

A demonstration of the hydrographic partition of the Benguela upwelling ecosystem at 26°40'S

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Abstract

Continuous CTD data from a series of recent cruises show that the distribution of the water mass characteristics in the central Benguela region from the Orange River mouth ($28^{\circ}38'S$) to Walvis Bay ($22^{\circ}57'S$) is discontinuous in the central and intermediate waters at about the latitude of Lüderitz ($26^{\circ}40'S$). The central and intermediate water masses at the shelf edge and shelf break north of the Lüderitz upwelling cell have a high salinity relative to the potential temperature compared to similar waters south of the upwelling cell. It is shown that the feed waters for the wind-induced upwelling on the shelf to the north and south of the Lüderitz discontinuity are different in character and source. The distribution of the water masses shows that the shelf-edge poleward undercurrent provides low-oxygen water from different regions in the Atlantic Ocean to be upwelled onto the shelf. North of the Lüderitz upwelling cell, the central and intermediate waters come from the oxygen-depleted Angola Basin, while south of the discontinuity those waters are from the interior of the adjacent Cape Basin, which is less oxygen deficient. This has implications for the dispersion of low oxygen water and the triggering of anoxic events, and consequences for the biota on the shelf, including commercially important fish species.

INDEX TERMS: Upwelling and convergences; water masses; continental shelf processes; eastern boundary currents; fronts and jets

KEYWORDS: South Atlantic; water masses; Benguela Current; Lüderitz upwelling cell; environmental barrier.

Introduction

The upwelling of the Benguela ecosystem on the South African and Namibian continental shelf is driven primarily by wind forcing. A high pressure system over the central South Atlantic ocean gyre induces south-easterly winds along the southern African coast, modified by seasonal low pressure over the continent and eastward moving cyclones to the south (Nelson and Hutchings 1983, Tyson 1986). These influences tend to promote the upwelling-favourable south-easterly winds during the spring and summer seasons in the southern part of the Benguela upwelling system (south of Hondeklip Bay, about $30^{\circ}18'S$); and during autumn and spring in the northern Benguela, from about Cape Cross ($21^{\circ}46'S$) to north of Cape Frio ($18^{\circ}26'S$); while the central Benguela (from about $26^{\circ}S$ to $28^{\circ}S$) experiences almost perennial upwelling-favourable conditions (Shannon 1985, Shannon and Nelson 1996). The upwelled water that reaches the surface over the shelf is drawn primarily from central water masses above 180–200 m depth (Andrews and Hutchings 1980, Shannon and Nelson 1996).

Three major current systems external to the ecosystem influence the waters within the Benguela upwelling system: the eastern boundary current of the South Atlantic (the Benguela Current); the cyclonic equatorial circulation to the north in the Angola Basin (the Angola Current); and the western boundary current of the South Indian Ocean to the south (the Agulhas Current). Thus uniquely among eastern boundary current upwelling systems, the Benguela has warm water current systems on both poleward and equatorward boundaries.

At $32^{\circ}S$ the transport of the Benguela Current above $\sigma_0 = 27.75 \text{ kg.m}^{-3}$ is about $21 \times 10^6 \text{ m}^3.\text{s}^{-1}$ toward the north (Peterson and Stramma 1991, Stramma and Peterson 1989). Embedded within this flow is the input from the Agulhas Current that retroflects south of Cape Town and sheds rings from the retroflection (Gordon 1985, 1986, Lutjeharms 1981). These rings, moving generally in a north-westerly direction (Byrne *et al.* 1995), may interact with the upwelling

system (Duncombe Rae *et al.* 1992b) and influence the fish species on the shelf (Duncombe Rae *et al.* 1992a). The shelf-edge jet flowing from the western Agulhas Bank (Bang and Andrews 1974) also brings warm water and fish eggs and larvae into the Benguela ecosystem near the surface.

The influence of the northern current begins at the Angola/Benguela Front (ABF). The surface expression of this strong temperature front is highly mobile, moving north and south rapidly, but the front maintains position between 14° and 16°S through the year (Meeuwis and Lutjeharms 1990). The waters of the Angola Current enter the Benguela along the shelf edge and slope as a poleward undercurrent, bringing low-oxygen water into the northern Benguela below the seasonal thermocline (Nelson 1989). Occasionally the wind forcing of the Benguela upwelling abates dramatically and the ABF encroaches much further into the northern Benguela, establishing an *El Niño* phenomenon in the South Atlantic (Shannon *et al.* 1986).

In the ocean basins adjacent to the African continent the bottom water is North Atlantic Deep Water (NADW) in the Angola Basin and Antarctic Bottom Water (AABW) in the Cape Basin, overlaid by NADW up to about 2000 m below the surface. Above the NADW is Antarctic Intermediate Water (AAIW), and the main thermocline, up to the atmosphere-influenced seasonal thermocline and the surface (Chapman and Shannon 1985, Shannon 1985). For this contribution only the water masses of the intermediate layer and above are considered. The intermediate water occurs on the slope and shelf edge and the water masses below are too deep to influence upwelling.

At Lüderitz the wind forcing is perennial and the front between the upwelled water on the shelf and the oceanic water (the oceanic front) is far offshore. This upwelling centre has been characterised as the most intense in terms of the wind forcing (Bakun 1996). The bathymetry of the shelf is wide and shallow at Port Nolloth and the Orange River Mouth and, moving north, narrows abruptly south of Lüderitz. The modelling of coastal trapped waves by van Ballegooyen (1995)

indicated that abrupt changes in the topography of the shelf inhibits the propagation of the wave in the alongshore direction and redirects the energy across the shelf, resulting in strong cross-shelf velocities near the shelf edge. Monteiro (1996) proposed the “gate hypothesis” to explain the distribution of total alkalinity and carbonate. One of the “gates” identified was associated with the Lüderitz upwelling cell. The mechanism alluded to in maintaining the inhibition of poleward flow was wind controlled upwelling combined with changes in topography.

In the Central Benguela region between Lüderitz (26°S) and the Orange River shelf (30°S) relatively few cruises have provided data on the characteristics and dynamics of the water. The studies of plankton and pelagic fish distribution that have been done suggest a discontinuity between the northern and southern Benguela (Badenhorst and Boyd 1980, Barange and Pillar 1992, Boyd and Cruickshank 1983) but it has not been definitively investigated. Certain species occur only north or south of the Lüderitz upwelling (O’Toole 1977, Shannon and Pillar 1986) and the area has been investigated as a barrier to the interchange of pelagic species (Agenbag and Shannon 1988). The hypothesis put forward was that the persistent winds induced appreciable offshore movement and created excessive turbulence yielding an environment unsuitable for the consistent passage of organisms through the area.

The cycle of collapse and recovery of the Namibian pelagic fishery (Kanandjembo *et al.* 2001, Schülein *et al.* 1995), most recently in 2001 (A.J. Boyd, M.C.M., pers. comm.), has re-awakened interest in the Lüderitz cell as a barrier and prompted re-examination of its effects and functioning. The intention of this paper is to describe the characteristics and the distribution of the water masses and water types present in the Central Benguela to gain insight into the functioning of this part of the system.

Data and Methods

Data were drawn from the Southern African Data Centre for Oceanography (SADCO) and the Marine and Coastal Management (M.C.M.) oceanographic database. For the horizontal sections, a standard product of the Data Centre was used in extracting data at a particular level. The data accessed covered the period from 1983 to 2002. The distribution of these data shows that most research surveys in this period have concentrated on the southern Benguela, and only a limited number of stations have been occupied near the Orange River Mouth ($28^{\circ}38'S$; $016^{\circ}27'E$) and farther north.

For the vertical sections, data from the recent transects of the Lüderitz and Orange River shelf regions on the Benguela Environment, Fisheries, Interaction, and Training (BENEFIT) cruises of FRS *Africana* (V155 in June and July 1999, and V166 in February and March 2002), and the Agulhas-South Atlantic Thermohaline Transport Experiment (ASTTEX) deployment cruise (RV *Melville*, January 2003) were used (Fig. 1). On the FRS *Africana* V155 cruise, a General Oceanics rosette and MkiIIC CTD was used to collect 1 metre resolution data. Sensors were calibrated in the laboratory and with samples taken at sea. Temperature was accurate to $\pm 0.005^{\circ}\text{C}$ and salinity to ± 0.008 . On the FRS *Africana* V166 cruise, a Sea Bird 12-bottle carousel and SBE 9/11+ CTD with flow pumped through temperature, conductivity, and oxygen sensors was used. The temperature was accurate to better than $\pm 0.005^{\circ}\text{C}$, the error in salinity was ± 0.005 , and dissolved oxygen to ± 0.05 mL/L against the bottle samples. Data from the RV *Melville* cruise were of WOCE quality (D.A. Byrne, U. Maine, pers. comm.). Standard oceanographic parameters (density, potential temperature, etc.) were calculated using the Unesco. (1983) algorithms.

Hydrographic profiles from the extremities of the Benguela upwelling system are depicted in the TS diagram (Fig. 2). Stations representing the Angola Basin waters were selected from the BENEFIT cruises on FRS *Africana* (V155 in July

1999, and V166 in March 2002). In the Cape Basin, data from the ASTTEX deployment cruise in January 2003, and the FRS *Africana* V166 cruise were used. The criteria for selection of these station lines were related to the closeness of the station spacing, the completeness of the data, and the offshore extent of the line.

The water masses which were observed in the data are identified in Figure 2. To facilitate discussion of these water masses and their properties, these water masses are described below.

Water Mass Definitions

The Benguela upwelling system has two major inputs of water from external sources: the equatorial Atlantic in the north and the South Atlantic/South Indian in the south. Only water masses at densities $\sigma_{\theta} \leq 27.5 \text{ kg.m}^{-3}$ are considered in detail here, as these are pertinent to the shelf and slope above the 1000 m isobath. Surface, central, and intermediate water mass definitions from the literature are shown in Table 1 and the ones discussed in this contribution are shown in Figure 2. These water masses are summarised briefly here.

AAIW is formed at the surface in the sub-polar and polar regions and is recognised by a salinity minimum in the water column. AAIW has distinct characteristics in the northern and southern Benguela (Shannon and Hunter 1988, Talley 1996). There is a high salinity AAIW (HSAIW) in the Angolan Basin which enters the northern Benguela in a poleward undercurrent along the shelf edge. The southern Benguela has a low salinity AAIW (LSAIW) close to the Subtropical Front.

Like the AAIW, the central water has a northern, high salinity component (HSCW) originating in the tropical Angola Basin and is the WSACW or SACW of the literature (see Table 1). The low salinity component of the central water

(LSCW) is found in the Cape Basin and is called Eastern South Atlantic Central Water (ESACW) in the literature.

Above the central waters the high salinity, high temperature surface water was referred to as Tropical Surface Water (TSW) by Mohrholz *et al.* (2001). Since water with similar characteristics is found at the surface in the South East Atlantic outside the tropics, the term Oceanic Surface Water (OSW) is preferred for this paper. The surface water is subject to the influence of precipitation and continental runoff from rivers into the Angola Basin resulting in low salinities at the surface. This water is labelled LSSW (Mohrholz *et al.* 2001). In the southern Benguela the run-off phenomenon is also observed, here caused by the outflow from the Orange river—run-off water (ROW)—although far less evident in extent and persistence than in the north, the Orange River flow being intermittent and controlled by dams in the hinterland.

The central water on the shelf is upwelled near the coast by the persistent winds. In contact with the atmosphere the temperature, in particular, and salinity, to a lesser extent, may be modified under the influence of solar heating and freshwater flux. This water is designated Modified Upwelled Water (MUW).

In general terms, the intermediate, central, and upper waters can be summarised as having either (a) a high salinity, high temperature character indicating a tropical influence; or (b) a low salinity, low temperature character indicating an antarctic or subantarctic influence, together with the appropriate surface modifications of the surface and upwelled water when this comes into contact with the atmosphere near the surface and is subject to solar heating, Ekman, and turbulent mixing processes.

Results

In the following sections, data from transects shown in Figure 1 were selected to show the distribution of the water masses in the Benguela system. It should be

noted that the vertical sections were obtained from cruises which took place at different times of the year. The possibility of aliasing due to the seasonality of the Benguela system could not be discounted. Although the discussion below is from a quasi-synoptic viewpoint, it should be borne in mind that precise positions of features may vary from time to time and that seasonal variability may occur. This aspect of the system could not be adequately addressed owing to the relatively low data density in both space and time.

The water masses present in the northern Benguela are shown by the section across the shelf at $18^{\circ}23'S$ (Mowe Point, Fig. 3). The characteristics show that this water was predominantly of a tropical origin with high salinity in the central and surface water. In the inshore part of the section, low salinity water was evident at the surface. It is assumed that this water was upwelled from the central water level and warmed by insolation.

At Walvis Bay ($22^{\circ}57'S$, Fig. 4), five hundred and forty kilometres further south, the water masses were of the high salinity kind inshore over the shelf. Low salinity central water was also evident within the water column over the outer part of the shelf. This section does not extend far enough offshore to identify the water masses at the shelf edge.

Still further south at Line E ($25^{\circ}14'S$), approaching the Central Benguela, the low salinity water masses predominate over the slope and basin (Fig. 5). The high salinity water mass regime is present over the shelf edge and on the shelf.

In the Central Benguela near Lüderitz (Fig. 7) vertical temperature and salinity sections (not shown) showed that the water at the surface had been recently upwelled. In the water mass diagram, the central water thermocline was split into two parts, with a low salinity characteristic above and a high salinity characteristic below. The Antarctic Intermediate water also showed a dual nature here, with a high salinity layer above a low salinity layer. The HSCW appeared extensive, extending off the shelf over deep water, in contrast to the section further north at $25^{\circ}14'S$ (Fig. 5) where it was constrained to the shelf and shelf edge.

At 26°40'S (Lüderitz) this water character appears to extend far across the shelf, suggesting that the shelf and shelf edge water were deflected offshore (westward) along the line of stations. This presents a contradiction to the accepted theory of poleward undercurrents, as just south of this section the 1000 m and shallower isobaths turn toward the east, only bending offshore near 28°S on approaching the Orange Banks.

Further south on the Orange River shelf, at 28°28'S, the water was almost completely of the low salinity variety (Fig. 8). The small amount of high salinity central or intermediate water that was evident appeared deep in the water column on the slope.

The southern Benguela waters are relatively low in salinity in the central and intermediate levels, typified by the section across the shelf at 31°12'S (near Olifants River mouth) shown in Figure 6.

Discussion

Poole and Tomczak (1999) examined the Atlantic Ocean thermocline (central water) layer for the South Atlantic and identified two source water mass regimes: Eastern South Atlantic Central Water (ESACW) and Western South Atlantic Central Water (WSACW). The ESACW is derived from the Indian Central Water through the Agulhas Current, and the WSACW is derived from the Brazil Current through the Brazil/Malvinas Confluence in the western South Atlantic subtropical gyre. In the eastern basins of the South Atlantic, the WSACW is present in the Angolan Basin while the ESACW is found in the Cape Basin. Mohrholz *et al.* (2001) found the characteristics of WSACW to be modified in the region of the Angola/Benguela Front (ABF) from their source water characteristics by processes of the upper layers in the equatorial Atlantic. The difference in TS characteristics between northern and southern Benguela central waters was

noted by Stander (1964) and was then ascribed to modification undergone during meridional movements.

Below the main thermocline, the AAIW on the west coast of southern Africa has a salinity of 34.35, rising to 34.5 near the ABF (Duncombe Rae 1998, Mohrholz *et al.* 2001, Shannon and Hunter 1988, Talley 1996). Higher salinities are found in the intermediate water on the east coast, and in the Agulhas Current, due to the influence of occasional intrusions of Red Sea Water (Gründlingh 1985). These latter high salinity AAIW sources, however, appear not to influence the intermediate water of the Central Benguela.

Horizontal sections of the data used here at various levels suggest that the generally accepted broad circulations depicted by (Shannon and Nelson 1996, after Chapman and Shannon 1985) do not reflect the whole detail of the circulation. The steric height anomaly at 500 dbar depicted by Reid (1989) shows two opposing gyres within the South Atlantic raising the expectation that the water might have different characteristics at this level in each gyre. The two gyres have a confluence in the region of the Lüderitz upwelling cell, but the intensity and detail of the position of this confluence is not resolved. This circulation was further discussed and elaborated on by Mercier *et al.* (2003).

Monteiro (1996) observed discontinuities in the carbonate distribution in the Benguela system at the major upwelling centres, which sites he called “gates” (Fig. 9). These discontinuities in the poleward flow on the Benguela shelf are characterised by strong wind stress, a maximum cyclonic wind stress curl, and narrowing of the shelf. One of the sites identified, at Cape Frio, is nearly coincident with the ABF, and therefore readily distinguishable in TS characteristics. The TS relationship at the Lüderitz upwelling centre is described here, while the third site, at Olifants River, does not appear to be discontinuous in TS at least. Monteiro’s (1996) results showed that the discontinuities are subject to seasonal changes, periodically breaking down. Unfortunately the TS data available for the

present study do not appear sufficiently dense in time and space to resolve the seasonal variations.

The constraint of the high salinity water to the shelf edge evident in Figure 5 appears consistent with a poleward undercurrent of Angola Basin origin. In the region of the Lüderitz upwelling centre, consistent with Monteiro (1996), the southward moving water in the poleward undercurrent appears directed offshore at about the same level as a local oxygen minimum in the central water of the Cape Basin gyre.

Discontinuity between water masses at line H (Fig. 7) and line L (Fig. 8) suggests that the Lüderitz upwelling cell at $26^{\circ}40'S$ stops the southward movement of high salinity central water in the poleward undercurrent.

As an indication of the extent of the exchange between the two kinds of central water, the proportion of the HSCW within the water column was determined as a fraction of the central water as defined above. The distribution of this proportion (Fig. 10) shows the exchange between the two extremes of the system occurring between Lüderitz and Cape Frio. As the vertical sections of water mass show, the water masses remain separable showing little mixing. It is only the extent of the denser high salinity portion that becomes less as the Lüderitz cell is approached.

Superficial interpretation of the vertical oxygen sections might lead to the inference that the low oxygen signature in the central water, which is present both north and south of the Lüderitz upwelling cell, is continuous across the cell. Examination of the characteristic temperature and salinity shows that the water masses are different, leading to the conclusion that the low oxygen signature south of the Lüderitz cell has a different origin from that to the north, since the water masses are different. What is the source of this low oxygen signature? Oxygen minimum layers caused by biological oxygen demand are a global phenomenon in the intermediate and central waters, most plainly evident on the eastern margins of the ocean basins (Childress and Seibel 1998, Sverdrup *et al.* 1942).

The tropical ocean has a low oxygen content due to the high temperature

yielding a low oxygen saturation value. Moderate biological activity quickly leads to even lower oxygen concentrations in waters leaving the tropical regions. The low oxygen water from the Angolan Basin in the poleward undercurrent reaches the barrier at Lüderitz and leaves the shelf. South of Lüderitz, the source of the poleward undercurrent is central water from the Cape Basin, a cooler and less productive regime, hence the oxygen concentration in that layer is higher while still a relative minimum in the water column. On the Namaqua shelf, from 29°30'S to 32°S, biological activity reduces the oxygen concentrations to levels approaching those of the poleward undercurrent in the north, while on the Namibian shelf similar activity reduces the lower concentration source water to anoxic levels. Recent research reviews (Richardson and Garzoli 2003, Stramma and England 1999) and modelling results (Imasato *et al.* 2000) support this circulation scheme. Consistent with Monteiro's (1996) observations, periodic breakdown in the poleward movement of low oxygen water also occurs and has induced very low oxygen values as far as St Helena Bay and the Cape Peninsula (L. Hutchings, M.C.M., pers. comm.).

Conclusion

The Lüderitz/Orange River region appears to play an important role in the biological functioning of the Benguela upwelling system, acting as a barrier to the movement and exchange of some species between the southern and northern parts of the Benguela ecosystem.

Wind stress is a persistent forcing influence. The waters brought to the surface by the intense upwelling induced by the persistent winds along the coast from the Orange River mouth to Walvis Bay create strong fronts along the shelf-edge. The front is convoluted and dynamic and the water that is upwelled leaves the shelf in the form of filaments and frontal eddies (Duncombe Rae *et al.* 1992a, Shillington *et al.* 1990). Drifter studies (Largier and Boyd 2001) show that surface water over

the shelf south of the Lüderitz upwelling cell at 26°40'S tends to leave the shelf and head into deep water where it is caught up in the greater eastern boundary current circulation of the South Atlantic gyre.

The water mass analysis presented here shows that there is a hydrographic disjuncture in this area, more than the turbulence and upwelling generated by persistent wind influence might cause. The analysis shows that the central and intermediate water layers along the shelf north of the Lüderitz upwelling cell are not continuous with the central and intermediate water south of it. The “gate” hypothesis proposed by Monteiro (1996) on the basis of carbonate distribution is supported by the water mass TS characteristics. Are the changes in topography and wind forcing in this region sufficient to account for the hydrographic partitioning observed? Is it the upwelling process that blocks the poleward movement of the equatorial low-oxygen water from the Angola Basin? Or is there some other explanation for the apparent discontinuity? The seasonality of the disjuncture is unknown and could not be investigated in this contribution due to the general paucity of data in the region. This aspect therefore also requires further investigation.

Data collected over the shelf edge and into deeper water on the slope with CTD casts that extend through the entire water column (to near-bottom) are required to answer these and other questions definitively. A regional numerical model might also provide more insight into the fundamental processes controlling this internal boundary within the Benguela Upwelling system.

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Literature Cited

- AGENBAG, J.J. and L.V. SHANNON 1988 — A suggested physical explanation for the existence of a biological boundary at 24°30'S in the Benguela system. *S. Afr. J. mar. Sci.* **6**: 119–132.
- ANDREWS, W.R.H. and L. HUTCHINGS 1980 — Upwelling in the southern Benguela Current. *Prog. Oceanogr.* **9**(1): 81+2 figures.
- BADENHORST, A. and A.J. BOYD 1980 — Distributional ecology of the larvae and juveniles of the anchovy *Engraulis capensis* Gilchrist in relation to the hydrological environment off South West Africa, 1978/79. *Fish. Bull. S. Afr.* **13**: 83–106.
- BAKUN, A. 1996 — *Patterns in the Ocean*. California Sea Grant/CIB, 323 pp.
- BANG, N.D. and W.R.H. ANDREWS 1974 — Direct current measurements of a shelf-edge frontal jet in the southern Benguela system. *J. mar. Res.* **32**(3): 405–417.
- BARANGE, M. and S.C. PILLAR 1992 — Cross-shelf circulation, zonation and maintenance mechanisms of *Nyctiphanes capensis* and *Euphausia hanseni* (Euphausiacea) in the northern Benguela upwelling system. *Cont. Shelf Res.* **12**(9): 1027–1042.
- BOYD, A.J. and R.A. CRUICKSHANK 1983 — An environmental basin model for west coast pelagic fish distribution. *S. Afr. J. Sci.* **79**: 150–151.
- BYRNE, D.A., GORDON, A.L. and W.F. HAXBY 1995 — Agulhas eddies: a synoptic view using Geosat ERM data. *J. phys. Oceanog.* **25**(5): 902–917.
- CHAPMAN, P. and L.V. SHANNON 1985 — The Benguela Ecosystem Part II. Chemistry and related processes. *Oceanogr. Mar. Biol. Ann. Rev.* **23**: 183–251.
- CHILDRESS, J.J. and B.A. SEIBEL 1998 — Life at stable low oxygen levels: adaptations of animals to oceanic oxygen minimum layers. *Journal of Experimental Biology* **201**: 1223–1232.
- CLOWES, A.J. 1950 — An introduction to the hydrology of South African waters. *Investl Rep. Fish. mar. biol. Surv. Div. S. Afr.* **12**: 42 pp. + 20 Charts.
- DUNCAN, C.P. 1970 — *The Agulhas Current*. Ph.D. thesis, University of Hawaii, 76 pp.
- DUNCOMBE RAE, C.M. 1998 — Antarctic Intermediate and Central Waters in the Angola-Benguela Front region: results from the first BENEFIT cruise, April 1997. In: *International Symposium on Environmental Variability in the South-East Atlantic, 30 March to 1 April 1998, Swakopmund, Namibia*, p. 14.

- DUNCOMBE RAE, C.M., BOYD, A.J. and R.J.M. CRAWFORD 1992a — “Predation” of anchovy by an Agulhas ring: a possible contributory cause of the very poor year-class of 1989. In: *Benguela Trophic Functioning*, Payne, A.I.L., Brink, K.H., Mann, K.H. and R. Hilborn (Eds), *S. Afr. J. mar. Sci.* **12**: 167–173.
- DUNCOMBE RAE, C.M., SHILLINGTON, F.A., AGENBAG, J.J., TAUNTON-CLARK, J. and M.L. GRÜNDLINGH 1992b — An Agulhas ring in the South Atlantic Ocean and its interaction with the Benguela upwelling frontal system. *Deep-Sea Res.* **39**(11/12): 2009–2027.
- GORDON, A.L. 1985 — Indian-Atlantic transfer of thermocline water at the Agulhas Retroflexion. *Science* **227**: 1030–1033.
- GORDON, A.L. 1986 — Interocean exchange of thermocline water. *J. geophys. Res.* **91**(C4): 5037–5046.
- GRÜNDLINGH, M.L. 1985 — Occurrence of Red Sea water in the southwestern Indian Ocean, 1981. *J. phys. Oceanog.* **15**(2): 207–212.
- IMASATO, N., KOBAYASHI, T. and S. FUJIO 2000 — Study of water motion at the dissolved oxygen minimum layer and local oxygen consumption rate from the Lagrangian viewpoint. *J. Oceanog.* **56**: 361–377.
- KANANDJEMBO, A., D’ALMEIDA, G. and A. IITA 2001 — The distribution of pelagic fish in the Orange River region, July 1999: a separate marginal stock? *S. Afr. J. Sci.* **97**: 266–270.
- LARGIER, J. and A.J. BOYD 2001 — Drifter observations of surface water transport in the Benguela Current during winter 1999. *S. Afr. J. Sci.* **97**: 223–229.
- LUTJEHARMS, J.R.E. 1976 — The Agulhas Current system during the north-east monsoon season. *J. phys. Oceanog.* **6**(5): 665–670.
- LUTJEHARMS, J.R.E. 1981 — Features of the southern Agulhas Current circulation from satellite remote sensing. *S. Afr. J. Sci.* **77**(5): 231–236.
- MEEUWIS, J.M. and J.R.E. LUTJEHARMS 1990 — Surface thermal characteristics of the Angola-Benguela front. *S. Afr. J. mar. Sci.* **9**: 261–279.
- MERCIER, H., ARHAN, M. and J.R.E. LUTJEHARMS 2003 — Upper-layer circulation in the eastern Equatorial and South Atlantic Ocean in January–March 1995. *Deep-Sea Res. I* **50**: 863–887.

- MOHRHOLZ, V., SCHMIDT, M. and J.R.E. LUTJEHARMS 2001 — The hydrography and dynamics of the Angola-Benguela Frontal Zone and environment in April 1999. *S. Afr. J. Sci.* **97**: 199–208.
- MONTEIRO, P.M.S. 1996 — *The oceanography, the biogeochemistry and the fluxes of carbon dioxide in the Benguela upwelling system*. Ph.D. thesis, Univ. Cape Town, S. Afr, 354 pp.
- NELSON, G. 1989 — Poleward motion in the Benguela area. In: *Poleward Flows Along Eastern Ocean Boundaries*, Neshyba, S.J., Mooers, C.N.K., Smith, R.L. and R.T. Barber (Eds), *Coastal and Estuarine Studies* **34**: 111–130.
- NELSON, G. and L. HUTCHINGS 1983 — The Benguela upwelling area. *Prog. Oceanog.* **12**: 333–356.
- O'TOOLE, M.J. 1977 — *Investigations into some important fish larvae in the South East Atlantic in relation to the hydrological environment*. Ph.D. thesis, University of Cape Town, pagination discontinuous, 8 sections + 7 supporting papers pp.
- PETERSON, R.G. and L. STRAMMA 1991 — Upper level circulation in the South Atlantic Ocean. *Prog. Oceanog.* **26**: 1–73.
- POOLE, R. and M. TOMCZAK 1999 — Optimum multiparameter analysis of the water mass structure in the Atlantic Ocean thermocline. *Deep-Sea Res. I* **46**: 1895–1921.
- REID, J.L. 1989 — On the total geostrophic circulation of the South Atlantic Ocean: Flow patterns, tracers, and transports. *Prog. Oceanog.* **23**: 149–244.
- RICHARDSON, P.L. and S.L. GARZOLI 2003 — Characteristics of intermediate water flow in the Benguela current as measured with RAFOS floats. *Deep-Sea Res. II* **50**(1): 87–118.
- SALAT, J., MASÓ, M. and A.J. BOYD 1992 — Water mass distribution and geostrophic circulation off Namibia during April 1986. *Cont. Shelf Res.* **12**(2/3): 355–366.
- SCHÜLEIN, F.H., BOYD, A.J. and L.G. UNDERHILL 1995 — Oil-to-meal ratios of pelagic fish taken from the northern and the southern Benguela systems: seasonal patterns and temporal trends, 1951–1993. *S. Afr. J. mar. Sci.* **15**: 61–82.
- SHANNON, L.V. 1985 — The Benguela Ecosystem Part I. Evolution of the Benguela, physical features and processes. *Oceanogr. Mar. Biol. Ann. Rev.* **23**: 105–182.

- SHANNON, L.V., BOYD, A.J., BRUNDRIT, G.B. and J. TAUNTON-CLARK 1986 — On the existence of an El Niño-type phenomenon in the Benguela system. *J. mar. Res.* **44**: 495–520.
- SHANNON, L.V. and D. HUNTER 1988 — Notes on Antarctic Intermediate Water around southern Africa. *S. Afr. J. mar. Sci.* **6**: 107–117.
- SHANNON, L.V. and G. NELSON 1996 — The Benguela: large scale features and processes and system variability. In: *The South Atlantic: Present and Past Circulation*, Wefer, G., Berger, W.H., Siedler, G. and D.J. Webb (Eds), Berlin Heidelberg: Springer-Verlag, pp. 163–210.
- SHANNON, L.V. and S.C. PILLAR 1986 — The Benguela ecosystem. 3. Plankton. *Oceanogr. Mar. Biol. Ann. Rev.* **24**: 65–170.
- SHILLINGTON, F.A., PETERSON, W.T., HUTCHINGS, L., PROBYN, T.A., WALDRON, H.N. and J.J. AGENBAG 1990 — A cool upwelling filament off Namibia, southwest Africa: preliminary measurements of physical and biological features. *Deep-Sea Res.* **37**(11A): 1753–1772.
- STANDER, G.H. 1964 — The Benguela Current off South West Africa. *Investigational Reports of the Marine Research Laboratory of South West Africa* **12**: 43.
- STRAMMA, L. and M. ENGLAND 1999 — On the water masses and mean circulation of the South Atlantic Ocean. *J. geophys. Res.* **104**(C9): 20863–20883.
- STRAMMA, L. and R.G. PETERSON 1989 — Geostrophic transport in the Benguela Current region. *J. phys. Oceanog.* **19**: 1440–1448.
- SVERDRUP, H.U., JOHNSON, M.W. and R.H. FLEMING 1942 — *The Oceans: their Physics, Chemistry, and General Biology*. Englewood Cliffs, New Jersey: Prentice-Hall, x+1087 pp.
- TALLEY, L.D. 1996 — Antarctic Intermediate Water in the South Atlantic. In: *The South Atlantic: Present and Past Circulation*, Wefer, G., Berger, W.H., Siedler, G. and D.J. Webb (Eds), Berlin Heidelberg: Springer-Verlag, pp. 219–238.
- TYSON, P.D. 1986 — *Climatic Change and Variability in Southern Africa*. Cape Town: Oxford University Press, 220 pp.
- UNESCO. 1983 — Algorithms for computation of fundamental properties of seawater. *Unesco Technical Papers in Marine Science* **44**: 53.

VAN BALLEGOOYEN, R.C. 1995 — *Forced synoptic coastal-trapped waves along the southern African coastline*. Master's thesis, University of Cape Town, 221 pp.

WYRTKI, K. 1971 — *Oceanographic Atlas of the International Indian Ocean Expedition*. Washington, D.C.: National Science Foundation, 531 pp.

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Water Mass	Θ ($^{\circ}\text{C}$)	S	σ_{Θ} ($\text{kg}\cdot\text{m}^{-3}$)	Defined by	Notes
AABW	0.4 – 1	34.7 – 34.75		Mohrholz <i>et al.</i> 2001	Defines a block in TS space
NADW	2 – 3	34.82 – 34.88		Mohrholz <i>et al.</i> 2001	Defines a block in TS space
AAIW	3 – 5	34.25 – 34.45		Mohrholz <i>et al.</i> 2001	Defines a block in TS space
AAIW			27.0 – 27.4	Talley 1996	
AAIW	4 – 6	<34.6		Clowes 1950, Duncan 1970	
RSW		34.7 – 38	27 – 27.7	Lutjeharms 1976, Wyrteki 1971	S=34.7 in the Mozambique Channel
WSACW	6.552 – 16.266	34.402 – 35.692		Poole and Tomczak 1999	Defines a line in TS space
SACW	8 – 16	34.7 – 35.65		Mohrholz <i>et al.</i> 2001	Based on Poole and Tomczak's (1999) definition of WSACW. Defines a line in TS space

continued . . .

Table 1: (continued)

Water Mass	Θ ($^{\circ}\text{C}$)	S	σ_{Θ} ($\text{kg}\cdot\text{m}^{-3}$)	Defined by	Notes
ESACW	5.956 – 14.407	34.407 – 35.302		Poole and Tomczak 1999	Defines a line in TS space
ESACW	5.96 – 14.41	34.1 – 35.3		Mohrholz <i>et al.</i> 2001	Defines a line in TS space
TSW	<31	\sim 36.5		Mohrholz <i>et al.</i> 2001	
LSSW	\sim 30	>31		Mohrholz <i>et al.</i> 2001	Source is river runoff
UCW				Mohrholz <i>et al.</i> 2001	Characteristics not provided
CUW	12 – 18	34.9 – 35.2		Salat <i>et al.</i> 1992	Cool Upwelled Water
AW	12 – 18	35.5 – 35.2		Salat <i>et al.</i> 1992	Angolan Water
OW	16 – 22	35.2 – 35.5		Salat <i>et al.</i> 1992	Oceanic Water
SUW	<15	35.3 – 35.5		Salat <i>et al.</i> 1992	Saline Upwelled Water

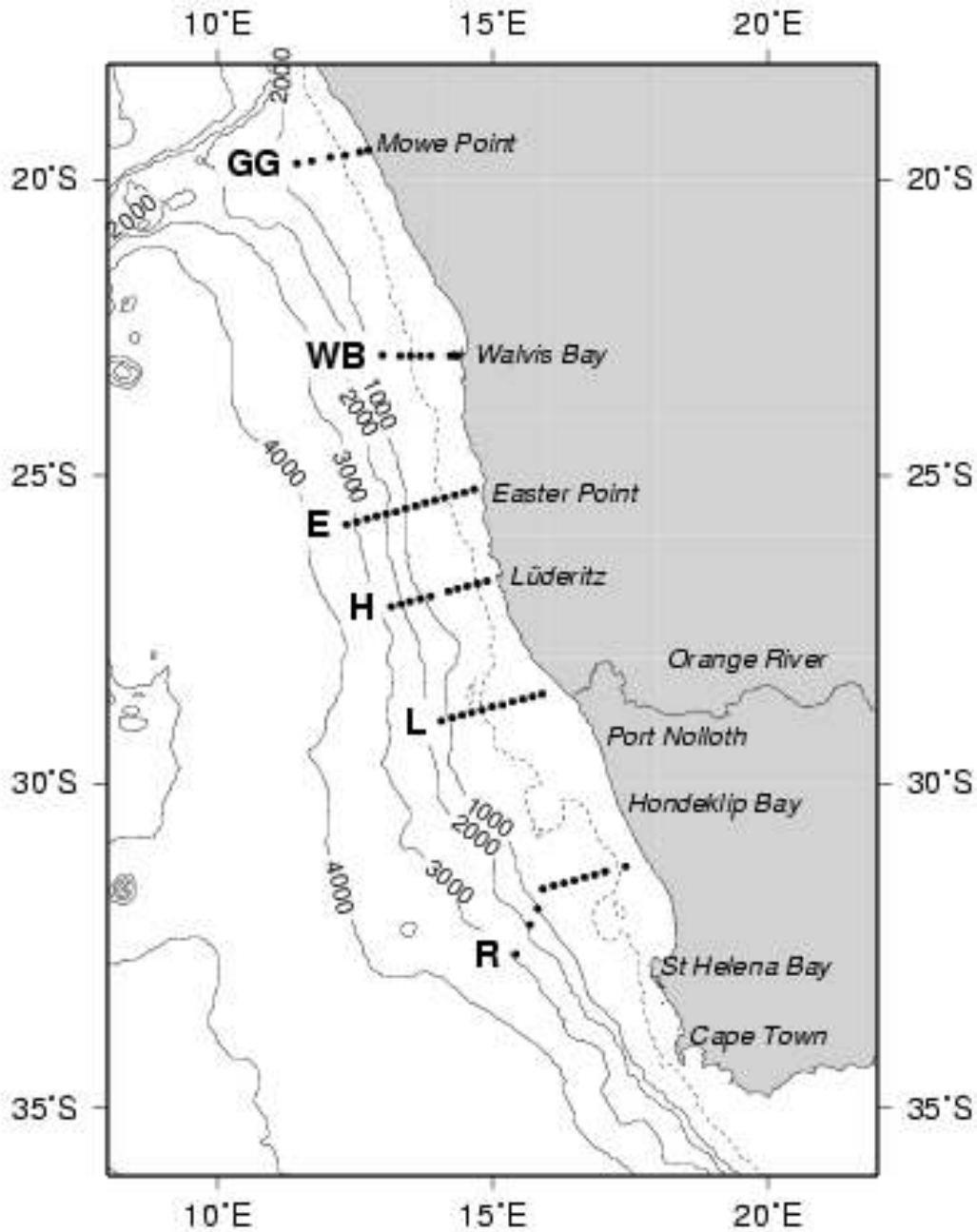


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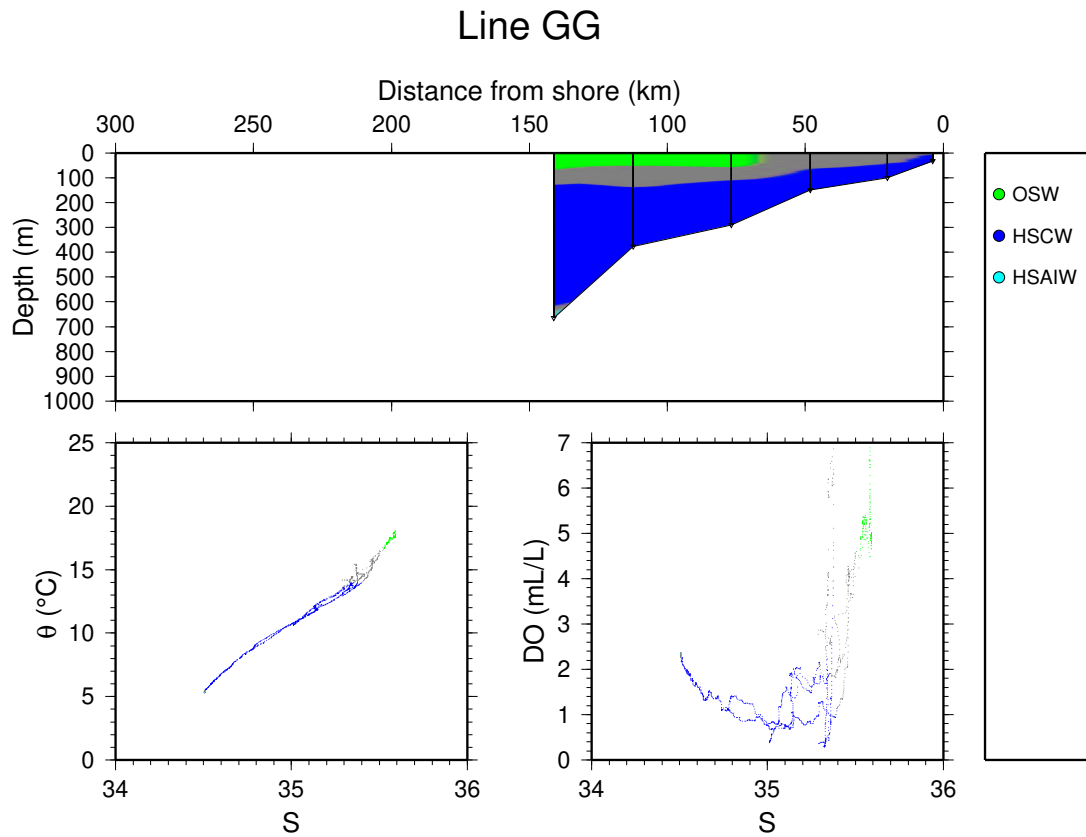


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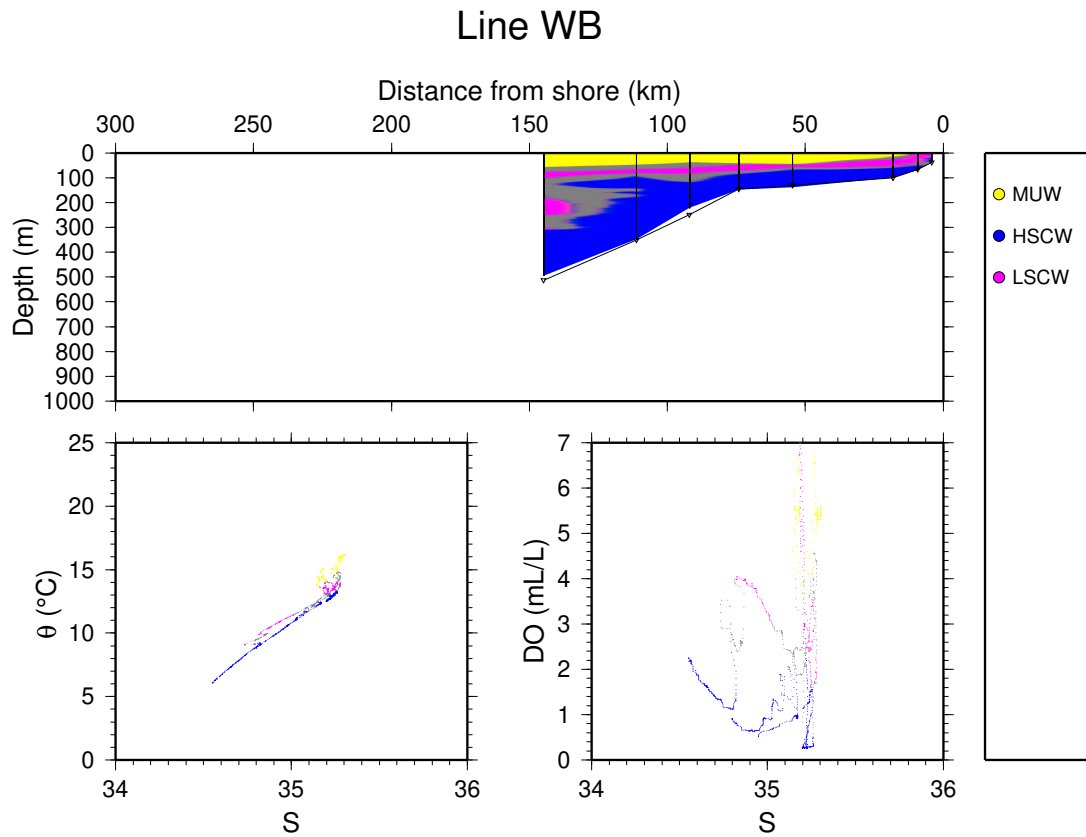


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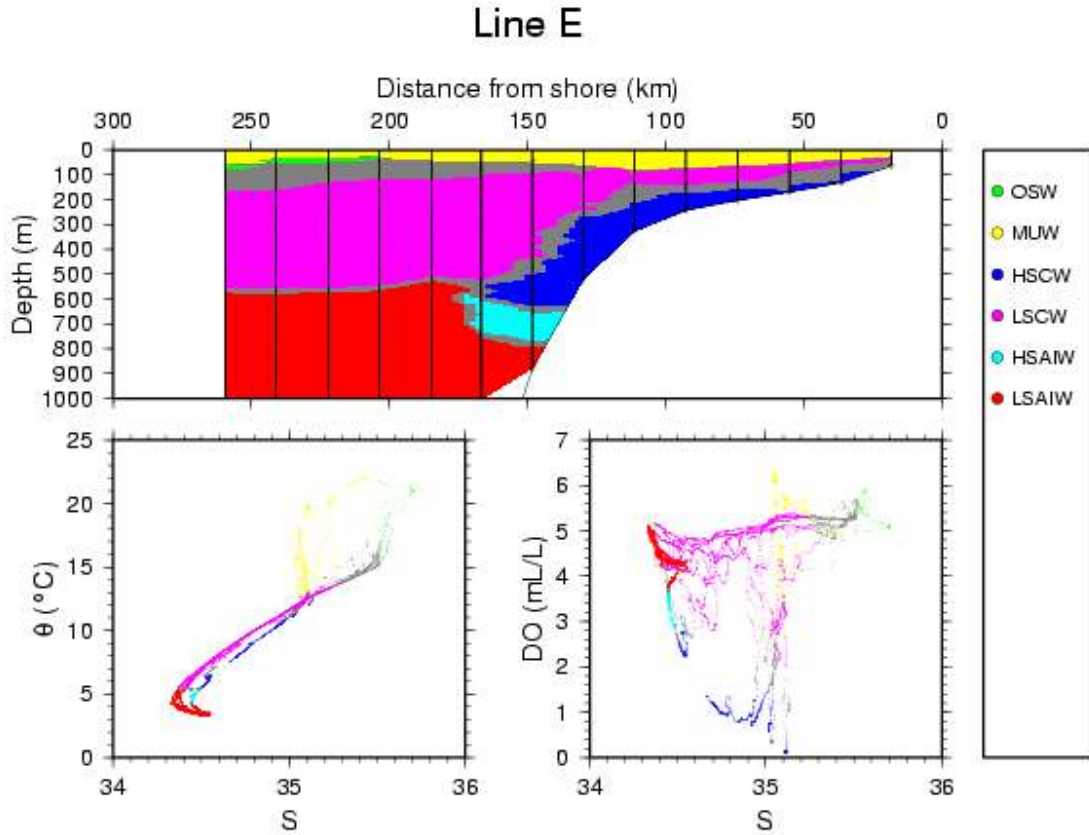


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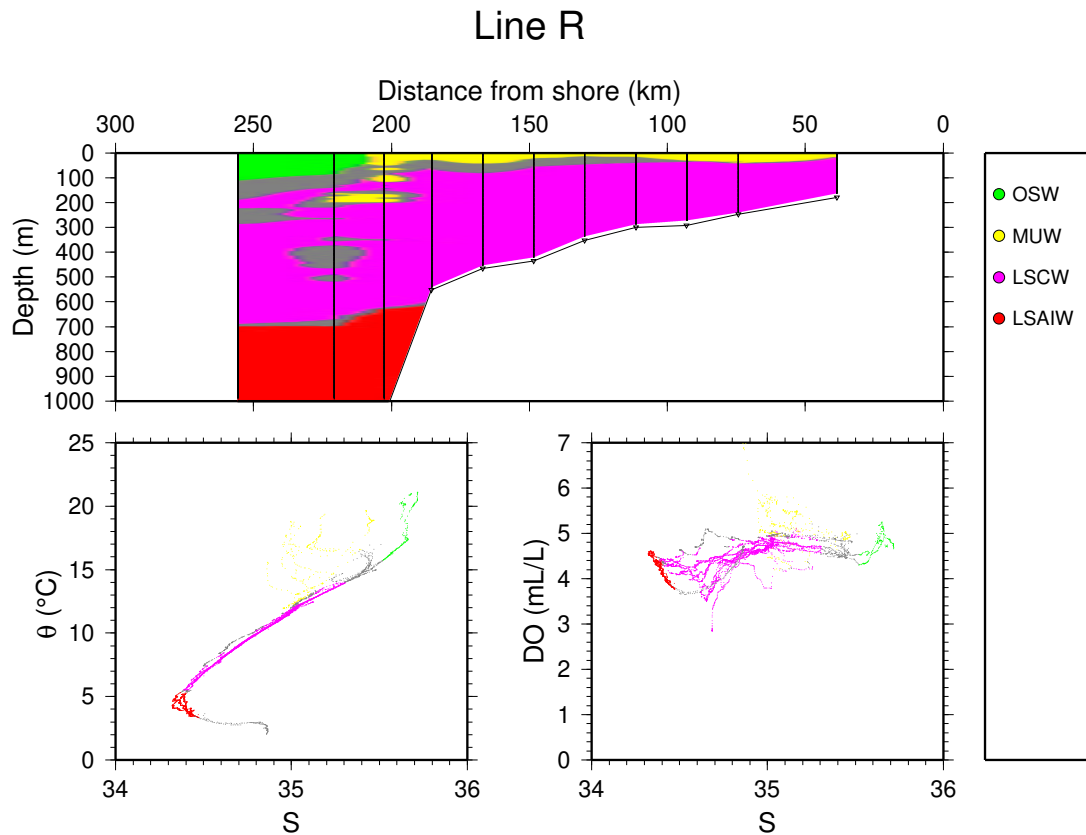


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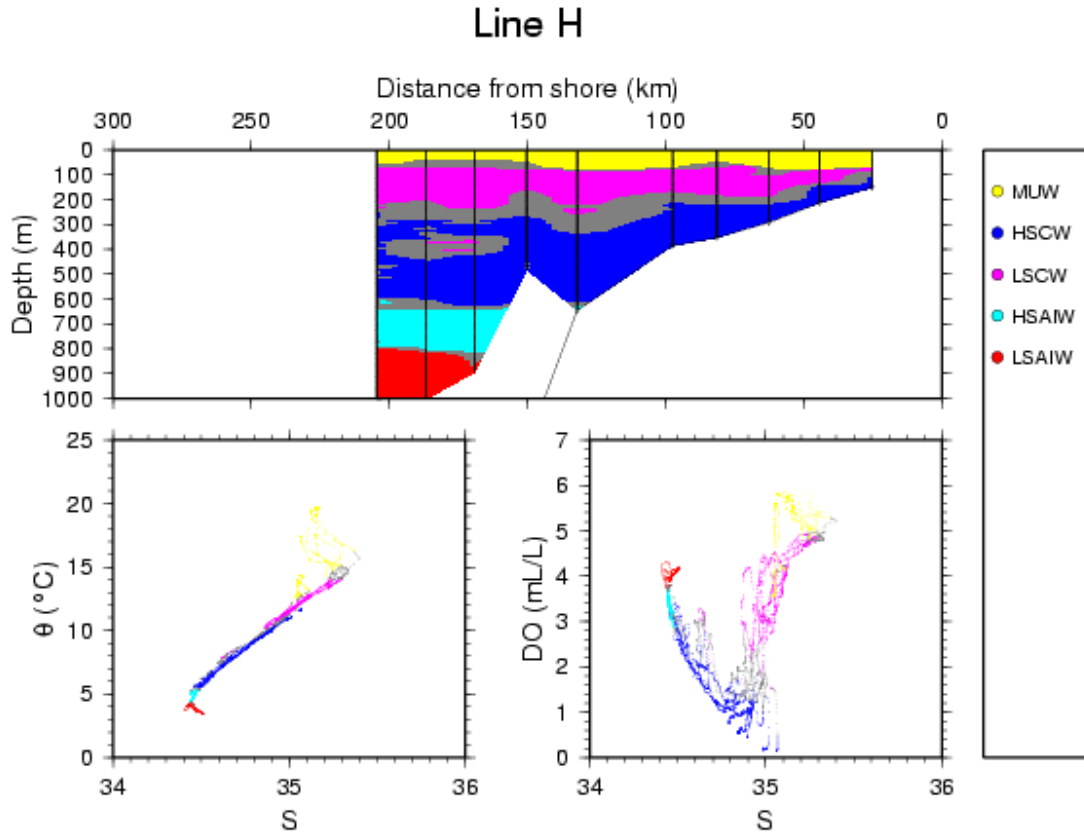


Figure 7: Water masses on a section ($26^{\circ}42'S$) across the shelf at Lüderitz (Line H, March 2002). The water masses appearing on the figure are indicated alongside in the legend, and defined in the text and Figure 2. Parameter/parameter plots of potential temperature (Θ) and dissolved oxygen (DO) against salinity (S) are shown.

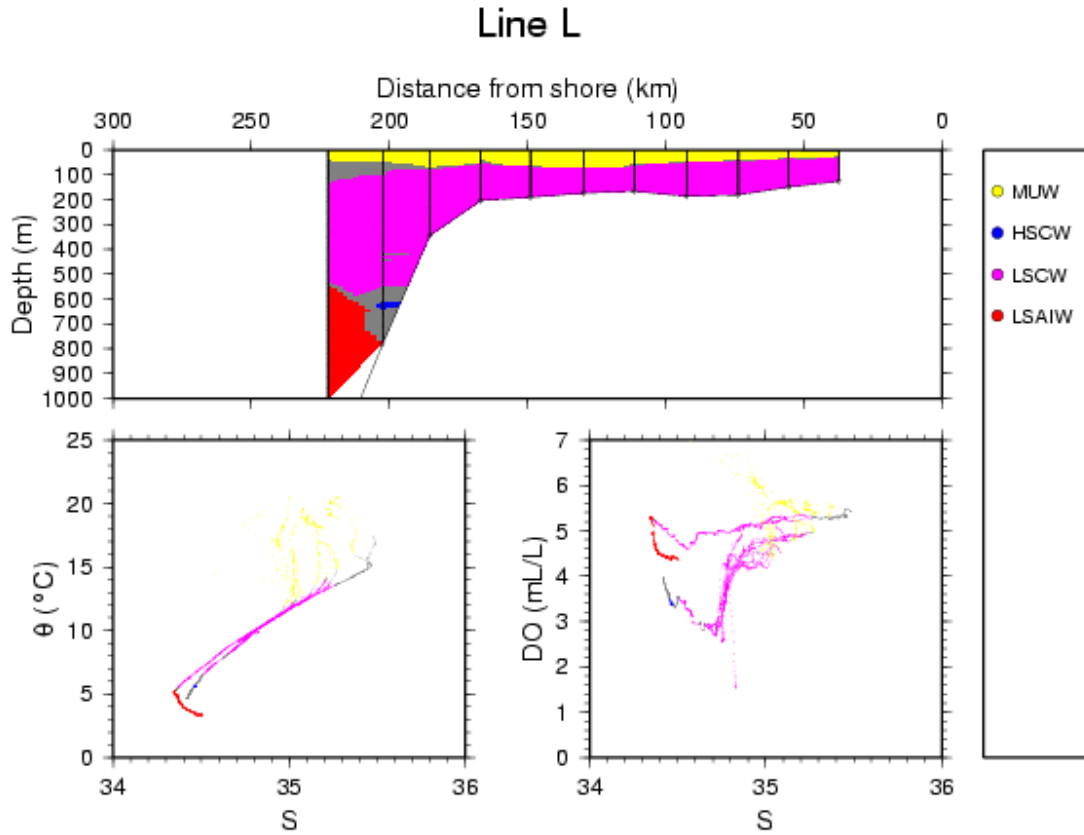


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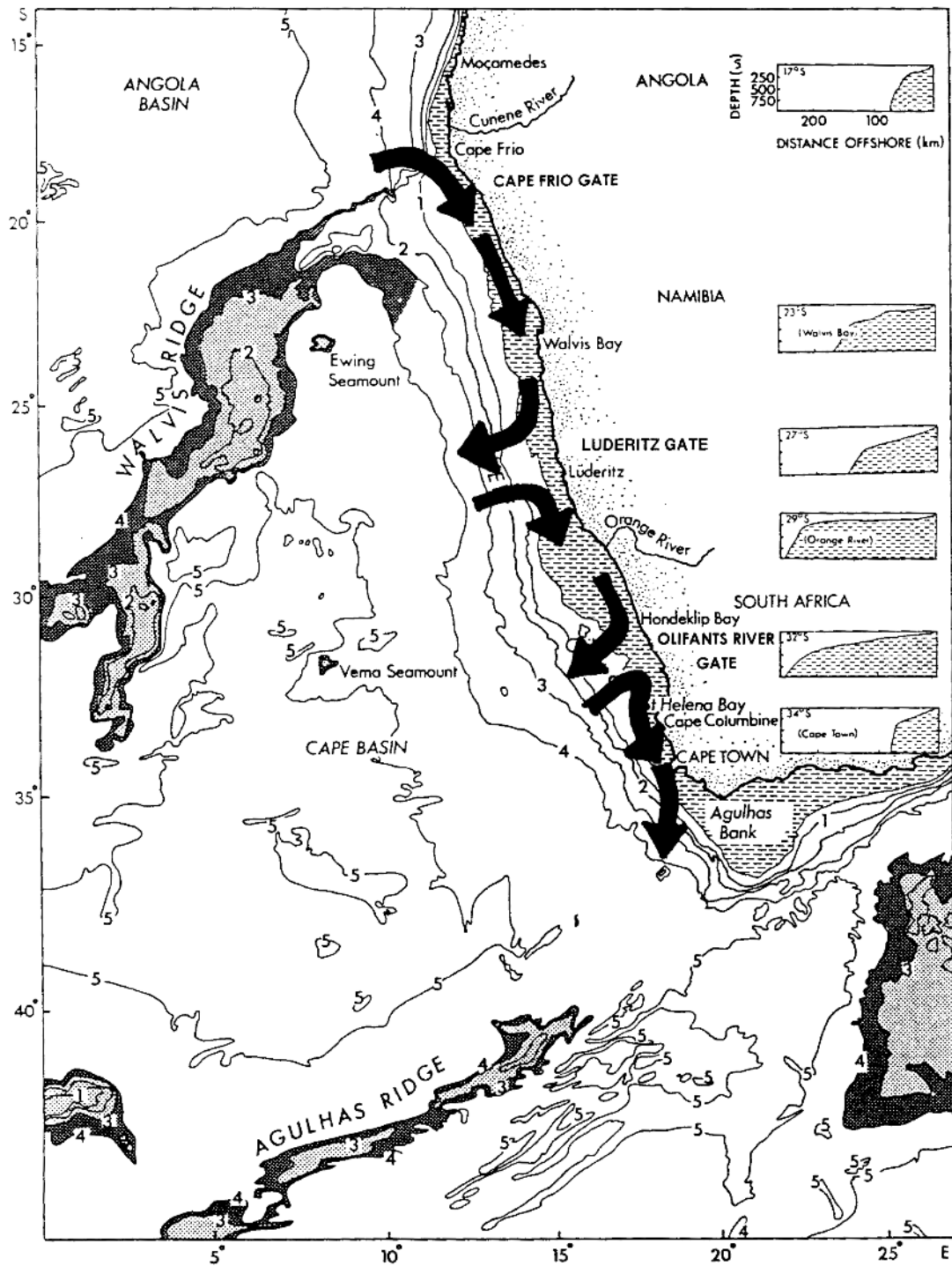


Figure 9: A map of the Benguela system showing the subsurface inflow and corresponding outflow of central water between the slope and the shelf. (From Monteiro 1996.)

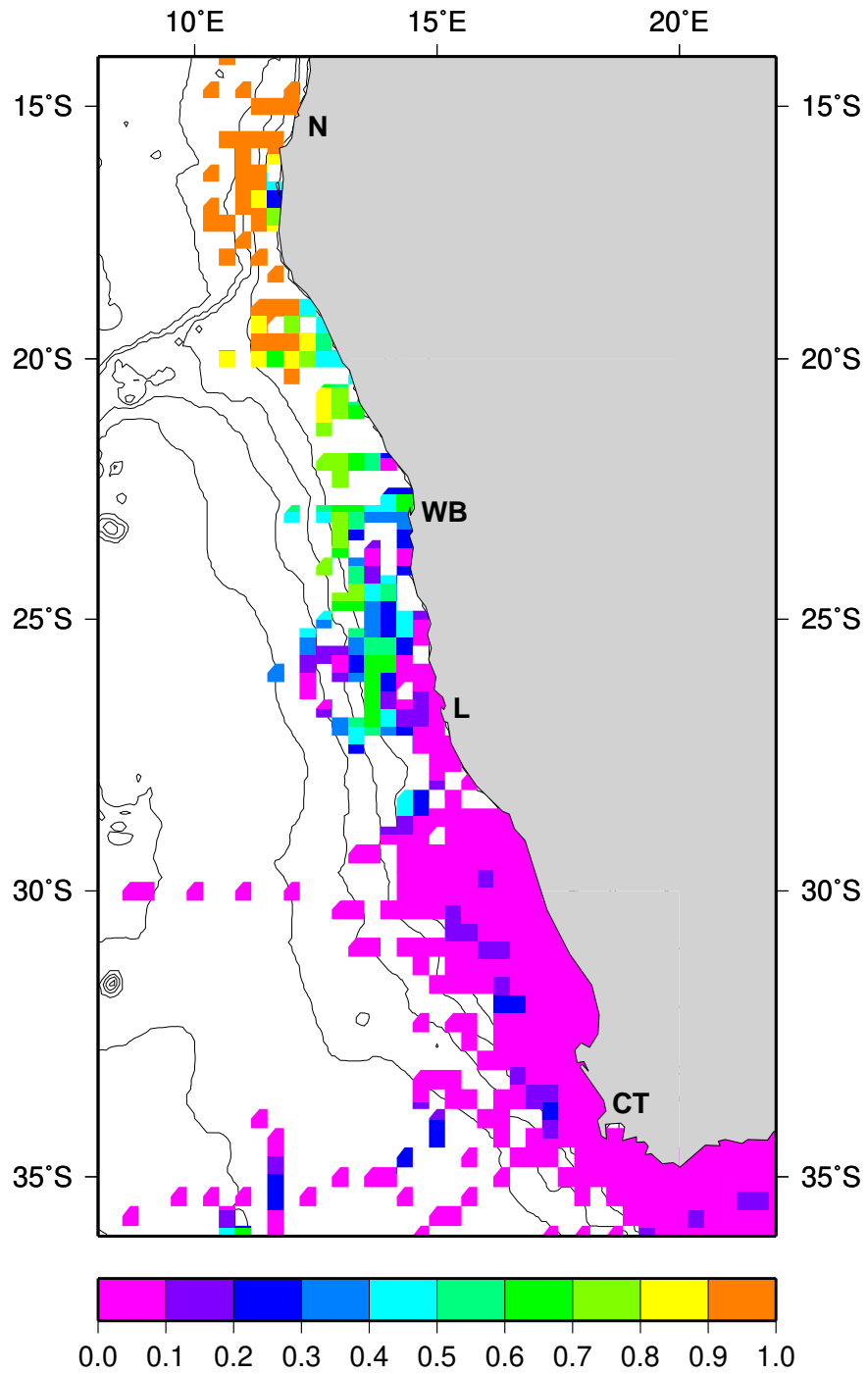


Figure 10: Proportion of High Salinity Central Water within the central water mass on the Benguela shelf.