The ocean environment off southeastern Africa: a review

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The ocean environment off southeastern Africa consists of a continental shelf region of diverse widths and an off-shelf circulation that is similarly multifaceted. These factors lead to a complex and as yet imperfectly understood coastal and shelf habitat for living organisms. To complicate this further, the coverage of the region by hydrographic and other investigations differs markedly. Some regions have been relatively thoroughly studied whereas in others no hydrographic or current observations of any kind have been made to date. The only attribute that connects the coastal oceans of this region is that they all belong to what may be considered to be the greater Agulhas Current system. This consists of the East Madagascar Current, the Mozambique Channel eddies and the Agulhas Current proper. In this paper I review current knowledge on the region from both a physical as well as a biological oceanographic point of view. Some of the most glaring gaps in our knowledge of the region are identified.

Introduction

The geographical distribution of coelacanths has been of perennial interest and in this issue aspects of this matter are addressed based on the newest information. Various environmental issues may play a role in this distribution. First, suitable habitats dependent on continental shelf morphology are required. Second, the environment must supply the appropriate food at the correct times in the life cycle of these fish. Not entirely independent of the latter is the physical environment, including currents, water characteristics such as temperature and the degree of variability in all of these. Our current understanding of how the environment has influenced where coelacanths have been found is hampered by a complex circulatory system, in the South-West Indian Ocean, and a dearth of observations and information on it. To appreciate this fully, a better understanding of the large-scale circulation is perhaps a first requisite.

The greater Agulhas Current system

The waters of the South-West Indian Ocean are largely fed by the South Equatorial Current, a shallow wind-driven flow that lies in a zonal band over the width of the tropical Indian Ocean.[1] A large part of this current is prevented from reaching the east coast of Africa by the interposed land mass of Madagascar (Fig. 1), while the remainder passes the northern tip of Madagascar on its way to east Africa. That part of the South Equatorial Current that runs into the east coast of Madagascar divides into a component that carries water equatorward as the northern branch of the East Madagascar Current as well as an analogous southern branch. The point of bifurcation between these two branches has not been accurately determined and may exhibit a meridional shift with season (A. Cooke, pers. comm.). The waters of the northern branch eventually join the uninterrupted part of the South Equatorial Current at the northernmost point of Madagascar (Fig. 1). The southern branch behaves in a very different way.

On passing the southern tip of Madagascar, the southern branch of the East Madagascar Current has been observed to retroflect,[3,4] returning most of its water eastward. This may not be a permanent disposition for this current's termination and on many occasions it may extend past the southern tip of Madagascar, creating vortex dipoles as a consequence.[5] The shelf along which the waters of the East Madagascar Current move is narrow, with the exception of the region south of Madagascar, where the shelf is much wider. The East Madagascar Current is narrow, intense and seemingly very stable. This is in strong contrast to the currents adjacent to the coast of Mozambique (Fig. 1).

Currents in the Mozambique Channel have classically been understood to be dominated by a strong western boundary current, the Mozambique Current, that was thought to feed directly into the Agulhas Current to the south. This interpretation, based largely on observations of ships' drift,[6,7] has been shown to be erroneous by analyses of historical hydrographic data[8] as well as by the results of a recent dedicated cruise in the region.[9] The latter has shown unequivocally that a continuous Mozambique Current does not exist, but instead that a string of eddies, both cyclonic and anti-cyclonic, with the anti-cyclonic eddies being the most intense, are formed at the narrows of the Mozambique Channel and that these eddies drift southward past the African continental shelf (Fig. 1). Some may eventually reach and be absorbed by the Agulhas Current,[10] thereby having an important effect on the behaviour of the current.

These two currents, the Mozambique Current and the southern branch of the East Madagascar Current, have long been thought to be the primary tributaries of the Agulhas Current, the major western boundary current of the southern hemisphere. It has now become clear that this is not the case.[11] There is no direct inflow from the southern branch of the East Madagascar Current to the Agulhas Current, nor is there a persistent Mozambique Current. It has instead been recognized that the contribution from these two regions to the Agulhas Current proper is in the form of eddies that act as important perturbations to the flow. The main source of the Agulhas Current in fact comes from recirculation in a South-West Indian Ocean subgyre.[11]

Somewhere along the shelf edge on the east coast of South Africa, between Maputo and Durban (Fig. 1), the Agulhas Current is fully formed. It generally follows the shelf edge quite closely[12] all the way downstream to Port Elizabeth. This stable path is interrupted only occasionally by a Natal Pulse, a singular meander in the current path that forces the current offshore. It moves with the current[13] at a rate of about 20 km per day. This unusual perturbation of the current trajectory is formed at the Natal Bight, a wider part of the shelf just upstream of Durban[14] (Fig. 6) and has marked consequences for the flow patterns on the adjacent shelf and for the behaviour of the Agulhas Current farther downstream. When it reaches the much wider shelf to the south of Africa, the Agulhas Bank, where the continental

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slopes are also much weaker, the Agulhas Current starts to exhibit the kind of meanders that are such a distinctive characteristic of most other western boundary currents.[15] Associated with these meanders are shear edge eddies and plumes of warm surface water at the shelf edge. Having passed the southernmost tip of the Agulhas Bank, these plumes from the border of the Agulhas Current may be carried along the western shelf edge of the bank as Agulhas filaments[16] (Fig. 1). These contribute to the inter-ocean leakage of water masses and have also been implicated[17] in the transport of organisms and eggs from the Indian to the South Atlantic Ocean. Just beyond the separation of the Agulhas Current from the constraining shelf edge, it retroflects,[18] with most of its water subsequently following the Subtropical Convergence in an eastward direction as the Agulhas Return Current.[19] The configuration of a tight retroflection loop is inherently unstable and occludes at irregular intervals forming an Agulhas ring with a diameter of 300 km or more[20] and extending to the ocean floor. These rings, the largest of their kind in the world ocean,[21] drift off into the South Atlantic Ocean, carrying their contents of anomalous salt, heat and Indo-Pacific biota with them across the ocean basin.[22] They slowly decay by spinning down and may even split[23] or rejoin each other. This process of ring shedding and inter-ocean exchange of water forms a major component of the exchange of organisms between these two ocean basins. Tropical biota in Agulhas rings may survive passage past the southern tip of Africa, since they are to some extent sheltered from the environment in a slowly dissipating ring. They may thus reach tropical regions of the Atlantic without being unduly influenced by the colder regions through which they have passed. This interesting conjecture has to date not received much research attention.

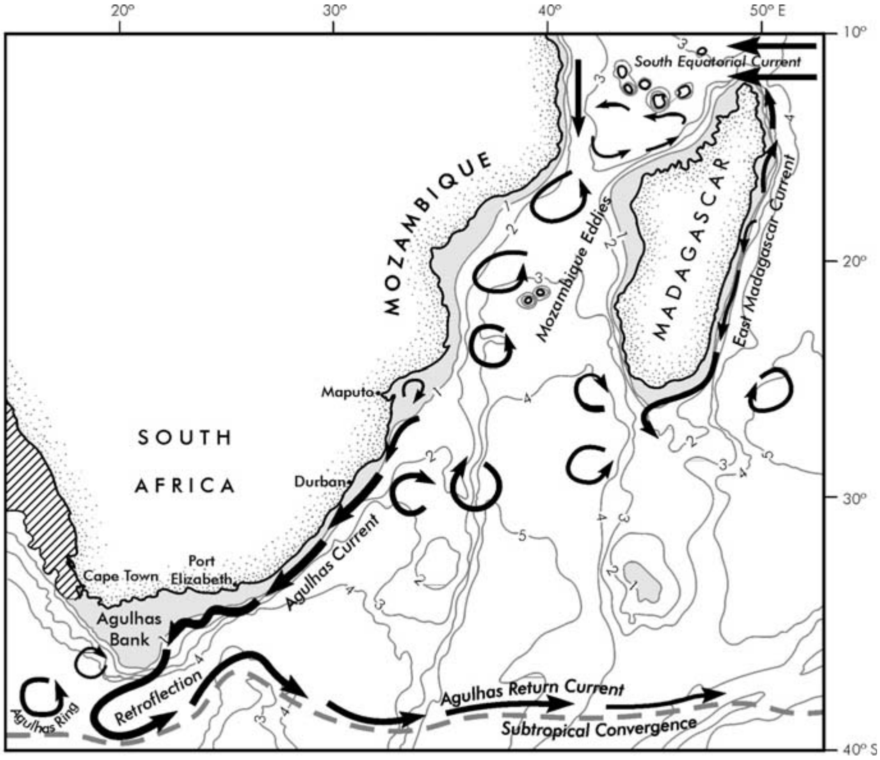

Fig. 1. A portrayal of the South-West Indian Ocean with the dominant current configurations as they are presently understood. These include major currents and eddies in black and the principal coastal upwelling as a hatched area. The bathymetry is shown by faint lines and is given in kilometres. Regions shallower than 1 km are shaded. The diverse character of currents along the shelf edges as well as the variety of shelf widths for the region is immediately apparent. (After Lutjeharms.[2])

To summarize: the deep-sea circulation of the South-West Indian Ocean is dominated by the greater Agulhas Current system. The Agulhas Current proper consists of a northern and a southern component with distinctly different flow characteristics, the northern part being very stable, the southern part meandering. It is fed largely by a sub-gyre of the South-West Indian Ocean, while the circulations in the Mozambique Channel and in the region to the south of Madagascar act as stimuli to the behaviour and trajectory of the current. These current configurations have a determining effect on the hydrographic and dynamic conditions of the waters on the adjacent slope and shelf,[2,24] dependent on the width and morphology of the bathymetry. This will be discussed in more detail below, starting with the Mozambique Channel.

Mozambique Channel

Analyses of altimetric data from satellites show[25] that the flow characteristics on the western side and the eastern side of the Mozambique Channel are very different. The current variability, or eddy kinetic energy, on the western side is very high whereas that on the eastern side is very low. This flow representation agrees well with the concept of a train of energetic eddies continuously moving poleward along the western shelf (Fig. 1) and has been supported by modelling studies.[26] Few direct observations are available on the eastern side of the channel,[27,28] but these few are useful and, with surface drift measurements from ships, indicate[6,7] that in general the currents here are weak and variable in direction. These flow patterns in the Mozambique Channel can have marked effects on the adjacent shelf and slope regions.

It may be surmised that passing eddies would affect the flow over the adjacent shelf region. Regrettably, there are insufficient observations to support this inference. Satellite images of chlorophyll *a* distributions indicate[29] that when eddies pass the shelf edge, they draw off substantial amounts of shelf water. This holds true not only for the western side of the channel, but also for the eastern side where eddies formed south of Madagascar—probably by the termination of the southern branch of the East Madagascar Current[5]—interact with shelf waters off south-western Madagascar. Not only may these eddies have an influence on the adjacent shelves, but they have a noticeable biological effect by themselves. It has been shown, for instance, that great frigate birds feed preferably at their edges.[30]

The water masses of the Mozambique Channel are characteristic of those found at these latitudes in the rest of the Indian Ocean.[31] Salinities in the upper layers lie between 35.00 and 35.40. Sea-surface temperatures show a seasonal cycle and can exceed 30°C during parts of summer over most of the channel. Water below the very top layer (at about 18°C) comes in two types, Equatorial Indian Ocean Water (also called Tropical Surface Water) and Subtropical Indian Ocean Water (also called Subtropical Surface Water). Subtropical Surface Water is characterized in most of this region by a subsurface salinity maximum. Tropical Surface Water is found in the northern part of the channel, the latter in the southern part. The distribution of these water types varies with time[8] and no permanent delimitation between them exists. The waters on the shelves would consist of these three water masses, except for those regions where there is substantial upwelling from depths down to 900 m, where evidence for the presence of Indian Central Water may also be found. Such upwelling centres are found off Angoche[32,33] and in the Delagoa Bight.

At Angoche there is a substantial offset in the shelf edge and passing Mozambique eddies may generate intense lee eddies (Fig. 2).[34] This may be an intermittent process, but to date there are insufficient observations to support this supposition. The other major offset in the shelf edge is farther south, in the Delagoa Bight off Maputo (Fig. 1). A larger number of observations here have shown[35] that a lee eddy is found in this bight at least 50% of the time. It is expected to affect the water movement profoundly at the shelf edge and over the shelf itself. No observations of increased primary productivity have been made in the Delagoa Bight eddy yet, but such observations in the Angoche eddy[34] have shown some remarkable results. Chlorophyll *a* values are low over the greatest part of the Mozambican shelf, the highest value of 98 mg/m^3 being found at the shelf edge, but in the Angoche eddy they are up to 600 mg/m^3. Zooplankton biomass lies between 20 and 40 mg/m^3 over the outer shelf, whereas values up to 160 mg/m^3 have been found over the inner shelf. Downstream of the Angoche eddy, however, values reach 320 mg/m^3. The importance of this and similar eddies for the productivity and the creation of habitats for higher-trophic animals along this shelf is clear. The cause of the elevated zooplankton biomass over the inner shelf has to do with river runoff (Fig. 3).

River runoff from the Mozambican landmass is substantial, seasonal, but with huge episodic events when tropical (atmospheric) cyclones reach this coast. Rivers carry large amounts of nutrients and organic material that affect the biota on the shelf and are reflected in the nature of the sediments on certain parts of the shelf such as on the Sofala Banks. As can be seen in Fig. 3, the diluting effect of the freshwater outflow is visible some distance from the river mouths. In some instances it has an effect in the surface layers only (section II, Fig. 3); in other cases (sections I and II, Fig. 3) it may include a large part of the water column. The impact of these terrigenous influences on fish distributions is as yet uncertain.[37] Current information shows that the fish distributions over most parts of the shelf vary enormously, both spatially and temporally. This is particularly true over the wide parts of the shelf off Mozambique. The shelf configuration on the other side of the channel is very different.

To the north, the Madagascar shelf forms part of the Comoro Basin (Fig. 1). The circulation in this basin is anti-cyclonic and the Comoro Gyre seems fairly stable.[38] Speeds are low, except on the western side where currents of up to 0.5 m/s have been measured. Very little is known about the waters over the rest of the western Madagascar shelf. Water masses are Tropical and Subtropical Surface

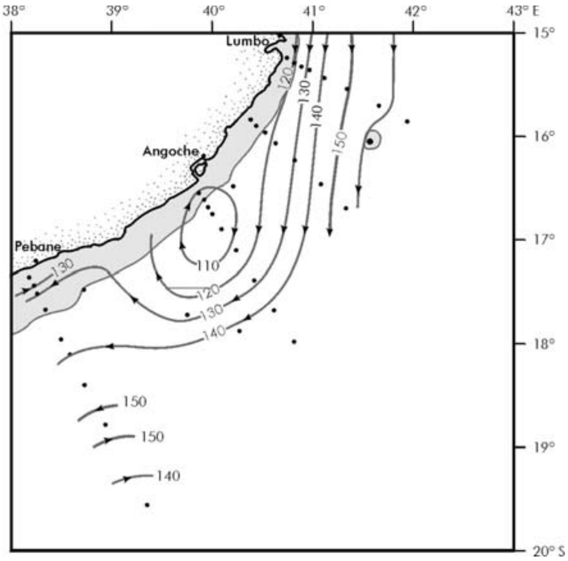

Fig. 2. Upwelling in a lee eddy off Angoche on the western side of the Mozambique Channel. The dynamic topography of the sea surface relative to the 600-dbar level is given in dynamic centimetres, based on a cruise undertaken in 1980. Dots give the geographic location of hydrographic stations. The bathymetry shallower than 1 km is shaded. (After Lutjeharms[2]; based on Nehring *et al.*[33])

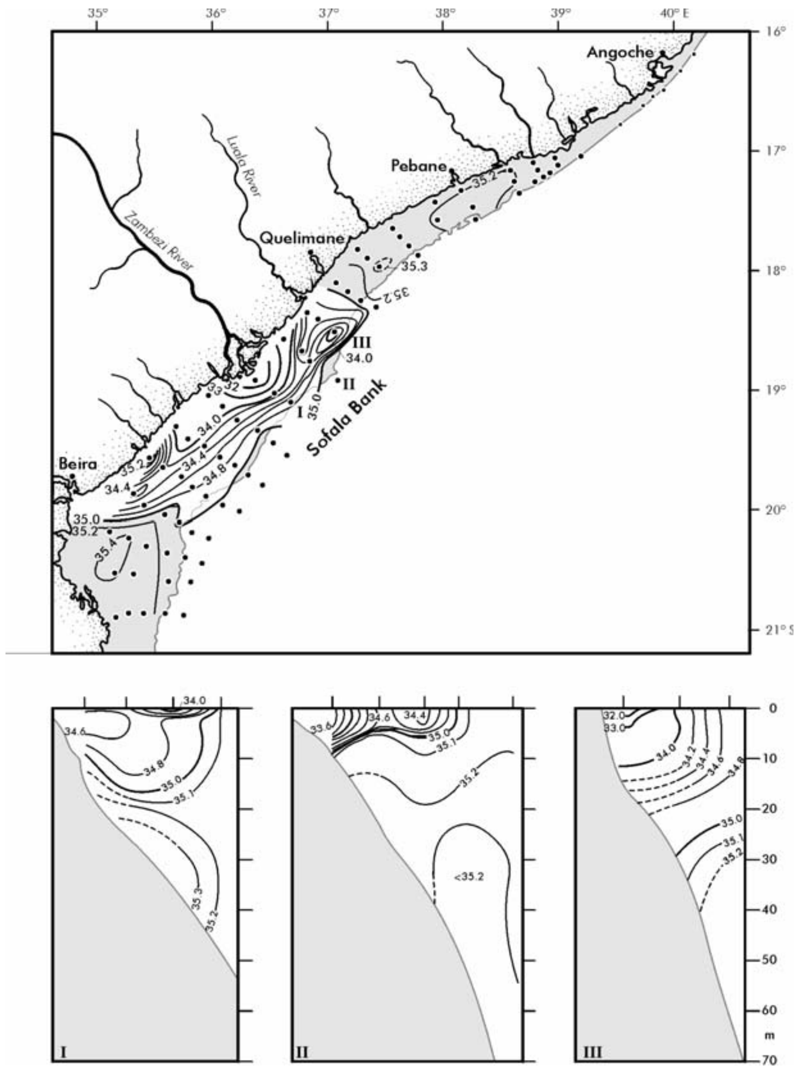

Fig. 3. Surface salinities over the Sofala Bank, the wide, shallow shelf off central Mozambique. Dots indicate station positions. Locations of stations used in constructing the vertical sections in the bottom panels are shown by roman numerals in the upper panel. The region shallower than 50 m is shaded. Fresher water (<35.0) extended to a depth of 15 m directly off the Zambezi River mouth (section I); to 30 m off the Luala River mouth (section III). The high salinity values south of the city of Beira are due to runoff from salt marshes. (After Lutjeharms[2]; according to Jorge da Silva.[36])

Water. In the central part of this shelf, the strongest subsurface oxygen minimum for the region is to be found[2] (M. Roberts, pers. comm.). Whether this is a persistent phenomenon and the reason for its presence are unknown. This lack of information is a direct result of the dearth of observations for this area. This is even truer for the shelf region off eastern Madagascar.

Shelf regions east and south of Madagascar

The most obvious characteristic of the shelf region east of Madagascar is that it is consistently narrow and that its slope is so precipitous (Fig. 1). From theory,[14] this implies that the bordering current should be unwavering. Altimetry observations suggest that the East Madagascar Current is indeed very stable. No other observations are available. This current has all the characteristic of a normal western boundary current (Fig. 4). It is narrow, deep and a directly measured speed in the core of its southern branch[39] is 0.66 m/s. The split in the southern and northern branch takes place at about 17 to 18°S.[7] Since the atmospheric pressure systems over the South Indian Ocean, that force this current, move meridionally with season, this may also be true of this point of divergence. The shelf being so narrow, one may assume that the shelf waters follow the direction of the offshore current closely. Apart from the current measurements mentioned above, there are hardly any data, hydrographic or otherwise, available for this shelf region to verify this assumption.

Where the southern limb of the East Madagascar Current leaves the shelf edge (Fig. 1), there is an upwelling cell that seems not to be directly wind-driven.[40,41] It may be forced by the passing current. The temperatures in the cell have been observed to be at least 2°C lower than elsewhere on this shelf and there is evidence of enhanced chlorophyll *a* values. The first hydrographic observations taken to investigate this upwelling cell directly[42] show this clearly (Fig. 5). In this figure, the drop in sea-surface temperature on sailing across the cell is matched closely by a corresponding increase in chlorophyll *a*. Salinity at the surface was 35.6, showing that the upwelled water was Subtropical Surface Water and had been upwelled from a depth of at least 200 m. The very few available data on the biogeography of the region do not show a discernible effect of this upwelling cell. The distribution of fish is scattered,[43] with no clear pattern.

The presence of a strong, invariant current at the shelf edge must have important implications. For the region east of Madagascar these implications are still relatively unclear, but for the northern Agulhas Current this is much better known because of a considerably more complete database.

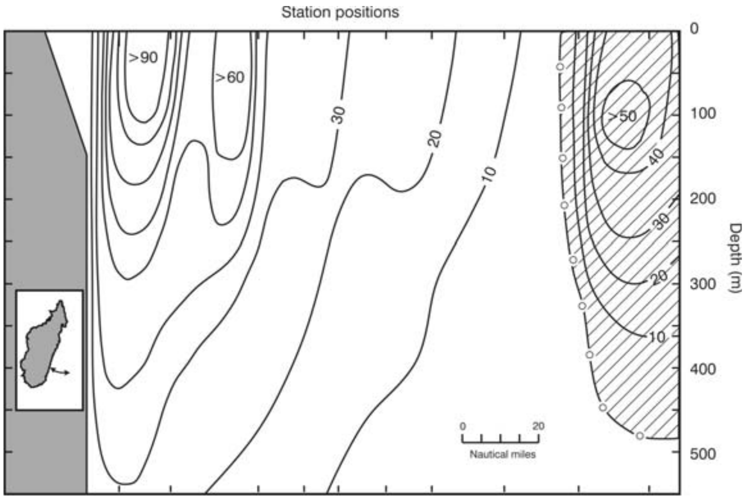

Fig. 4. Vertical section across the southern limb of the East Madagascar Current (according to Lutjeharms *et al.*[3]), showing the instantaneous speed, based on an interpretation of hydrographic data. This narrow current can be seen to be hugging the slope edge of a very narrow shelf.

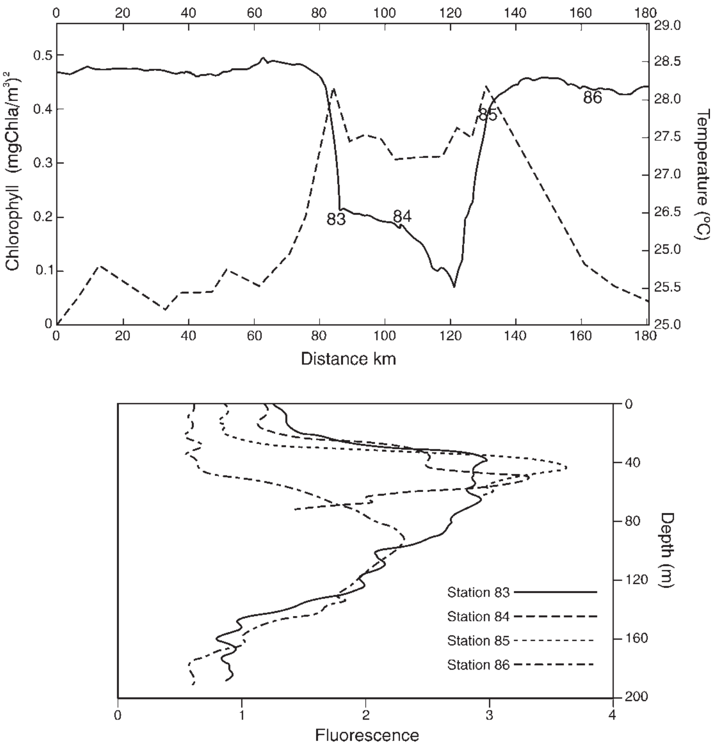

Fig. 5. Traces of sea-surface temperature and chlorophyll *a* across the shelf south-east of Madagascar. In the upper panel, the strong negative correlation between the surface temperature and chlorophyll *a* demonstrates the presence of an active upwelling cell at this location (after Lutjeharms[73]). In the lower panel, the vertical traces of chlorophyll *a* for stations in the upwelling cell show that there was a subsurface chlorophyll maximum at a depth of roughly 50 m during these observations. The station numbers given by the legend for the vertical traces correspond to the numbered locations of the surface traces in the upper panel.

The northern Agulhas Current system

The general setting of the northern component of the Agulhas Current and its coastal seas is shown in Fig. 6. There are no hydrographic or kinematic data that can be employed to establish exactly where the Agulhas Current starts, but bedload movements of shelf sediments indicate[44] that it is about halfway between Richards Bay and Maputo, at about 28°S. The fact that the start of the Agulhas Current along the coast has to be inferred from its influence on the shelf is indicative of the decisive impact this major current has on the adjacent shelf and slope. This influence depends to some extent on the width of the shelf. For the northern Agulhas Current, this comes mainly in two parts: the narrow shelf downstream of Durban and the wider Natal Bight upstream of the city.

The Natal Bight forms a substantial offset in the coast, its northern part being shallower than 50 m, the southern part deepening to about 100 m off Durban. Offshore it is virtually enclosed by the strong Agulhas Current. The current edge exhibits speeds of 1.5 m/s here,[45] has a seasonal temperature range at the sea surface of between 20° and 28°C and salinities of 35.0 to 35.5 This typifies largely Tropical Surface Water. Subtropical Surface Water is found at depths of between 150 and 250 m, about 60 km offshore. On the shelf the water is a mixture of these two. This comes about because Subtropical Surface Water is upwelled inshore of the Agulhas Current, in the region between St Lucia and Richards Bay (Fig. 6). This upwelling cell may have a disproportionate influence on the whole ecosystem of the Natal Bight.[46–48] In it, cold, nutrient-rich water is uplifted and brought onto the shelf, from where it spreads over a large part of the shelf (Fig. 7). At the sea surface this upwelling cell is typified by colder, saltier water and enhanced chlorophyll *a*. By comparison, the influence of the principal current flowing into the bight, the Tugela River (Fig. 6), is minor. The circulation of water over the Natal Bight seems to be complex.

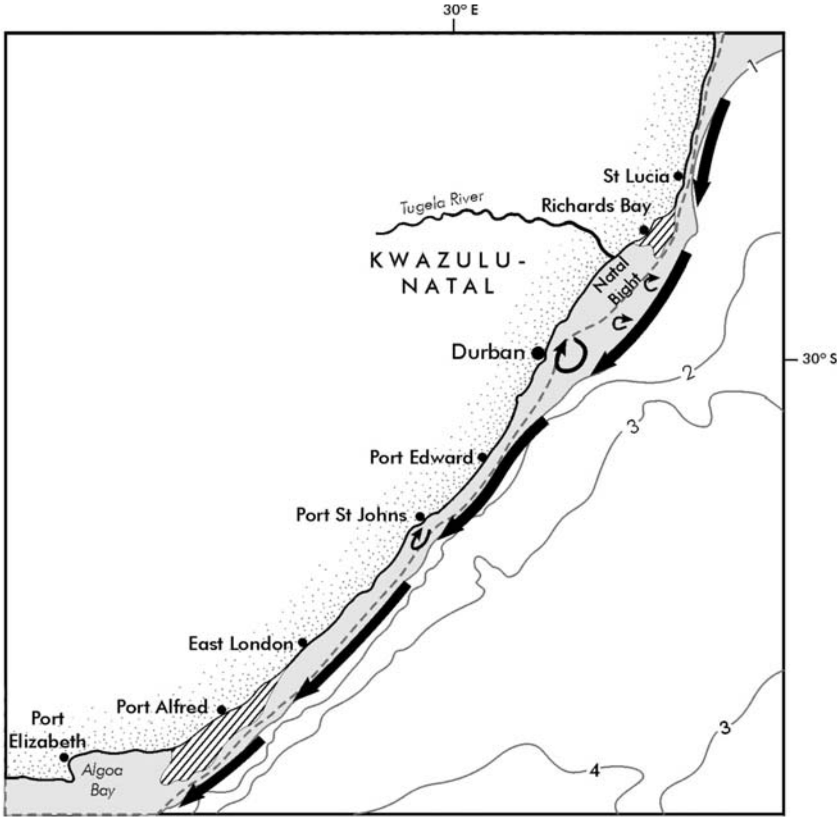

Fig. 6. A portrayal of the general circulation patterns of the northern Agulhas Current system (according to Lutjeharms[2]). Persistent currents and eddies are shown in black, upwelling cells are hatched and the shelf region shallower than 1 km is shaded. The bathymetry is given in kilometres except the 200-m isobath, which is represented as a broken line. Wider regions of the shelf are the Natal Bight upstream of Durban and the Agulhas Bank downstream of Algoa Bay.

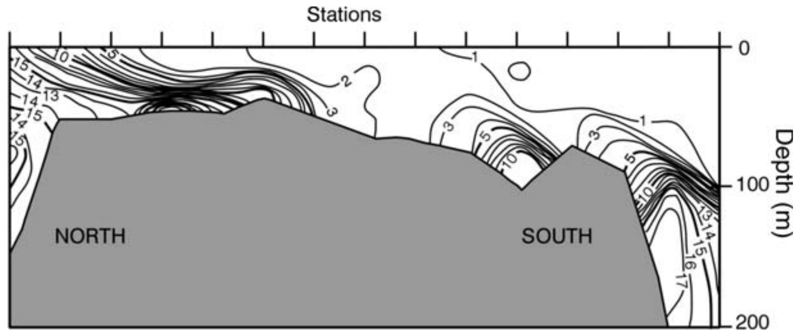

Fig. 7. A vertical section across the Natal Bight, from north to south, showing the distribution of dissolved nitrate in mmol/l. Nitrate-rich water is upwelled in the St Lucia upwelling cell to the north and from there is advected over the greater part of the shelf. Off the southern end of the shelf a dome of higher nitrate values corresponds to a recurrent lee eddy off Durban. (After Meyer *et al.*[48])

Close to the shelf edge, and thus to the Agulhas Current, the movement seems to be largely parallel to that of the current.[49] Periodic reversals[50] may be due to shear edge eddies that have been observed[51] on the border of the current along the Natal Bight. On moving closer to the coast, the percentage of current observations that are parallel to and in the same direction as the Agulhas Current becomes progressively reduced.[49] Otherwise the circulation on the shelf has been surmised to be vaguely cyclonic,[52] consisting of one or more eddies. Since the shelf waters are shallow over the Natal Bight, a strong wind of some duration could markedly change this flow and the vertical stratification (Fig. 7).[47] There is a further important coastal offset that underlies the Natal Bight morphology, in the shelf configuration at Durban (Fig. 6). This creates the setting for the formation of a lee eddy by the passing Agulhas Current.

This lee eddy has been observed in hydrographic data as well as in the studies of drifters[53] and has a cyclonic motion. It is also evident in the vertical nutrient section shown in Fig. 7 as a dome of higher nutrient values just off the southern end of the Natal Bight. The nutricline is noticeably shallower when there is an eddy present here than when there is none.[54] The persistence and frequency of occurrence of this lee eddy is not known. Surface current estimates[55] suggest that it may be present about 50% of the time. It has not been shown to affect primary productivity or the biogeography of other organisms. It has, however, been demonstrated that, with the formation of a Natal Pulse, the cyclonic eddy off Durban is carried downstream enveloped on the seaward side by this meander in the Agulhas Current. The passage of this combination of current elements causes sudden current reversals at the shelf edge and over the shelf itself.[56] Otherwise the currents downstream are stable.

The speed at the landward edge of the Agulhas Current increases with distance downstream from Durban. Whereas it averages 0.5 m/s at Durban, it may reach 2.16 m/s at Port Elizabeth (Fig. 6). Current speeds over this narrow shelf may reach 1 m/s less than 10 km from the coast. The only location where there is evidence for the shelf waters not to be moving in concert with the Agulhas Current is at Port St Johns, where there is a small offset in the coast that may lead to a lee eddy with the current next to the land generally in the opposite direction to that of the Agulhas Current.[49] These shelf waters are oligotrophic, that is, consistently poor in nutrients and thus in primary productivity, right up to the start of the Agulhas Bank (Fig. 1), where a strong upwelling cell is located.

The southern Agulhas Current

The general flow patterns for the Agulhas Bank and vicinity are portrayed in Fig. 8. This triangular region is the widest part of the shelf off South Africa, with the greatest distance from shore to shelf edge being 250 km. At this widest part a shallower bathymetry, the Alphard Bank, separates the shelf into a western and an eastern Agulhas Bank with distinctly different hydrographic and dynamic characteristics. The eastern part is under the influence of the passing Agulhas Current, the western part is typified by seasonally modulated, coastal upwelling. Because of the width of the Agulhas Bank, the direct influence of deep-sea currents is much less in evidence. Several flow features are important for an understanding of the circulation of waters over the bank. The first of these is the Port Alfred upwelling cell.

There exists substantial evidence[57] that a durable upwelling process is active in the vicinity of Port Alfred (Fig. 8). Its presence is not always apparent at the sea surface, where wind may play a role[58] in the stimulation of outcropping events, but seems more persistent at depth. The water that is upwelled is South Indian Central Water that comes from a depth greater than 400 m and is in consequence rich in nutrients.[59] From the vicinity of Port Alfred, this cold (<10°C) water moves along the 100-m isobath of the greater part of the Agulhas Bank, forming a distinctive ridge of cold water. The presence of this ridge is mirrored in the distribution of surface chlorophyll *a*[60] and other biota. Occasionally, strong winds with sufficient duration mix the water column sufficiently for water in this cold ridge to outcrop,[61] but in general it is not apparent at the sea surface. It may nevertheless play a decisive role in the water column stratification of the bank (Fig. 9). This time series shows the seasonal cycle of summer warming of the water column from above, with the attendant increase in vertical stratification. In winter this stratification is broken down by cooling from above and by vertical convection, supported by strong winds. This sequence depicts the normal hydrographic characteristic for shelves in the subtropics. In the case of the Agulhas Bank an additional factor plays a role. As can be seen in Fig. 9, the water column is more or less simultaneously cooled from below. This enhances the vertical stratification substantially. It is believed that this peculiar sequence is a result of the continuous inflow of cold water from below as the upwelled water from the Port Alfred upwelling cell spreads over the greater part of the bank. It is not yet known to what extent this enhancement of the stratification leads to greater primary productivity or a more suitable environment for biota at higher trophic levels. The waters and the stratification on the Agulhas Bank are also influenced in a more direct fashion by the passing Agulhas Current.

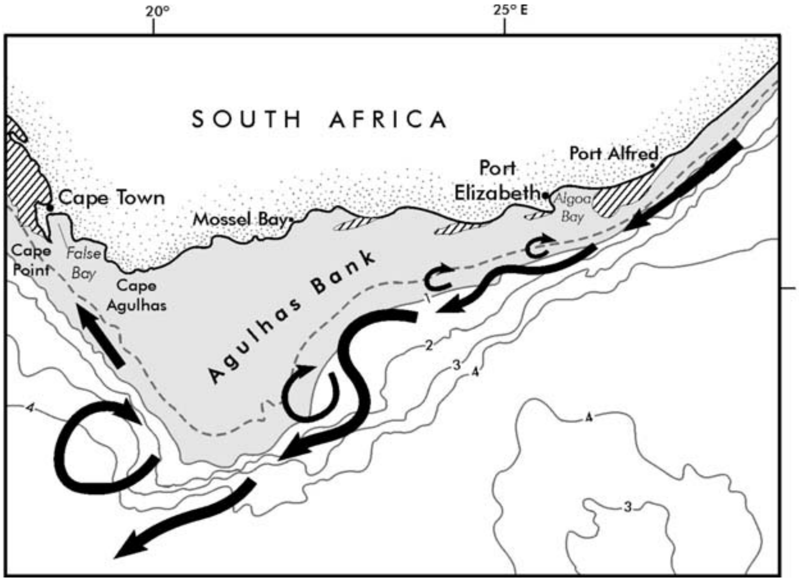

Fig. 8. A portrayal of the general circulation patterns of the southern Agulhas Current system and the adjacent wide shelf, the Agulhas Bank (according to Lutjeharms[2]). Persistent currents and eddies are shown in black, upwelling cells are hatched and the shelf region shallower than 1 km is shaded. The bathymetry is given in kilometres except the 200-m isobath, which is represented by a broken line.

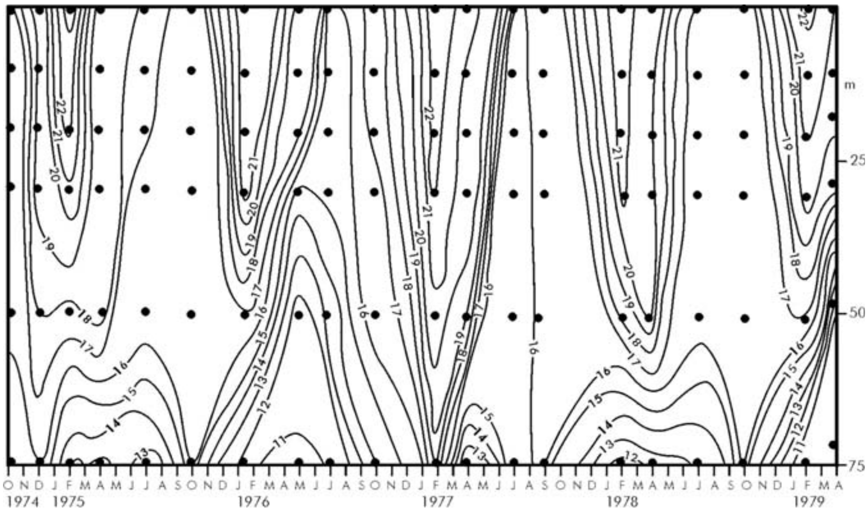

Fig. 9. A time series of the vertical temperature profile over the central part of the Agulhas Bank. This is based on a hydrographic station that was repeated at two-monthly intervals from 1974 to 1979. Dots indicate depths at which nutrient samples were taken. The seasonal heating from above is juxtapositioned to cooling from below. (After Lutjeharms[2]; according to Lutjeharms *et al.*[59])

Along the eastern edge of the Agulhas Bank the meandering current forms a series of shear edge eddies that move downstream with the current. These meanders have attendant plumes of warm water.[15] At the shelf edge the downstream passage of shear edge eddies will generate a sequence of currents setting in opposite directions. It has been surmised that the deeper water upwelled in these cyclonic eddies could be inserted onto the bank, but, to date, illustrations[62] of this process have been the exception rather than the rule. The warm plumes have been observed to move onto the bank. Since they may be fairly shallow features,[15] their shoreward penetration may well be a function of the reigning winds. The anomalously warm shelf water from shear edge plumes may penetrate all the way to the coast on occasion.[63] The contribution of this warm water from offshore on the stratification of the shelf waters has not been quantified yet. Eddies are also found on the western side of the Agulhas Bank (Fig. 8), but these have a different origin.

It has been demonstrated[64] that the passing Agulhas Current generates a substantial lee eddy here and that members of this eddy class will sporadically move off into the South-East Atlantic Ocean. During its presence, water movement along the shelf edge will be poleward. On other occasions anti-cyclonic Agulhas rings may move past this western side of the Agulhas Bank, by contrast setting the shelf edge currents in an equatorward direction. The observed slope of the isopycnals along this shelf edge in turn suggests that there should be a shelf edge jet[65] here, carrying water rapidly towards the upwelling regions off the South African west coast. Warm surface plumes on the shore side of the Agulhas Current in fact often follow this route[16] from the southern tip of the Agulhas Bank, confirming that an equatorward motion here does take place. Direct observations[66] indicate that the postulated shelf edge jet may be an intermittent phenomenon. Apart from this motion past the shelf edge, the western Agulhas Bank is characterized mainly by coastal upwelling.

For those parts of the Agulhas Bank not affected by either strong currents at the shelf edge nor by wind-driven coastal phenomena, the motion probably falls into three categories. The very top layers are almost certainly influenced largely by the wind.[67] Measurements of the bottom layer[68] over the eastern Agulhas Bank have shown that this water moves parallel to the isobaths and in the direction of the Agulhas Current, that is, southwestward. However, by far the dominant movement mode for the water column is inertial,[69] with the abovementioned movement parallel to the Agulhas Current being the small residual.

Remaining knowledge gaps

The level of understanding of matters pertaining to the oceanography of the coastal oceans off southeastern Africa—and in particular the edge of the continental shelf—is extremely inhomogeneous. Some components have been fairly well investigated, such as the Agulhas Bank and the seas off the KwaZulu-Natal coast. Other shelf regions are among the least studied in the world. Prime examples of the latter are the shelf regions of Madagascar. This seems to indicate that, in a perfect world, future research should be focused on those regions where our ignorance is greatest. This is bound not to happen, for a number of reasons. These include the limited capacity of several countries in the region to fund research on their coastal seas. Other reasons include logistical demands and the tendency for scientists to be more interested in research questions that have emerged from regions that have already been studied than in carrying out pioneering explorations in areas that are largely unknown.

However, to some extent this lack can be assuaged by collaborative undertakings such as the African Coelacanth Ecosystem Programme (ACEP).[70] Although the programme has a different focus, some of its cruises have already collected hydrographic data in regions, such as the western shelf of Madagascar,[2] where there have been very few before. Taking cognizance of the data gaps identified here may help ACEP in addressing those when the opportunity arises. On a purely subjective basis, it seems that the following regions and processes might be most in need of elucidation.

A primary investigation of the hydrographic and kinematic characteristics of the shelves off Madagascar and the influence of offshore currents and eddies on these, seems essential. One would like to learn the nature of the East Madagascar Current along its full length and its possible seasonality. The waters on the western side of Madagascar remain largely *mare incognitum*; one would like know the effect of land runoff as well as of passing eddies and offshore currents on this shelf region. The hydrography of the eastern side of the Mozambique Channel remains largely cloaked in mystery.

The shelf regions off Mozambique are marginally better known than those of Madagascar. The role of passing Mozambique eddies, of lee eddies such as those at Angoche and the Delagoa Bight and of intermittent river runoff are clearly processes that need to be better understood if this environment is to be managed based on scientific understanding. Such investigations fall within the means and capacity of countries in the region. Modelling the Mozambique Channel system and the waters over the adjacent shelves would help direct expensive, but necessary, observations at sea.

In the Agulhas Current proper, several areas of ignorance stand out. First, a more precise position needs to be determined where the Agulhas Current starts to have an influence on the shelf and shelf edge. The role of the St Lucia upwelling cell on the ecosystem of the Natal Bight is in urgent need of research attention. This is also true of the similar upwelling cell at Port Alfred that may play a major role in the hydrography and ecosystem of the whole Agulhas Bank. A dedicated cruise to investigate the hydrography of the Agulhas Bank as a whole in a quasi-synoptic fashion is clearly called for.

Satellite remote sensing and numerical modelling[71] have been of great value in learning about local coastal oceans in a cost-effective manner. They give useful indications of how ocean systems work and where to measure and observe them most efficaciously. If a solid understanding of the systems and processes is required, a *sine qua non* remains: to make dedicated, well-focused and interdisciplinary observations at sea.

This review was compiled, by invitation, especially for this suite of papers dealing with research on the coelacanth and its environment in the Western Indian Ocean. A more extensive review of the region's coastal oceans, including its meteorology, geology and chemistry, is to be found in *The Sea*.[2] An elegant review of the mesoscale variability in the South-West Indian Ocean has been written by de Ruijter *et al.*[72] and an extensive monograph on the Agulhas Current system as a whole has also recently been published.[73] These may be valuable for the interested reader wanting access to a wider list of publications and information.

I thank Tony Ribbink for this invitation, the National Research Foundation and the University of Cape Town for financial support, and Eric Machu and Adrian Webb for the production of Fig. 5.

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