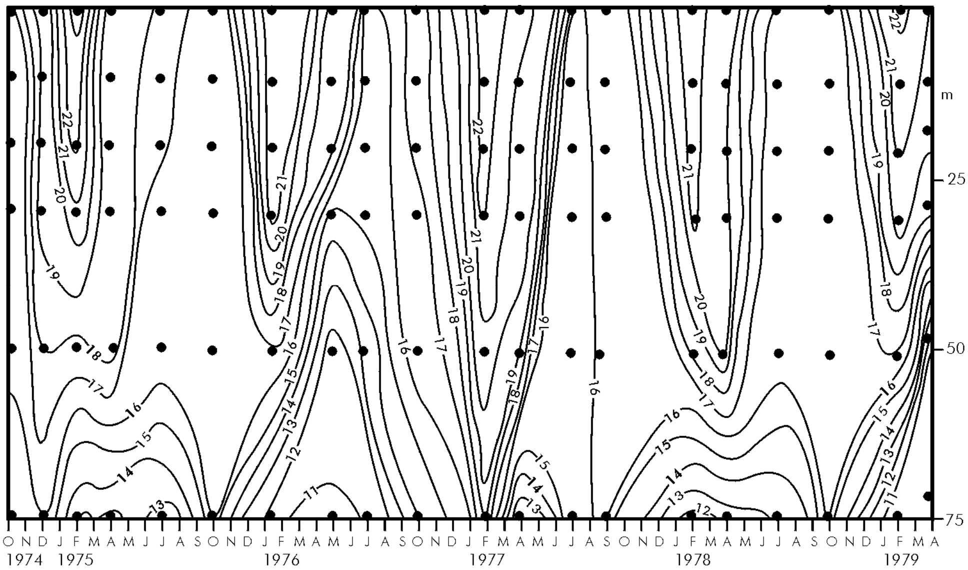

Fig. 20-018 Time series of the temperature profile for a hydrographic station on the central Agulhas Bank for the period 1974 to 1979. Dots indicate standard depths at which nutrient samples were taken. (After Lutjeharms et al., 1996.)

the Port Alfred upwelling cell. It enhances the thermal stratification of the water column from below over most of the bank and brings nutrients onto the full extent of the shelf. These nutrients may not be available to the phytoplankton throughout the year, but follow an annual cycle. Observations show (Carter et al., 1987) that the subsurface chlorophyll-*a* peak is closely associated with the behaviour of the seasonal thermocline. This stratification on the Agulhas Bank follows a rather peculiar cycle (Eagle and Orren, 1985; Lutjeharms et al., 1996; Fig. 20-018).

During the winter months storm winds and convection mix the upper water column to depths of 75 m or more; in summer fewer extreme wind events and increased insolation establish a seasonal thermocline that may be at 50 m or deeper. Summer winds have been shown to be too weak (Largier and Swart, 1987) to break down the seasonal thermocline. The winter mixing of the water column raises the temperature of the bottom water in winter, being warmest in July (Swart and Largier, 1987). All this is normal for shelf regimes in the subtropics. On the Agulhas Bank this seasonal stratification is however enhanced by cold water from *below* (Fig. 20-018) thus establishing a seasonal thermocline and nutricline about twice as strong as would normally be expected. It is believed that the inflow of all this cold, nutrient-rich water is from the Port Alfred upwelling cell.

The result of this seasonal behaviour of the water column is also reflected in the temperature/salinity characteristics of the Agulhas Bank. In spring the temperature range is restricted to 14 – 18 ˚C, salinity to 35.0 to 35.5; by contrast, in winter this ranges from 10 – 23 ˚C, salinity 34.6 to 35.8. The nutrients follow suite. Average sea surface temperatures are between 21 – 26 ˚C over the eastern Agulhas Bank, representing the horizontal offshore gradient towards the Agulhas Current (Schumann and Beekman, 1984). In winter this is reduced to 16 – 19 ˚C. In summer the average temperature difference between the water at the surface and at 80 m depth is as high as 11 ˚C; in winter the highest gradient is 5 ˚C. With the seasonal collapse of the nutricline the subsurface chlorophyll-*a* peak also disappears (McMurray et al., 1993). Nevertheless the seasonal thermocline on the eastern bank is usually shallower and better developed compared to that of the western part of the bank.

The movement of the waters of the eastern Agulhas Bank can most probably be placed into three categories: the very surface layer, the bottom layer and the rest of the water column. The very surface layer moves largely with the wind (Lutjeharms et al., 1986a). Comparison of the movement of a drifter with progressive wind stress vectors rotated 35˚ to the left has demonstrated this quite admirably (Harris, 1978). Analyses of ships' drift, corrected for windage on ships' superstructure, show (Tripp, 1967) no distinct patterns or seasonal cycles. Since the dominant wind directions are parallel to the coast, so will the top water layer therefore move. This is particularly important from a pollution point of view since tar balls (Shannon and Chapman, 1983; Shannon et al., 1983) will be beached only under onshore wind conditions. The bottom waters, where they have been measured (Swart and Largier, 1987), move largely parallel to the isobaths and in the direction with the Agulhas Current. The movement of the rest of the water column is more complex. Schumann and Perrins (1982) have shown that the highest energies on the shelf are to be found at inertial periods. The bottom motion described earlier consists of the residual drift after the inertial current signals have been removed. The influence of the Agulhas Current is not always clear.

As mentioned above, the major characteristic of the Agulhas Current along the shelf edge of the eastern Agulhas Bank is the presence of shear edge eddies of various sizes (Lutjeharms et al., 1989a). These eddies move downstream with the current and are most prevalent in the concave part of the shelf edge (Lutjeharms et al., 2003a). There is evidence (Hutchings, 1994) that the spawning of anchovy takes place preferentially just inshore of the shelf edge where these eddies are common. The passage (Schumann and van Heerden, 1988) of such eddies inverts the shelf edge current that is usually dominated by the Agulhas Current. Cold water is upwelled in the core of these cyclonic features and is has therefore been surmised that they are instrumental in bringing this cold water onto the shelf (Chapman and Largier, 1989). This has been observed very infrequently (e.g., Schumann and Beekman, 1984). The warm water plumes associated with the shear edge features bring warm Agulhas Current water onto the shelf and this may enhance the shelf thermocline. In general these plumes may represent a relatively thin layer of warm water (e.g., Goschen and Schumann, 1990) and their subsequent movement over the shelf may be almost entirely driven by winds (Goschen and Schumann, 1994).

Once past the southern tip of the Agulhas Bank, the Agulhas Current proper moves offshore, but some of the plumes may be drawn along the edge of the western Agulhas Bank as Agulhas filaments.

5.4 The western Agulhas Bank

Agulhas filaments are relatively shallow features (~ 50 m) and may carry warm surface water as far as the coastal upwelling zone off south-western Africa (Lutjeharms and Cooper, 1996). To date there has been only occasional evidence (e.g., Mitchell-Innes et al., 1999) that warm surface water from these filaments may intrude over the shelf in an analogous fashion to that of plumes adjacent to the eastern Agulhas Bank. Why Agulhas filaments are drawn so rapidly equatorward is also not entirely clear. This has been assumed (Lutjeharms and Valentine, 1988) to be due to passing Agulhas rings. Such ring prevalence may be the origin of the hypothesised shelf edge jet (e.g., Hutchings, 1994) that has been put forward as a mechanism to move anchovy larvae northward towards the coastal upwelling region of the west coast (e.g., Boyd et al., 1992). Then again, whenever direct current observations of the currents over the shelf edge have been made (e.g., Fowler and Boyd, 1998) no evidence for any persistent north-westerly setting current could be found.

However, there is strong evidence that there is a tendency for the circulation off the shelf of the western Agulhas Bank to be cyclonic, which would lead to currents at the shelf edge to move poleward instead. Modelling (Lutjeharms et al., 2003a) and hydrographic observations (Penven et al., 2001a) now suggest that this is due to a cyclonic eddy driven by the Agulhas Current in the lee of the Agulhas Bank. The discrepancy between an equatorward shelf edge jet and a poleward movement driven by an Agulhas Bank lee eddy had not yet been resolved. Apart from the difference in current behaviour at the shelf edge, the western Agulhas Bank also differs from the eastern bank by extensive coastal upwelling.

The main, wind-driven upwelling along the west coast normally starts at Cape Point (south of Cape Town, viz. Fig. 20-016), but during about 10% of the time there also is contiguous upwelling all the way between Cape Agulhas and Cape Point (Lutjeharms and Meeuwis, 1987; Lutjeharms and Stockton, 1991). This latter upwelling, as expressed as a biologically productive region, may extend from less than 20 to 100 km offshore (Mitchell-Innes et al., 1999). At Hermanus and Gansbaai, between Cape Point and Cape Agulhas, annual surface temperatures range (Largier et al., 1992) from 17 ˚C in January to 15 ˚C in August with a small maximum in May. With a higher incidence of south-westerly winds in summer, the upwelling here is most intense in that season (Boyd et al., 1985), as can easily be modelled (Penven et al., 2001b). Constant westerly or south-westerly winds may induce downwelling, but upwelling can recur within a matter of days under the influence of winds of the correct direction and sufficient speed (Jury, 1988). The vertical temperature gradients in this upwelling are strongest in summer, weakest in winter (Schumann and Beekman, 1984). Cool, low-salinity Central Water was upwelled to within 20-40 m of the sea surface from January to April during a survey in 1975 (Boyd et al., 1985) and from September to November when south-easterly winds are dominant. Only between February and April was it observed to break the surface. Climatologically it is also present in July and December (Lutjeharms and Stockton, 1991). Vertical stratification was best developed in summer, due to the uplift of cooler Central Water and the onshore advection of warm surface water from the Agulhas Current and the Agulhas Bank. This is reminiscent of the cycle of stratification over the central Agulhas Bank (Eagle and Orren, 1985; Fig. 20-018). Nutrients moved closer to the surface in spring and summer, causing a modest spring bloom (Mitchell-Innes et al., 1999), but generally did not penetrate the thermocline until vigorous mixing to a depth of 60-80 m in winter.

Over the rest of the western Agulhas Bank the stratification seems much weaker than over the eastern bank. The uplift of the isopycnals towards the coast over this shelf region is naturally evident in the distribution of nutrients with high values covering the greater part of the shelf (Lutjeharms et al., 1996) than over the eastern Agulhas Bank.

The prevailing currents on the western Agulhas Bank are in a north-westerly direction in summer; in winter those along the southern parts of this coastline may be south-eastward (Harris, 1978). Water characteristics are the same above the thermocline than on the eastern Agulhas Bank, but below the thermocline the waters are slightly less salty and have lower nutrient loads (Chapman and Largier, 1989). This has been taken as evidence that this water has an Atlantic rather than an Indian Ocean origin and that the bottom water here on average moves in a south-easterly direction. In general the water movement here is parallel to the isobaths (Largier et al., 1992), but in both directions. Nevertheless, inertial currents may still be the dominant movements on shorter time scales (Schumann and Perrins, 1982).

Evidently, the coastal upwelling on the western Agulhas Bank will have a dramatic effect on the ecosystem of this part of the bank. In contrast to the eastern bank, chlorophyll-*a* values are considerably higher (Largier et al., 1992). Phytoplankton concentrations are lower (De Decker, 1973) than in the upwelling region along the west coast, both measured as numbers of cells and as settled volume. Remarkably, zooplankton settled volumes are almost consistently higher. Biota in higher trophic levels (e.g., Roel et al., 1994) do not show any patterns clearly related to the upwelling, including euphausids.

5.5 Coastal processes

The wind-driven upwelling along the western part of the Agulhas Bank is a specific coastal process, but there are a number of other such locations and processes on the Agulhas Bank that are largely divorced from what happens over the broader expanses of the shelf. Perhaps the most important of these is intermittent upwelling at the promontories along the coast of the eastern Agulhas Bank (Schumann et al., 1982; viz. Fig. 20-016).

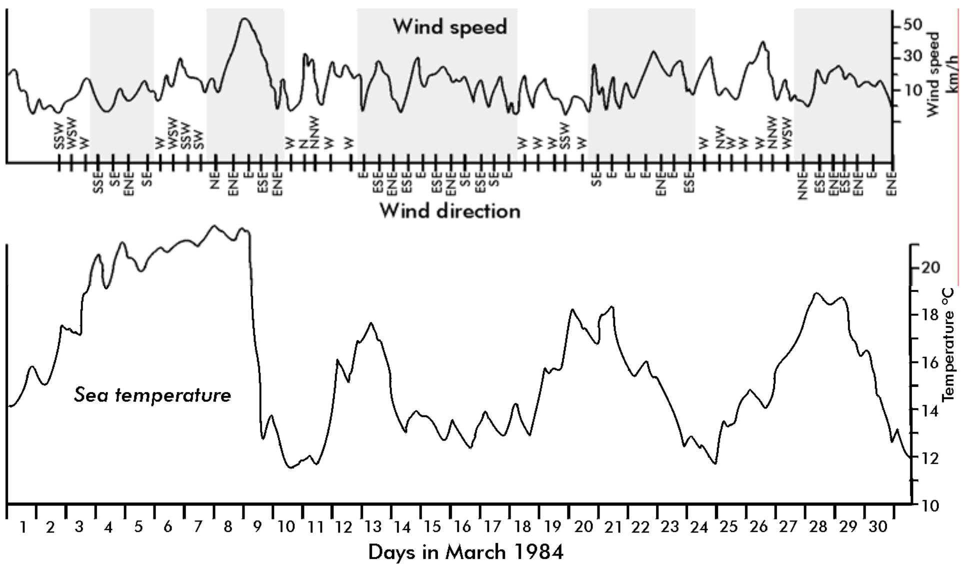

Fig. 20-019 Sea surface temperatures and wind speeds at Gouriqua (near Mosselbaai, viz. Fig. 20-016) on the south coast of South Africa during March 1984. Wind speed is shown as a curve; wind direction by letters on the abscissa of the wind speed curve. (According to Lutjeharms, 1998.) Temperatures rise and fall at the coastline in direct response to the direction and speed of the local wind.

On the whole the seasonal cycle of sea surface temperatures at this coast is considerably better developed than that along the northern Agulhas Current. Average temperatures at Port Elizabeth, for example, range from 21 ˚C in January to about 15 ˚C in July/August (Lutjeharms, 1998) whereas those at East London vary only from 19 ˚C to 17 ˚C. Intermittent coastal upwelling along the south coast is superimposed on this seasonal sequence. It occurs only at prominent capes (Schumann et al., 1982) under suitable wind directions (e.g., Goschen and Schumann, 1995) and with winds above a certain threshold (Schumann et al., 1995). Upwelling is seen less than 10% of the time, the highest incidence being in summer. The local effects can be quite dramatic (Fig. 20-019). Beckley (1983, 1988) has reported temperatures dropping by 8 ˚C over a period of 24 h at a cape site compared to one less than 40 km away. Goschen and Schumann (1995) have observed reaction times of a few hours. These upwelling events may last from one to 5 days (Schumann, 1999). Wind events in along-coast winds have a frequency peak between 4 and 8.5 days, with a maximum at 7 days (Schumann et al., 1991) indicating the driving role of the winds.

Nevertheless an analysis of chlorophyll-*a* intensity at this coastline (De Villiers, 1998) suggests that the correlations between primary productivity and sea surface temperature is much better than between primary productivity and upwelling inducing winds. Along the very farthest eastern side of the Agulhas Bank it may be difficult to distinguish between local, wind-induced upwelling and the advection into the region of cold water that has been upwelled in the Port Alfred upwelling cell (e.g., Schumann et al., 1988). Upwelling events of this kind have in fact been observed to attract large flocks of sea birds. This phenomenon remains unexplained, since the short duration of most upwelling events would not result in greatly enhanced primary productivity. It has been hypothesised (Schumann et al., 1988) that the convergence associated with an upwelling front may have caused concentration of food items for birds. The counterpart of coastal upwelling of cold water is advection of warm water into coastal embayments.

Along the far eastern side of the Agulhas Bank the likelihood of an intrusion of warm surface water from the adjacent Agulhas Current right to the coast may be high. Under southerly wind conditions water from plumes may reach the coastline and cause a temperature rise of 3 ˚C or more in surface water. They may also cause a distinct layering in offshore water. To some extent the coastal morphology plays a role in the manner in which offshore events may influence the water masses or circulation at the coast. At certain locations, such as Algoa Bay at Port Elizabeth (viz. Fig. 20-016), the local winds may create circulations restricted to a bay (Goschen and Schumann, 1994). A prominent case of localised circulation is found in False Bay, the large, rectangular Bay on the most western tip of the western Agulhas Bank, just south-east of Cape Town (viz. Fig. 20-016).

The surface circulation of this bay is complex (Gründlingh and Largier, 1991). On the eastern side there is intermittent, wind-driven upwelling (Cram, 1970) that brings nutrient rich water to the surface (Taljaard, 1991). The border of this upwelling may on occasion form a zonal front across the mouth of the bay (Lutjeharms et al., 1991). Only one hydrographic survey of the bay as a whole has been made (Gründlingh, 1992b, Taljaard, 1991) and as part of that investigation two sections across the bay were repeated shortly after. These repeat measurements have dramatically demonstrated the variability to be expected.

During the observations in 25-27 April 1989, cold, fresher upwelled water from farther east along the coastline was advected into the western side of the bay, creating a meridional front, evident throughout the water column. During the repeat survey between 27 and 29 April 1989, the situation had changed completely. Now there again was a meridional front near the centre of the bay, but with the cold water on the *east*, brought about by substantial upwelling on that side. A shallow thermocline (30 m) remained well-developed in the northern, shallower part, but more variable in the southern part of the bay. Surface currents are also very variable and show a range of different patterns (Atkins, 1970), probably wind generated (Jury, 1991). The bay is surrounded by mountains, creating a strong orographic effect on the air flow. At depth, by contrast, the currents seem much more steady and consistent (Gründlingh et al., 1989). Water enters on the western side and leaves on the eastern side. As might be expected the vertical stratification is very seasonal, particularly in the southern, deeper parts (Gründlingh, 1992b). Huge demographic shifts to the shores of the bay have placed enormous pressure on its self-cleaning ability. As in many other parts of the shelf seas discussed above, ignorance of the flushing rate and many other aspects of the circulation and the ecosystem make its proper management hazardous.

To sum up: the shelf waters of the Agulhas Bank may be placed into three physical/chemical provinces according to the influence of the Agulhas Current, or lack thereof. These are: the Port Alfred upwelling cell, the coastal upwelling of the western Agulhas Bank and, third, the wider shelf outside the immediate influence of the Agulhas Current. The Port Alfred upwelling cell may be permanent at depth, with a surface outcropping driven by local winds. Cold, nutrient-rich water is brought onto the shelf here and may spread over the greater part of the Agulhas Bank. There is a high likelihood that this inflow of bottom water is the driving force for the very intense seasonal thermoclines over the wider shelf region. The northward advection of warm Agulhas plumes is assumed to play a minor role. The unusual intensity of the stratification over this shelf may be crucial to the local ecosystem and, in particular, to the successful spawning of economically important fish species. The upwelling on the western Agulhas Bank is a seasonal phenomena and forms part and parcel of the greater Benguela upwelling system.

6. Future directions

From the above brief review it should be abundantly clear that the multidisciplinary characteristics of this part of the world ocean are very imperfectly understood. This is particularly true for the coastal oceans. This ignorance is easily explained: very few observations have been made on these continental shelves as a whole; in large parts, none. In some respects this makes it easy to suggest future research directions.

In shelf regions where hardly any data whatsoever are available, any new measurements are welcome. In other respects it makes it very difficult. To identify the key elements that need to be addressed as a matter of urgency – particularly for contiguous Third World countries with severely limited funds and research capability – is near to impossible. With these caveats, let us proceed by examining the research needs for the coastal oceans in the sequence in which they were discussed in the preceding sections, starting with the shelf regions of the Mozambique Channel.

The wide shelf on the eastern seaboard of Mozambique plays a recognised important role in local fisheries and thus in the economy of the adjacent country (e.g., Sætre and de Paula e Silva, 1979; Brinca et al., 1981). Its waters are likely to be predominantly influenced by the reigning winds and in particular the occasional incidence of severe cyclones. The effects of such winds on the hydrographic characteristics, especially vertical stratification, the primary productivity and the distribution of biota need urgent research attention. It has now been shown conclusively (De Ruijter et al., 2002) that there is no continuous, intense Mozambique Current that borders this shelf region, but that instead a series of eddies are formed in the narrows of the channel that subsequently progress poleward. The influence of these drifting eddies on the adjacent shelf is not known yet. Quartly and Srokosz (2004) have shown that they extract water, rich in phytoplankton, from the surface layers of the shelf. These potentially important processes need to be studied with *in situ* measurements. These recent research developments also point to the need for more, extensive deep-sea investigations.

The lack of hydrographic stations to describe and demarcate the water masses and the circulation in the deeper parts of the Mozambique Channel (Lutjeharms, 1977) also has an effect on what is known on the influence of the deep-sea on shelf waters. Although recent work (e.g., De Ruijter et al., 2002; Ridderinkhof and De Ruijter, 2003) has started to fill the most obvious gaps, much remains to be done. The hydrography and kinematics of the eastern side of the Mozambique Channel, for instance, remain cloaked in mystery. The influence of this particular deep-sea region on the western shelf of Madagascar therefore also remains unknown.

For the whole South West Indian Ocean this eastern side of the Mozambique Channel is probably the coastal ocean about which least is known. At the northern tip of Madagascar some work was done on shelf and adjacent coastal processes during the 1960s (e.g., Angot and Ménaché, 1963; Gerard, 1964; Angot and Gerard, 1966; Donguy and Piton, 1969), but along the central and southern parts there is – to my knowledge – no adequate information whatsoever. The most basic investigations on water masses, current patterns, biota and their respective variabilities need to be undertaken here. This is also true for the eastern shelf of Madagascar.

As was seen in the preceding sections, only the most basic facts are know about the two branches of the East Madagascar Current along this shelf of Madagascar. Since the shelf here is very narrow (Figure 20.1) the fast moving waters of this current are more than likely to have a decisive influence on the shelf waters. However, as long as no detailed observations are made and no careful monitoring is done, this reasonable hypothesis has to remain in the realm of speculation. Of particular importance is a better understanding of the upwelling cell at the south-eastern corner of Madagascar. Only one set of dedicated observations have been made here to date (Machu et al., 2002) and much more needs to be learnt about the possible influence of this upwelling on the biological productivity of the region. Anecdotal information from local subsistence fishermen suggests (M. Rouault, personal communication) that it may be a rich region for fisheries. Its investigation therefore also may hold considerable economic and fisheries management consequences. In comparison to these shelf regions off Madagascar and Mozambique, comparatively much more is known about the shelf regions off South Africa.

For the shelf region inshore of the northern Agulhas Current a number of things stand out that need further investigation if we are to understand the physico-chemical and biological behaviour of these particular shelf waters. It has been hypothesised that the upwelling cell at the northern tip of the Natal Bight, at St Lucia, may control the nutrient supply to the whole bight and thus the ecosystem of this shelf province. The intensity of this upwelling cell and the progress of water from there onto the shelf of the rest of the bight need to be monitored carefully if this hypothesis is to be verified. The shelf downstream from the bight is much narrower (Figure 20.1) and the water movement on it therefore conceivably much simpler. The one exception to this simple movement in sympathy with that of the Agulhas Current may come about due to the passage of Natal Pulses.

This irregularly occurring meander on the trajectory of the Agulhas Current has been shown to have a dramatic influence on the currents over the adjacent shelf (Gründlingh, 1979; Lutjeharms and Connell, 1989) during its passage. To date this has been observed only fortuitously, although it is evident in some historical current meter records (e.g., Schumann, 1982). This shelf is the known conduit for the migration of whales and the annual sardine run. It is unknown what effect the passage of a Natal Pulse has on these migrations or if the unusual, but potentially beneficial, currents associated with these current meanders are in fact purposefully used by these animals. It would seem clear that this needs investigation. For the shelf off the southern Agulhas Current the research questions are different.

It has been surmised (Lutjeharms and Meyer, 2004) that the upwelling cell at the eastern end of the Agulhas Bank, adjacent to Port Alfred, may dominate the flux of bottom water onto this shelf region. This proposition has considerable implications for a proper understanding of the vertical stratification of the waters over the shelf, the nutrient supply to the shelf and the ecology of this large coastal region. Observations on this upwelling cell to date have all been inadvertent. The need for a dedicated observational programme seems essential, particularly since the Agulhas Bank is the spawning region for anchovy that sustain the prime pelagic fisheries of South Africa. Such a programme should at a minimum study the nature and driving forces of the Port Alfred upwelling cell, the movement of upwelled water from here and the variability of the system of bottom water supply. It is not only the bottom water that is of importance; the whole physico-chemical nature of the waters over the Agulhas Bank is - bearing in mind its probable economic importance - amazingly poorly known.

To date only two quasi-synoptic research cruises have been undertaken to establish the hydrographic structure of the Agulhas Bank as a whole (Lutjeharms et al., 1981b; 1983). During these cruises only the thermal structure of the water masses was measured. Notwithstanding the importance of this shelf region for the local fisheries, no dedicated hydrographic cruise or set of cruises has covered the full extent of the bank since the aforementioned cruises, nor are there immediate plans to rectify this situation. This seems a particularly serious gap in the knowledge of these coastal oceans that needs urgent attention.

The waters on the Agulhas Bank are influenced not only by normal solar and air-sea interaction processes, nor only by the imbedded upwelling cell, but also by interaction with the juxtapositioned Agulhas Current. As is evident from the above review, plumes of warm surface water from the Agulhas Current move onto the bank and may spread over extensive parts of it. It has consequently been surmised (Swart and Largier, 1987) that this input of advected surface water may play an important, if not decisive, role in maintaining the very strong vertical temperature gradients over the bank. Attempts at quantifying this process and comparing it with the role of insolation would be valuable and contribute to a better understanding of the factors playing a role in the hydrography of this important part of the South African shelf and its role in the ecology of the region, particularly the spawning of anchovy.

In short, even an entirely subjective listing of research priorities for the coastal seas of the South West Indian Ocean demonstrates unequivocally the urgent need for research in order to understand even the most fundamental, descriptive aspects of many of the shelf regions here.

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