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Characteristics of intermediate water flow in the Benguela current as measured with RAFOS floats

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Abstract

Seven floats (not launched in rings) crossed over the mid-Atlantic Ridge in the Benguela extension with a mean westward velocity of around 2 cm/s between 22S and 35S. Two Agulhas rings crossed over the mid-Atlantic Ridge with a mean velocity of 5.7 cm/s toward 285°. This implies they translated at around 3.8 cm/s through the background velocity field near 750 m. The boundaries of the Benguela Current extension were clearly defined from the observations. At 750 m the Benguela extension was bounded on the south by 35S and the north by an eastward current located between 18S and 21S. Other recent float measurements suggest that this eastward current originates near the Trindade Ridge close to the western boundary and extends across most of the South Atlantic, limiting the Benguela extension from flowing north of around 20S. The westward transport of the Benguela extension was estimated to be 15 Sv by integrating the mean westward velocities from 22S to 35S and multiplying by the 500 m estimated thickness of intermediate water. Roughly 1.5 Sv of this are transported by the ~3 Agulhas rings that cross the mid-Atlantic Ridge each year (as observed with altimetry). This value of the Benguela extension transport is the first one to have been obtained from long-term (two-year) observations and across the full width of the Benguela extension.

1. Introduction

A quantitative knowledge of Antarctic Intermediate Water (AAIW) circulation patterns and the associated heat and salt transport is important to climate studies because AAIW is a key part of the Atlantic meridional overturning circulation (MOC). Thermocline and intermediate water from the South Atlantic flows northward across the equator to the northern North Atlantic where the water is cooled and transformed into deep water which returns to the South Atlantic (Schmitz, 1996; Gordon et al., 1992; Sloyan and Rintoul, 2001). The low-salinity AAIW layer is one of the most prominent features of the Atlantic and can be clearly traced from the South Atlantic across the equator and into the northern North Atlantic.

The upper limb of the Atlantic MOC originates in the southeastern Atlantic where South Atlantic Current water merges with Indian Ocean leakage in the Benguela Current (Reid, 1989; Peterson and Stramma, 1991; Stramma and England, 1999; de

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Ruijter et al., 1999). The Benguela Current flows northward as the eastern part of the subtropical gyre of the South Atlantic (Fig. 1). Accurate knowledge of the circulation and amounts of source water in the Benguela Current has remained lacking because of the complexities of the ocean circulation and the lack of suitable direct measurements especially in the intermediate water, which contributes about half of the transport of the upper limb of the MOC (Gordon et al., 1992). Estimates of the amount of intermediate water entering the Benguela Current from the Agulhas range from near zero (Rintoul, 1991) to around 50% (Gordon et al., 1992). Knowledge of the relative amounts and subsequent pathways is important because Agulhas leakage water is warmer and saltier than South Atlantic Current Water of Drake Passage origin and could lead to a greater northward heat and salt flux.

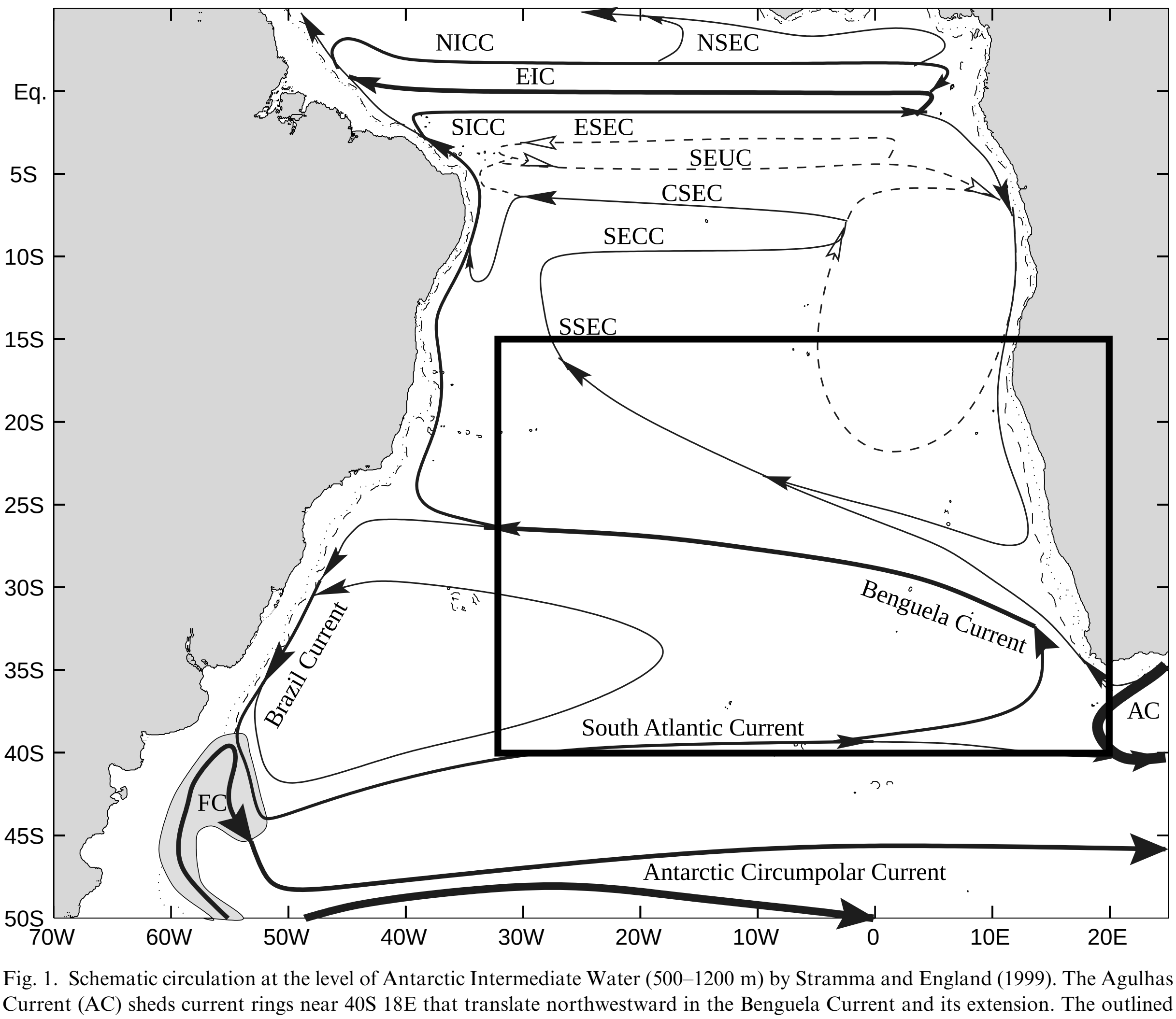


Fig. 1. Schematic circulation at the level of Antarctic Intermediate Water (500–1200 m) by Stramma and England (1999). The Agulhas Current (AC) sheds current rings near 40S 18E that translate northwestward in the Benguela Current and its extension. The outlined box (15S–40S, 20E–32W) shows the area of the Benguela Current float experiment and trajectories. Note that the main pathway of intermediate water to the North Atlantic is first northward in the Benguela Current, then westward in its extension, and finally northward along the western boundary north of 25S. Near the equator some intermediate water is entrained into zonal currents as described by Stramma and England (1999).

AAIW enters the subtropical gyre of the South Atlantic near its southwestern corner in the Brazil–Falkland confluence zone and also along the southern edge of the South Atlantic Current (McCartney, 1977; Tsuchiya et al., 1994; Boebel et al., 1999a). Some South Atlantic Current water enters the Benguela Current and some merges with the Agulhas Return Current and continues eastward past Africa. Part of this eastward flow loops into the subtropical gyre of the Indian Ocean and, via Agulhas Current leakage, feeds into the Benguela Current and the South Atlantic subtropical gyre. Because the subtropical gyres of the South Atlantic and Indian Ocean are partially connected, it is problematic to use water properties to clearly identify sources of the Benguela Current and to trace the source waters downstream.

Gordon et al. (1992) estimate that approximately 65% of the Benguela Current thermocline and as much as 50% of the Intermediate Water is derived from the Indian Ocean. In their scheme, the main supply of upper layer water flowing north across the equator is drawn from AAIW; the lower thermocline and intermediate water passes to lower latitudes of the South Atlantic where significant amounts of intermediate water is transferred into the thermocline which could account for the amount of South Atlantic thermocline water passing northward through the Straits of Florida as determined by Schmitz and Richardson (1991). In a recent study, Sloyan and Rintoul (2001) concluded that the Atlantic MOC is closed by cold, fresh intermediate water that is modified to warm, salty varieties by air sea fluxes and interior mixing in the Atlantic and southwestern Indian Ocean. They suggest that the lower thermocline and intermediate water ($T < 10°C$) in the Benguela Current comes from the South Atlantic Current and Agulhas Current in equal amounts. Unresolved issues are the relative amounts (at different depths) of Indian Ocean water and South Atlantic water that flow northward in the MOC as opposed to being recycled around the western side of the Atlantic subtropical gyre back into the South Atlantic Current. A recent study using floats suggests that around a third of the intermediate water in the western Benguela extension (the westward return flow of the subtropical gyre) flows northward in the MOC along the western boundary and two-thirds flows southward in the Brazil Current (Boebel et al., 1999b; see also Schmid et al., 2000).

Agulhas Current leakage is dominated by extremely energetic eddies. Ship and satellite data have revealed the presence of numerous large (300–400 km diameter) rings of the Agulhas Current embedded in the Benguela Current. The rings form as the western part of the Agulhas retroflection pinches off from the main current (Lutjeharms and Van Ballegooyen, 1988). Approximately 5–6 rings form per year (Goni et al., 1997; Schouten et al., 2000). Olson and Evans (1986) found that Agulhas rings are among the most energetic eddies in the world. The Agulhas ring shedding area has the highest levels of eddy kinetic energy in the southern hemisphere, with values reaching 1000–4000 cm^2/s^2 (Johnson, 1989; Patterson, 1985; Ducet et al., 2000).

Intermediate water of Indian Ocean origin is quickly dissociated from the rings in the Cape Basin west of Cape Town, and this water is blended with water from the South Atlantic Current and also from the tropical Atlantic (McDonagh et al., 1999). This rapid mixing in the Cape Basin has made it difficult to determine accurately the amount of Indian Ocean intermediate water that enters the Benguela Current in rings because source characteristics are rapidly obscured in the Cape Basin.

Difficulties in estimating the circulation of intermediate water in the Benguela Current are the low mean velocities at that level compared to the ring velocities and the weak shear in mean velocity profiles of geostrophic velocity (Garzoli and Gordon, 1996). Although there is significant shear in Agulhas rings, there is little shear in the region they are embedded. The small shear and paucity of direct velocity measurements to provide a reference for geostrophic velocity has limited our knowledge of the subsurface circulation patterns in the Benguela Current. One notable set of direct current measurements comes from the BEST (Benguela Sources and Transport) program moored current meter array coupled with inverted echo sounders along 30S (Garzoli et al., 1996; Pillsbury et al., 1994). These measurements spanned the whole Benguela Current in the Cape Basin from the coast of Africa out to the Walvis Ridge near 3E (but they missed possible flow associated with rings and the portion of the Benguela Current located southwest of 3E, 30S).

Results of the BEST program indicate that the northward transport in the Benguela Current at 30S is 16 Sv, and that 50% is chiefly South Atlantic water, 25% is Agulhas Water, and 25% is a blend of Agulhas and tropical Atlantic waters (Garzoli and Gordon, 1996). The results suggest that the Benguela Current has a stationary part located between the African Coast and 8E and a transient component located between 8E and the Walvis Ridge at 3E. This transient part is mostly composed of Agulhas rings (Garzoli et al., 1997; Goni et al., 1997). Other reports of Benguela Current transport range from around 15 to 25 Sv (Stramma and Peterson, 1989; Gordon et al., 1992; Sloyan and Rintoul, 2001). Differences in transport are probably due to real fluctuations of the currents, Agulhas rings which are sometimes observed and sometimes not, different assumptions about a level of no motion and different locations and end points of hydrographic sections.

As a complement to the BEST program and to directly measure the northward flow of intermediate water in the southeastern Atlantic we conducted the Benguela Current float Experiment during 1997–1999. We seeded floats in the intermediate water in order to directly measure its flow field for the first time using Lagrangian data. Thirty RAFOS floats were launched near a depth of 750 m across the full width of the Benguela Current near 30S, across the Benguela Current extension just upstream of the mid-Atlantic Ridge near 7W, and in three Agulhas rings.

During the float deployment cruise in September 1997 we measured 43 CTDO-LADCP profiles to 2000 m along 30S and 7W and radially from the center to the edge of three Agulhas rings (Roubicek et al., 1998). Each ring was surveyed with XBTs and a hull-mounted ADCP, which provided a measure of ring size and shape (Garzoli et al., 1999). The rings had previously been identified by satellite altimetry, and they were subsequently tracked by altimetry back to their formation near the Agulhas retroflection.

The Benguela Current Experiment is one of three components of KAPEX (Cape of Good Hope Experiments) which is the focus of a series of papers in this issue of *Deep-Sea Research II*. The overall objectives were to directly measure with floats the interocean exchange of water from the Agulhas into the South Atlantic and the advection of AAIW and its various mixing constituents in the South Atlantic. The two other components of KAPEX tracked floats in the South Atlantic Current region south of our float launch locations and in the Agulhas Current. Some of these floats overlapped with ours in the Cape Basin. A nice summary of the merged float data superimposed on maps of steric height is given in movies created by Olaf Boebel and which are available in an electronic annex to this issue of *Deep-Sea Research*. Dynamic aspects such as the rapid movement, evolution and interactions of numerous Agulhas rings and cyclones can be seen in the movies.

This paper first describes the Benguela Current Experiment floats and tracking and gives a summary of overall float displacements and trajectories. This is followed by descriptions of seven Agulhas rings and three cyclones tracked by looping floats, the complicated velocity field in the Cape Basin and over the Walvis Ridge, the velocity and transport of the Benguela extension near the mid-Atlantic Ridge, and finally an eastward current located near 20S that is the northern boundary of the Benguela extension. Detailed descriptions of individual rings and cyclones are given in the appendix.

2. Methods

Thirty RAFOS floats, two ALFOS floats, and two moored sound sources were launched from the R/V *Seward Johnson* during a cruise from Cape Town to Recife, September 4–30, 1997. The floats were launched along two lines, one roughly along 30S (15E–7W) across the Benguela Current and the other along 7W (18S–33S) across the Benguela Current extension. West of the Walvis Ridge ($\sim$0W) the 30S line heads southwestward and intersects the 7W line near 33S. Seven floats were launched in the three Agulhas rings that were located near the cruise track (see Garzoli et al., 1999).

The RAFOS floats (see Rossby et al., 1986) were purchased from Seascan Corporation in Falmouth, Mass., and assembled, calibrated (temperature, pressure), and ballasted at WHOI. The floats recorded temperature, pressure, and times of arrival (TOAs) from moored sound sources. At the end of their missions the floats dropped weights, rose to the surface and transmitted data to WHOI via the Argos satellite system.

The floats are quasi-isobaric, which means that a float does not follow an isopycnal but instead more closely remains near an isobaric surface. For example, in the presence of an upward displacement of the thermocline, a float would rise around 25–30% of the water displacement but sink relative to an isopycnal. This should be kept in mind when later we use float trajectories to infer water movement. The floats were ballasted for a depth of 750 m, which lies near the center of the intermediate water layer in the Benguela Current region. The initial float depths ranged from 660 to 800 db and the mean initial depth was 737 db. The deeper initial depths tended to be floats launched in the rings where the thermocline is deeper than that outside of rings. Ten floats were programmed to record TOAs twice per day during 18-month missions; 20 floats recorded TOAs once per day during 24-month missions. Two additional ALFOS floats (ALACE–RAFOS) obtained from Webb Research Corporation were used to monitor the sound sources. These two floats returned to the ocean surface at monthly intervals for two days by means of active ballasting similar to an ALACE float (Davis et al., 1992). At the surface they transmitted acoustic data.

Twenty-eight (93%) of the 30 RAFOS floats successfully surfaced and transmitted data. Two floats (375, 408) were never heard by Argos; we do not know why they failed. Float 407 went too deep, dropped its weight and surfaced after two days. Floats 385 and 392 surfaced before the end of their missions because of low battery voltage. The success rate is 90% based on obtaining trajectories from 27 of the 30 RAFOS floats. Overall we obtained 46 float-years of data from the RAFOS floats. One ALFOS float ceased after 150 days, but the other worked successfully for 3.5 years.

Three sound sources were purchased from Webb Research Corporation and were moored at depths near 800 m. Two sources were launched from the R/V *Seward Johnson* and the third from the R/V *Polarstern*. This help from our German colleagues allowed us time to survey the three Agulhas rings. One of the three sources (M10) ceased transmitting on January 7, 1999; the other two continued and are presently aiding French float tracking in the western basin (M. Ollitrault, personal communication).

Our three sources are part of an extended KAPEX source array to track floats over a large area around South Africa (see introduction to this issue). Some of the Benguela Current floats drifted across the mid-Atlantic Ridge into the western South Atlantic where tracking was supplemented by the WOCE Deep Basin Experiment (DBE) acoustic array (Hogg and Owens, 1999).

Floats were tracked using Matlab-based tracking software developed by Martin Menzel and Olaf Boebel and modified by Heather Hunt Furey at WHOI. In general the time series data and trajectories were good quality and few problems were encountered. Position errors are estimated to be around 4 km based on this and earlier float experiments (see for example, Richardson and Wooding, 1999). Details of the float experiment, float trajectories and time series are given in a data report (Richardson et al., 2002).

Statistics for groups of floats were calculated by two methods. In the first method all individual daily float velocity values (N) were grouped and average velocity, variance and T calculated, where T is an estimate of the integral time scale of the Lagrangian autocorrelation function of float velocities. Standard error of velocity was estimated using $[2T\overline{u'u'}/N]^{1/2}$, where $\overline{u'u'}$ is the variance about the mean velocity $\bar{u}$. In a second method each float was considered to give an independent estimate of mean velocity. Mean velocities from different floats in the Benguela Current extension were grouped and averaged. Standard error of

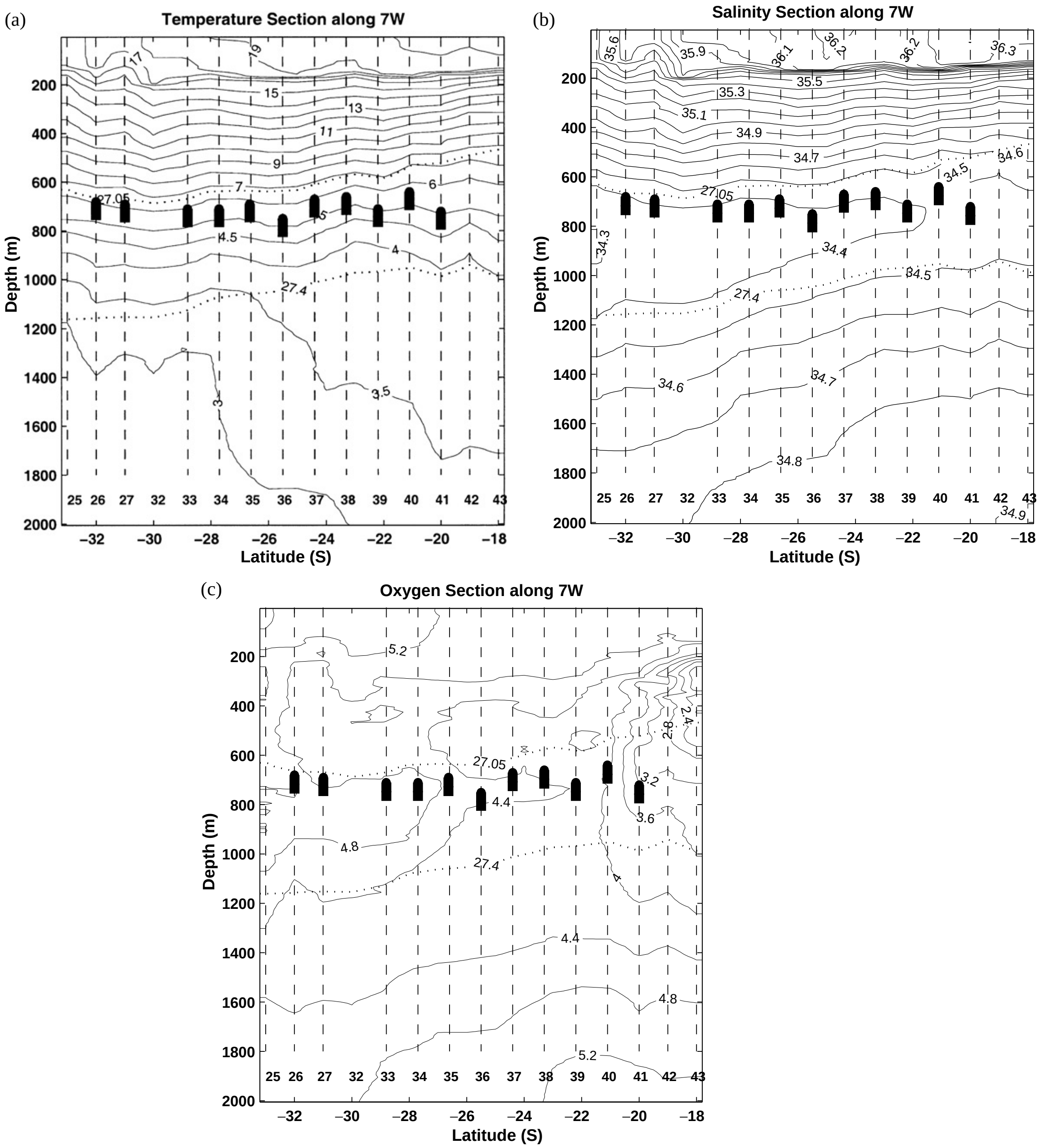


Fig. 2. Vertical sections of temperature, salinity, and oxygen measured along 30S and 7W during the float deployment cruise. Float launch locations are shown by small float symbols. Antarctic Intermediate Water (AAIW) is the tongue of low-salinity and high-oxygen water centered near 800 m. Dotted lines show the 27.05 and 27.40 density surfaces which bracket the AAIW (see Stramma and Peterson, 1989). Three Agulhas rings were located near but slightly off the sections; ring 1 at 31.0S 9.4E and ring 2 at 31.5S 2.3W near the 30S line, and ring 3 at 29.8S 6.1W near the 7W line. CTD stations near the center of the rings were excluded from these sections.

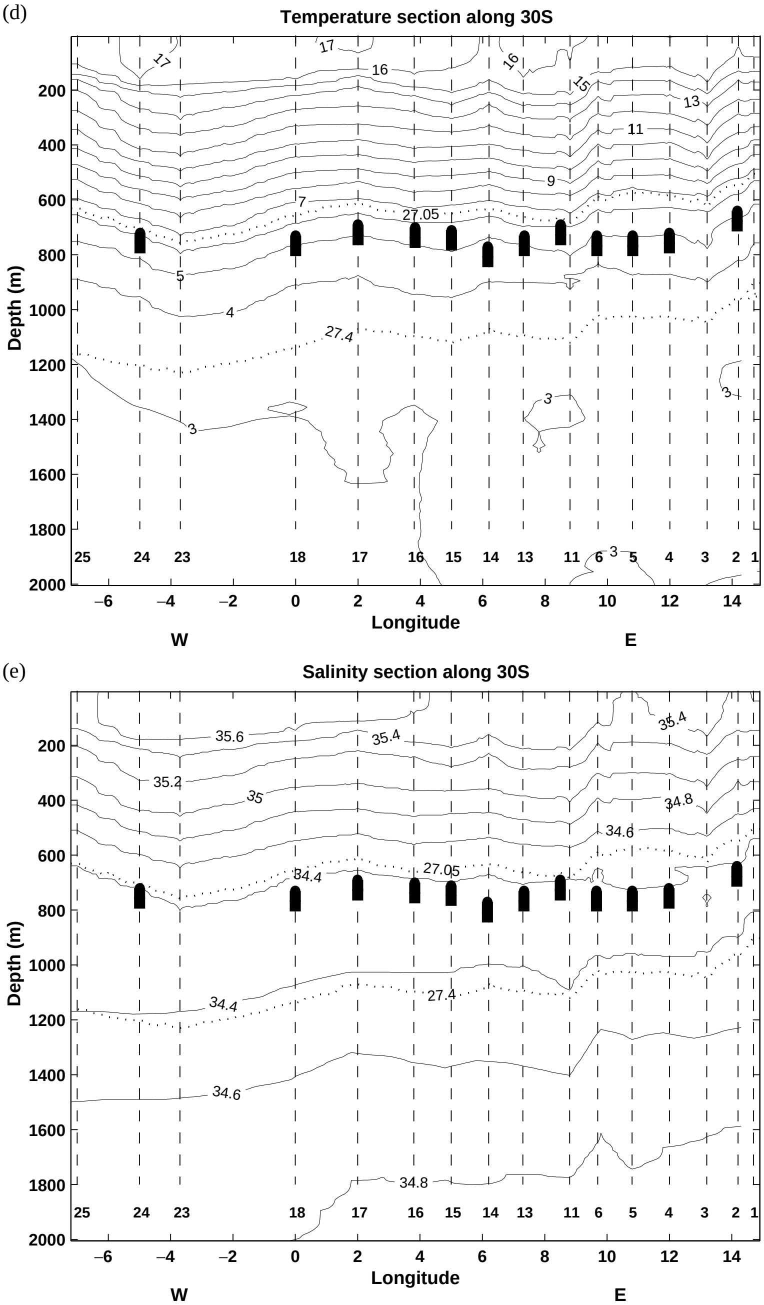


Fig. 2 (*continued*).

(f)

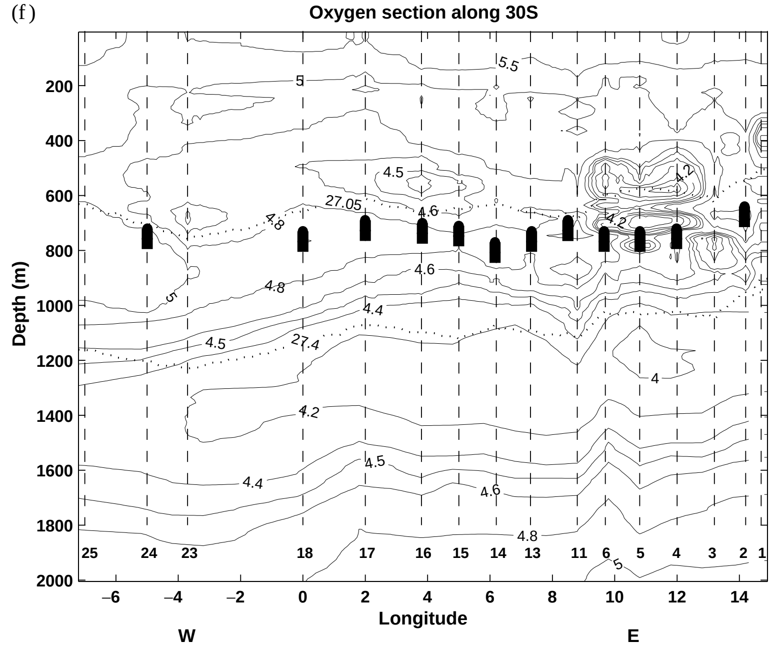


Fig. 2 (*continued*).

velocity was estimated using $\sqrt{\overline{u'u'}/(n-1)}$ where n is the number of mean velocity values in the group.

3. Overview of results

3.1. Initial conditions

Sections of temperature, salinity, oxygen and the equilibrium depths of the tracked floats along 30S and 7W are shown in Fig. 2. The floats equilibrated at temperatures below 6°C in the intermediate water layer characterized by low salinity (<34.4 psu) and high oxygen (>4.4 ml/l) centered between densities 27.05 and 27.40 kg/m^3. The 6 easternmost floats along 30S drifted generally southward during the first few months; the others along 30S drifted generally westward. The floats along 7W drifted generally westward except for the northern 3 floats which drifted eastward. A marked front was located south of 21S between low-salinity (<34.4) and high-oxygen (>4.0 ml/l) AAIW and high-salinity and low-oxygen water characteristic of the tropical South Atlantic north of 21S. This front coincides with the boundary between westward float velocity located mainly south of 21S and eastward velocity mainly north of 21S.

3.2. Displacement vectors

The long-term (18–24 month) float drifts can be seen in the displacement vectors that connect launch locations and surface positions (Fig. 3). All floats in the latitude range 22–35S went generally westward. Virtually all floats launched near 30S in the Cape Basin east of the Walvis Ridge drifted westward across the ridge. All floats launched along 7W (south of 23S) in the Angola Basin west of the Walvis Ridge, drifted westward across the mid-Atlantic Ridge. The longest displacement vectors were from floats launched in the three Agulhas rings. Typical mean velocities were 2–5 cm/s, with the fastest ones being from floats in rings. The three floats launched north of 23S drifted eastward in the Angola Basin.

3.3. Float trajectories

Float trajectories are more complicated than the displacement vectors and reveal several distinctive

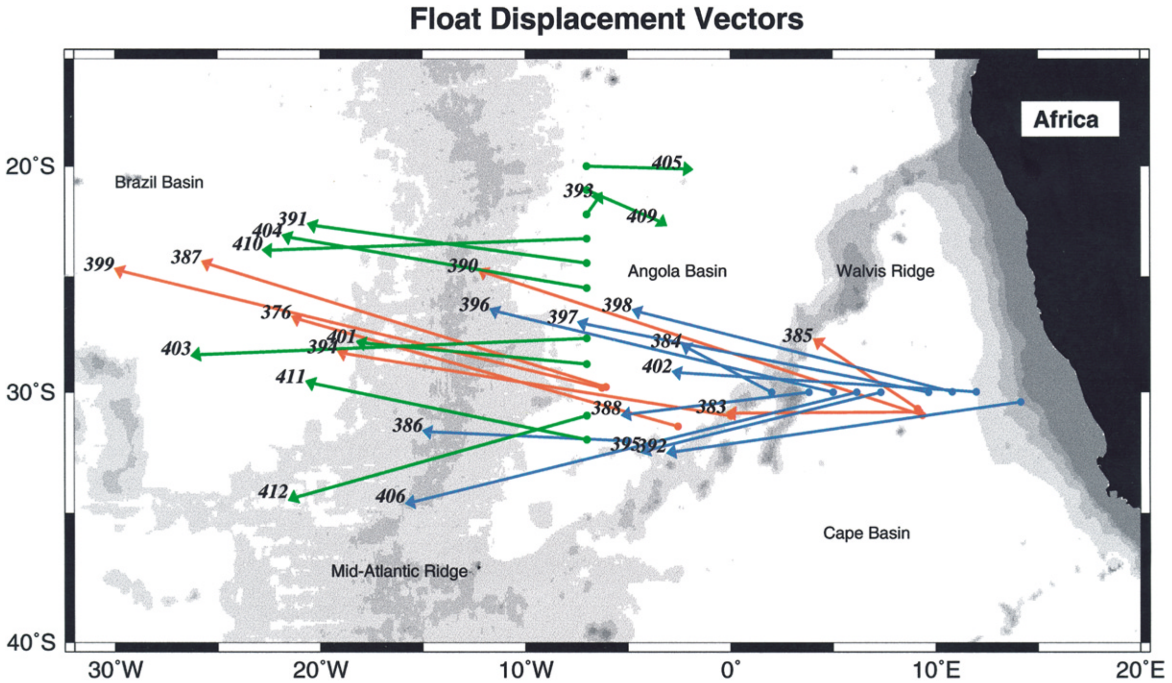


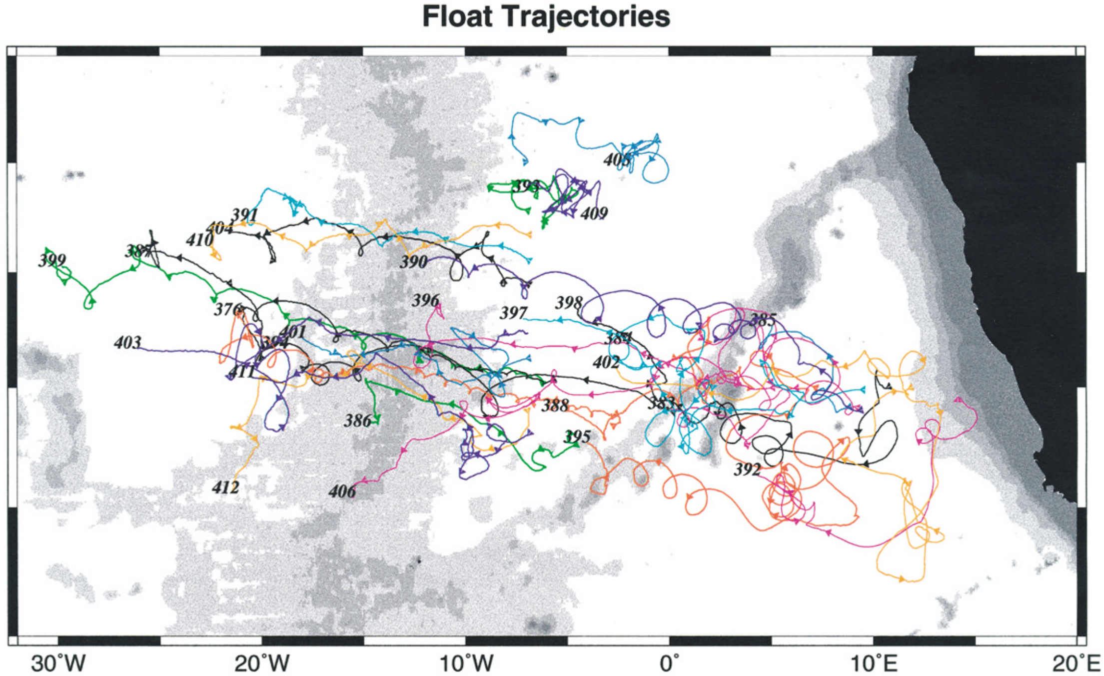
Fig. 3. Overall subsurface displacement vectors of the RAFOS floats from the start to the end of their 18–24-month missions. Blue vectors are displacement vectors of floats launched along the 30S (nominal) line, green vectors are from floats launched along 7W, and red vectors are from floats launched in the three Agulhas Current rings surveyed on the deployment cruise plus float 394, which was entrained into ring 2 shortly after launch. The average initial equilibrium depth (and range) of the floats is 740 m (660–800 m). Shaded regions indicate depths shallower than 1000 m (darkest shading), 2000, 3000, and 4000 m (lightest shading).

patterns (Fig. 4a). To help see the patterns the floats were subdivided based on looping characteristics into two groups, loopers and nonloopers. Floats that looped were interpreted to have been trapped in the swirl velocity of discrete eddies like the three surveyed Agulhas rings. The term "eddy" is used here to refer to both clockwise rotating cyclones and counterclockwise rotating anticyclones. Agulhas rings are warm-core anticyclones. A float that made two or more consecutive loops in the same direction was considered to have been in a discrete eddy. Changing float temperatures helped reveal when a float entered or left a warm-core ring or a cold-core cyclone.

Floats launched along 7W south of 23S that were not looping generally translated westward at around 2 cm/s. These trajectories look much more linear than those over and east of the Walvis Ridge. A complicated tangle of trajectories is located in the Cape Basin, consisting of some long southward displacements counter to the mean flow of the Benguela Current and many loops and partial loops in numerous energetic eddies (Fig. 5). North of 23S three trajectories near 7W show some eastward flow but all three floats there appeared to stagnate, two near 22S 5W (Fig. 4a). After stopping, these three floats appeared to oscillate in a northeast–southwest direction.

Trajectories of floats that looped in eddies are shown in Fig. 4b. Some loops in rapidly translating eddies look more like cusps than complete loops. Fig. 4b shows seven float trajectories in the three long-tracked Agulhas rings, five trajectories in four more anticyclones that are inferred to be Agulhas rings or pieces of rings, and three trajectories in three cyclones. All rings and one cyclone went northwestward; two cyclones went southwestward (Fig. 4c). Fig. 4d shows that the fastest speeds (reaching 40 cm/s) were measured in the Cape Basin usually associated with eddies.

(a)


Float Trajectories
20°S
30°S
40°S
30°W
20°W
10°W
0°
10°E
20°E
408
393
409
391
404
410
387
399
390
396
397
398
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376
401
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403
384
402
411
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383
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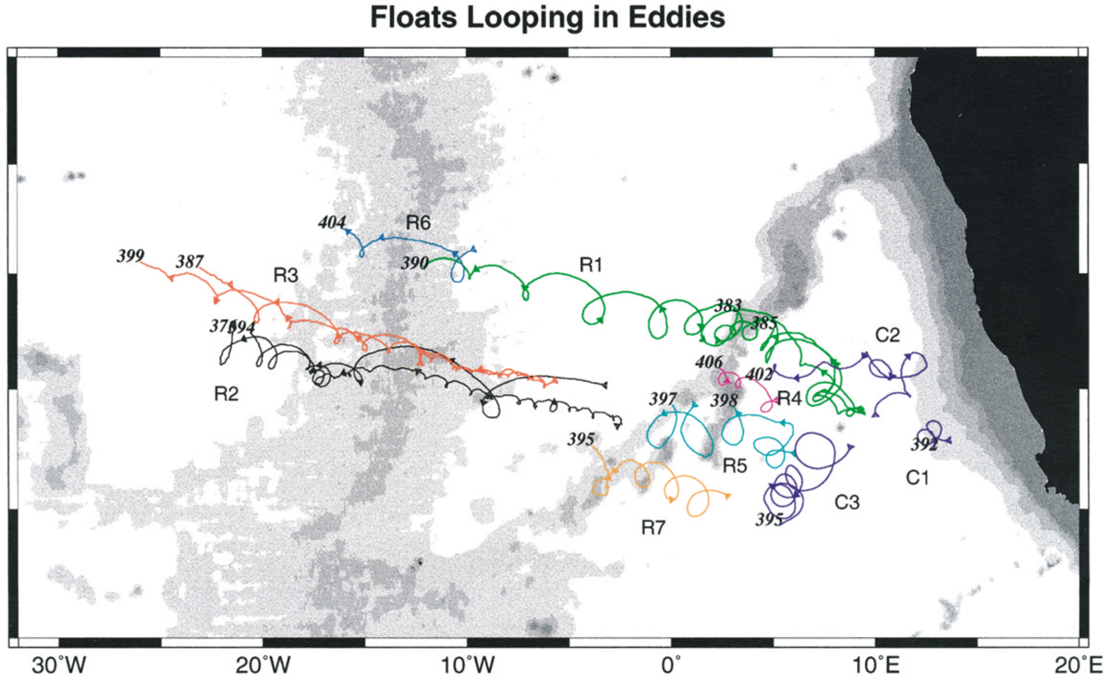
395
392
412
406

(b)


Floats Looping in Eddies
20°S
30°S
40°S
30°W
20°W
10°W
0°
10°E
20°E
404
R6
399
387
390
R1
R3
383
385
376
394
C2
406
402
R2
397
398
R4
395
392
R5
C1
C3
395
R7

Some fast floats (> 16 cm/s) looped in rings 1–3 as they translated northwestward over the mid-Atlantic Ridge.

These general features of the float trajectories are described in further detail below and in the appendix.

4. Rings and cyclones

Fifteen floats looped in 7 Agulhas rings and 3 cyclones (Tables 1 and 2). Many other floats were advected around the periphery of these eddies. All 12 floats launched in the Cape Basin looped or were advected around eddies, which suggests the eddies could be dynamically important. Different eddies are described individually in the appendix based primarily on the float data and supported by analyses of satellite altimetry. Their characteristics are summarized in Tables 1 and 2. Eddies are ordered chronologically starting with the earliest date a float began to loop. Rings 1–3 correspond to the three rings seeded with floats during the cruise.

Ring 1 was the longest tracked of all the eddies; float 390 remained looping during its whole 18-month mission, the only float to do so. The early history of ring 1 is described by Schmid et al. (2003). Rings 2 and 3 were tracked for 13 months.

The other rings and cyclones were detected when a float was entrained into them and started to loop. Five floats looped in four anticyclones that are inferred to be Agulhas rings or pieces of rings (Fig. 4b). The evidence from floats that they were in rings are the ring-like anticyclonic looping, warm float temperatures and the northwestward translation. Further evidence comes from altimetric tracking of these anticyclones by Schouten et al. (2000), and M. Schouten (personal communication) and from the steric height maps of the KAPEX movies. The altimetric tracks of these anticyclones look like typical Agulhas rings and their origin is near the Agulhas ring formation region. Therefore we conclude that the floats were looping in rings but usually for a shorter time than the rings could be tracked by altimetry. This suggests that ring water at 750 m is often exchanged with background water in the Cape Basin.

Three floats looped in three cyclones; other KAPEX floats (Boebel et al., 2003) looped in two of them which provided longer tracking of cyclone 1 and evidence of the merging of two cyclones into cyclone 2 (Fig. 5b). Of the 6 floats that were entrained into and looped in eddies in the Cape Basin, 52% of the looping days were in 3 rings and 48% in 3 cyclones, implying that cyclones occur about as frequently in the Cape Basin as rings. The fastest mean swirl speed of all the eddies was 21 cm/s in cyclone 3 (Table 1), which implies that cyclones can be at least as energetic if not more so than rings (at 750 m), although we need to be cautious since swirl speed varies within an eddy.

The origin of the cyclones is not clear and there may be different origins for different cyclones. Lutjeharms et al. (2003) and Boebel et al. (2003) report that many KAPEX floats launched in the Agulhas Current looped in several Agulhas cyclones that translated southwestward along the northern side of the Agulhas current. Floats looping in these cyclones entered the southern part of the Cape Basin often near 38S 15E. Although it is possible that some of these cyclones could have translated farther north in the Cape Basin like cyclone 2 did, none of the Agulhas

Fig. 4. (a) RAFOS float trajectories. Arrowheads are spaced at 60-day intervals. Shaded areas indicate depths of 1000, 2000, 3000, and 4000 m. (b) Floats looping in seven anticyclonic (counterclockwise rotating) Agulhas rings and three cyclones (clockwise rotating). The longest looping trajectories are those from floats launched in the three rings (rings 1–3) on the deployment cruise; ring 1 trajectories are green, ring 2 black, and ring 3 red. The mean velocity of these three rings is 5.4 cm/s toward 286°. Five floats were entrained for various amounts of time into four other rings, and three floats were entrained into three cyclones (purple). Agulhas rings are formed near 40S 18E in the southeastern corner of the figure. On at least 13 occasions other floats made single or partial loops around the eddies while they were being tracked by these looping floats (rings 1–5, cyclones 1–2). (c) Displacement vectors of the seven Agulhas rings (solid lines) and three cyclones (dashed lines) as tracked by looping floats. Ring 1 vector is bent to indicate where the ring crossed the Walvis Ridge. (d) Trajectories of floats color-coded to show speed. Colors for faster speeds were printed after slower speeds so that some slower speeds cannot be seen. Speeds reached 40 cm/s in the Cape Basin.

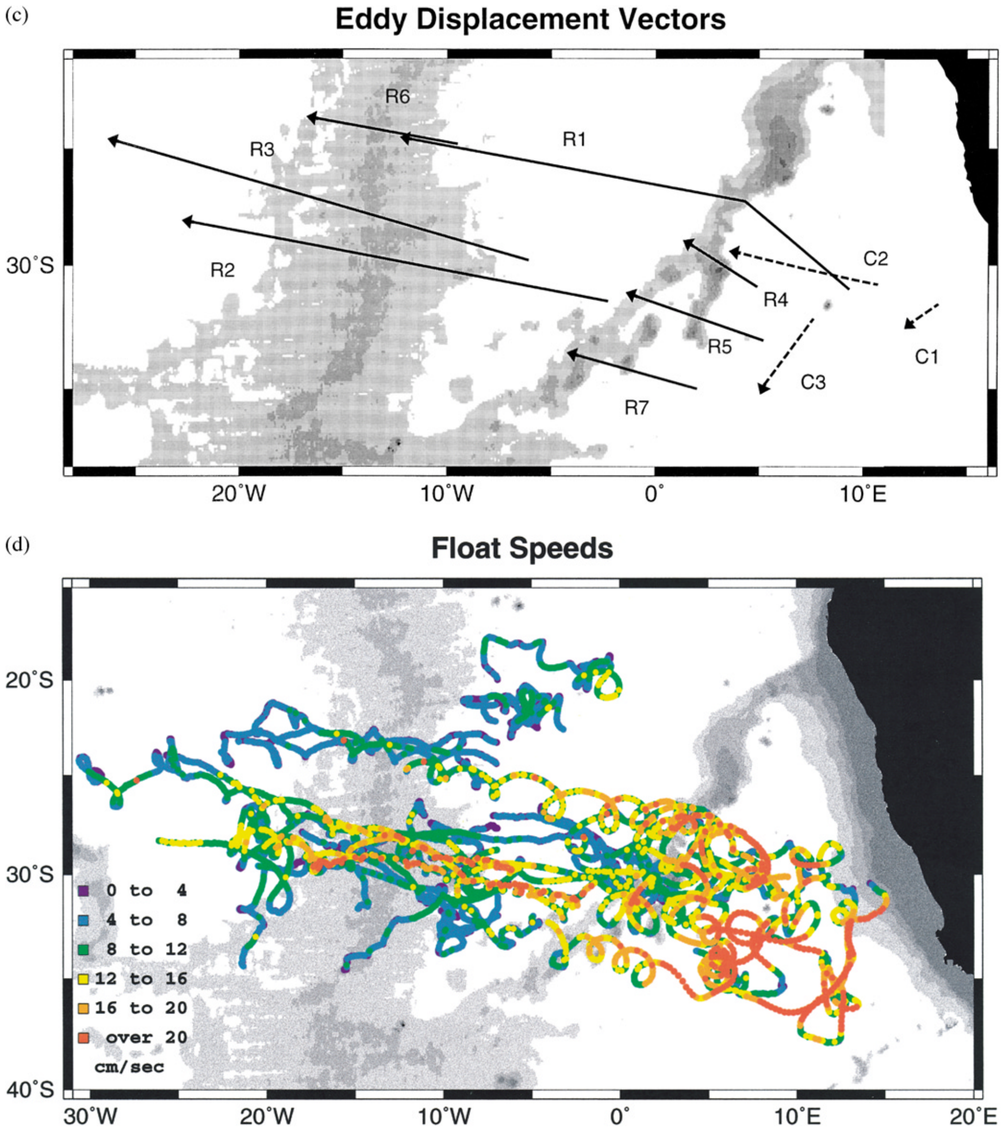


Fig. 4 (*continued*).

cyclones tracked by floats did so. Most cyclones in the Cape Basin appear to have translated southwestward.

A second possible source for cyclones is Agulhas rings which have been observed to interact with topography and break into pieces (Schouten et al., 2000). Roughly half of the rings observed to split into pieces did so near Vema Seamount. It is possible that the rings generated attached cyclones as some models predict (see Matano and Beier, 2003) and as meddies are thought to do (Käse and Zenk, 1996), and that the cyclone and ring could self advect or split apart as separate eddies. The northeastward translation of cyclone 2 could have been due to the self advection of an eddy pair. The numerous energetic rings in the Cape Basin provide a likely source for cyclones.

Table 1
Floats looping in eddies

Agulhas ring	Float	Start Date	Start Lat (S)	Start Long (E)	End Date	End Lat (S)	End Long (E)	Days tracked	Number of loops	Looping period (days)	Mean Swirl speed (cm/s)	Overall diameter (km)
1	390	970909	31.1	9.0	990301	24.6	−11.7	538	11	49	12	200
1	383	970909	31.1	9.0	980406	27.2	2.1	209	3.5	60	13	220
1	385	970909	31.1	9.0	980101	27.3	4.3	113	3	38	13	190
2	376	970914	31.5	−2.6	981026	28.2	−22.2	407	19.5	21	14	150
2	394	971101	30.9	−5.0	980926	28.3	−20.8	329	5	66	10	260
3	399	970917	29.8	−6.1	981023	24.7	−25.8	401	12	33	6	110
3	387	970917	29.8	−6.1	980812	25.1	−23.3	329	(8)	(41)	12	140
4	406	970930	30.9	4.9	971205	29.5	2.2	66	3	22	13	80
5	397	980507	31.7	2.5	980828	31.3	−0.9	113	2	56	13	190
5	398	980118	33.1	5.2	980525	31.8	1.9	127	3	42	14	170
6	404	980522	24.8	−9.5	981123	23.5	−16.2	185	2	92	6	150
7	395	990217	35.0	2.0	990830	33.0	−4.2	194	5	39	12	150
Cyclone												
1	392	971005	31.6	13.6	971123	32.3	12.4	49	2	24	14	80
2	402	980823	30.8	10.7	990525	29.5	4.1	275	5.5	50	9	120
3	395	980917	32.2	7.6	990203	34.8	5.3	139	5	28	21	210

Notes: Dates are estimates of when floats started and ended looping. Eddy numbers are ordered by the earliest date a float started looping. Positions are estimated from the loops. Floats were launched in rings 1–3 (except float 394) and were entrained into other rings and cyclones. Float 390 was looping in ring 1 and float 395 was looping in ring 7 when the floats surfaced. Other floats were detrained from the eddies before the float mission ended. Swirl speed was estimated using the root mean square speeds $\sqrt{\overline{u'u'} + \overline{v'v'}}$ about the mean velocity $\bar{u}, \bar{v}$, assuming that swirl speed is the main contributor to velocity variance. Overall diameter is of the largest loops.

Table 2
Eddy float statistics

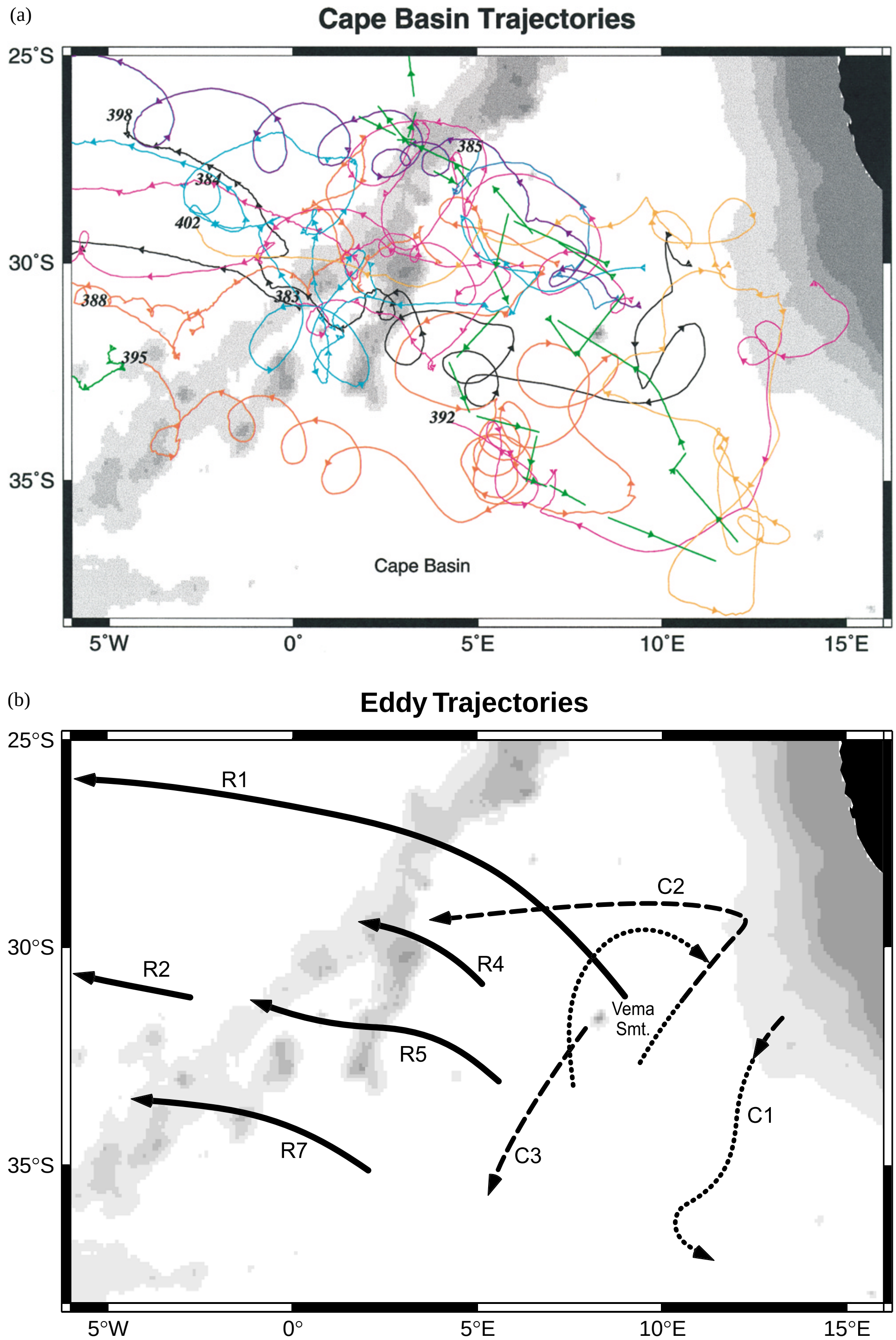
Ring	Float	$\bar{T}$ (°C)	$\bar{P}$ (db)	$\bar{u}$ (cm/s)	$\bar{v}$ (cm/s)	Speed (cm/s)	Dir	EKE (cm^2/s^2)
1	390	6.1	730	−4.6	1.5	4.8	288	72
2	376	7.2	782	−5.3	1.2	5.4	282	96
3	399	6.1	766	−5.7	1.7	5.9	287	20
4	406	5.2	822	−4.6	2.7	5.3	300	91
5	397,8	5.3	806	−2.0	1.0	2.3	297	92
6	404	5.2	764	−4.1	0.7	4.1	279	20
7	395	5.3	778	−3.9	1.6	4.2	292	78
Cyclone								
1	392	4.9	669	−2.0	−1.1	2.3	240	102
2	402	4.5	727	−2.2	0.7	2.3	287	43
3	395	5.0	756	−2.6	−2.8	3.4	223	228

Note: Statistics are based on the longest looping float in each eddy except both floats were used for ring 5 because they looped sequentially. T is temperature, P is pressure, and u and v are mean velocities in the east and north directions, respectively. Eddy kinetic energy is equal to $\frac{1}{2}(\overline{u'u'} + \overline{v'v'})$.

A third possibility is that flow along the eastern boundary (possibly associated with upwelling events) could become unstable and generate cyclones. Cyclone 1 and a few others observed with looping KAPEX floats seem to have originated near the eastern boundary (Boebel et al., 2003). On the other hand cyclone 2 translated toward the boundary before translating away from it which implies that the others observed near the eastern boundary may not have originated there.

5. Benguela current in the Cape basin

A notable result is the southward displacements of the 6 easternmost floats launched along 30S, excluding floats in ring 1 that went northwestward (Figs. 5a, 6). This direction is counter to the mean velocity of the Benguela Current, as seen in Fig. 1. Four of these floats (392, 402, 101, 395) drifted farther south than the southernmost latitude (34.7S) of Africa. Three floats (392, 398, and 395) drifted southward then turned and drifted northwestward in the Benguela Current. Two floats (402, 101) drifted around 800 km south,


(a)
Cape Basin Trajectories
25°S
30°S
35°S
5°W
0°
5°E
10°E
15°E
398
385
384
402
388
383
395
392
Cape Basin
(b)
Eddy Trajectories
25°S
30°S
35°S
R1
C2
R4
R2
R5
Vema
Smt.
C1
R7
C3
5°W
0°
5°E
10°E
15°E

but then they turned northward and passed by their launch locations after 12 months (float 402) and 17 months (float 101). These two imply low-frequency fluctuations of meridional velocity in the Cape Basin. Taken together, the six floats suggest that a large amount of southward flow occurred in the Cape Basin at least during the first several months of the floats' drift and possibly longer. The floats reached their southernmost points after various amounts of time from 3 months (float 392) to 16 months (float 395). All six floats eventually turned more westward in the Benguela Current and its extension as seen in the two-year displacements (Figs. 3, 6). Because of the large-amplitude, low-frequency fluctuations in this region, the six floats do not give a very accurate picture of the mean circulation there.

Low oxygen (<4.0 ml/l) tropical South Atlantic Water was observed at intermediate water depths at CTD stations 4–6, coinciding with floats 402, 398 and 397 that drifted southward. This provides direct evidence that low-oxygen, higher-salinity tropical water was being advected southward in the Cape Basin, possibly to as far south as 38S where float 402 reached and that it was being entrained into the Benguela Current. The complicated float trajectories described below suggest that the path of this water was very complex, not a simple southward advection implied by Fig. 6.

The floats drifted southward in the 1200-km-wide longitude band 2E–15E. Grouping all float velocities in this band (excluding ring 1 floats) and calculating monthly bin average velocities suggest that southward velocity occurred continuously over the first 4 months, with a 4-month average of 3.2 ± 1.6 cm/s where the standard error is based on the 4 monthly mean velocities. The implied southward transport was crudely estimated to be around 19 Sv by multiplying the 3.2 cm/s mean velocity by the 1200 km width and 500 m thickness of intermediate water. The southward transport is reduced to around 1 Sv when the average includes the full two years of the experiment. The implication is that significant amounts of southward transport can occur in the Cape Basin, all of which joins the Benguela Current and goes westward. However, at times the flow reverses direction as implied by the two floats that drifted northward there.

The southward drift of these Cape Basin floats seems to differ from some other data. For example, several other KAPEX floats (Boebel et al., 2003) and several ALACE floats (Davis and Zenk, 2001) drifted northward in the Cape Basin. Some of the best direct measurements of the mean flow along 30S come from the four BEST experiment current meters moored in the Cape Basin from June 1992 to October 1993 near a depth of 500 m (Pillsbury et al., 1994). The analysis of the records (not shown) implies generally mean northwestward velocity for the three moorings located farthest away from the eastern boundary. The current meter at 30.3S 13.2E recorded a mean of 5.6 cm/s toward 295°. The current meter at 30.0S 8.8E recorded a mean of 6.6 cm/s toward 319°. The current meter at 30.0S 5.0E recorded a mean of 2.5 cm/s toward 271°. The progressive vector plot of the 5.0E current meter shows a large southward displacement of around 500 km during three months that is rather similar to the southward displacements of floats 395 and 397 around the western side of ring 1. The other progressive vector plots from 8.8E and 13.2E are more linear towards the northwest and do not reveal any major southward displacements. Therefore the current meters show that the

Fig. 5. (a) Float trajectories in the Cape Basin and near the Walvis Ridge showing the complex motions there. Arrowheads are spaced at 30-day intervals. The monthly submerged displacements of ALFOS float 101 have been added. Much of the southward translation of floats in the Cape Basin appears to be caused by advection in or around numerous eddies there. (b) Trajectories of the rings (solid lines) and cyclones (dashed lines) inferred from looping float trajectories (see Fig. 4b). The dotted portion of cyclone 1 is based on two other KAPEX floats (176, 184, see Boebel et al., 2000) that looped in this cyclone for another four months (until the end of February 1998). The dotted portion of cyclone 2 is inferred from the trajectory of float 402 before its looping became obvious. Two other KAPEX floats (208, 230) looped in a cyclone in the vicinity of Vema Seamount (31.7S, 8.4E). This cyclone merged with cyclone 2 near 30.8S 11.3E in August 1998; KAPEX float 230 and our float 402 looped together in cyclone 2 until the end of float 230's mission in December 1998. Float 402 continued to loop in cyclone 2 until May 1999.

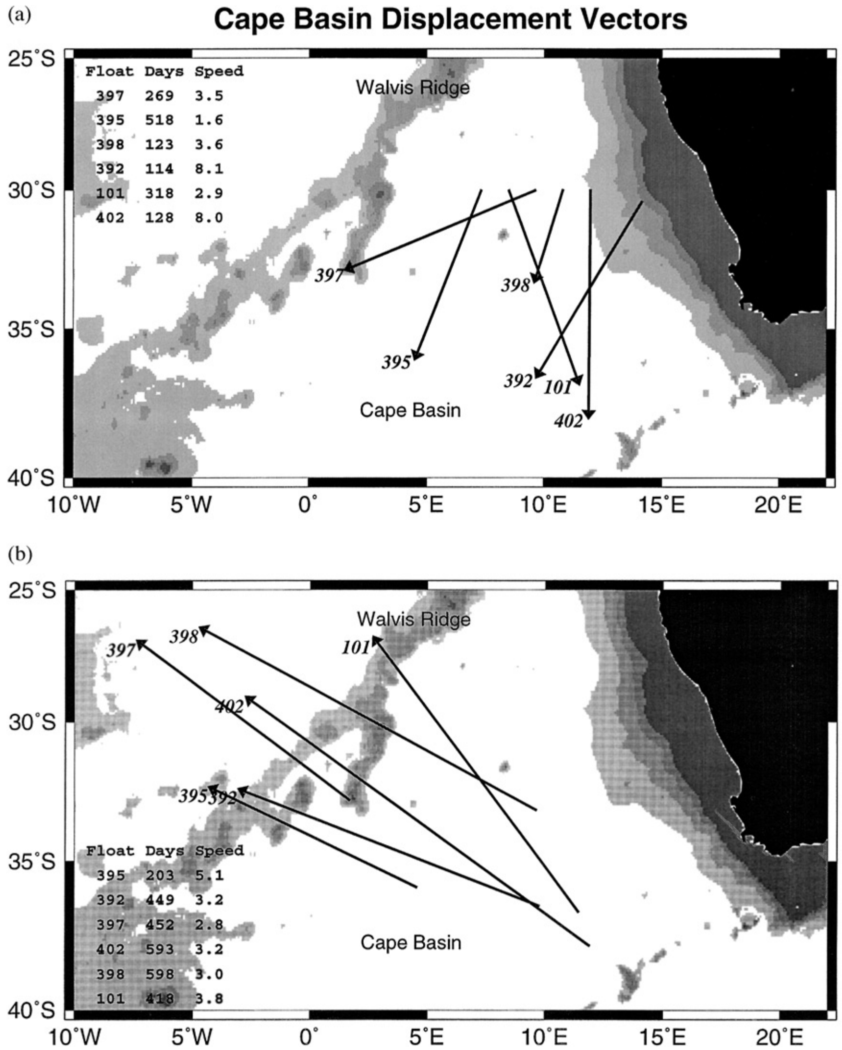


Fig. 6. (a) Southward displacements of the easternmost six floats launched along 30S in the Cape Basin (excluding floats in ring 1 which translated northwestward). Displacement vectors are drawn between the float launch locations and the southernmost point of each trajectory. Duration and mean velocity (cm/s) of the displacements are given in the inset. The southernmost displacement of ALFOS 101 is included even though its subsurface drift was interrupted when the float surfaced for two days every month. The accumulated surface displacement of float 101 on its way south was 95 km northwestward, counter to the vector shown here. The mean southward velocity of the floats calculated using the 6 average southward components is 4.0 ± 1.2 cm/s. (b) Displacement vectors between the southernmost points of each trajectory shown in Fig. 6a and the positions at the end of the two-year float missions. Duration and mean velocity are given in the inset. The mean velocity of the 6 floats is 3.4 ± 0.3 cm/s toward 303°.

mean 500 m flow near 30S is westward to northwestward at 2–6 cm/s but that occasional large southward displacements can occur possibly related to rings.

The current meter velocity and temperature time series display what looks like a succession of mesoscale fluctuations, some warm and some cold, that could be interpreted to be a series of rings and cyclones passing the moorings. The records suggest roughly equal numbers of rings and cyclones. Typical velocity fluctuations are around 20 cm/s, reaching over

30 cm/s, and dominant time scales are several months.

The floats in the Cape Basin also reveal a preponderance of eddies there. Our floats and the other KAPEX floats looped in numerous energetic rings and cyclones, giving the impression that the Basin is almost filled with them (Boebel et al., 2003; Schmid et al., 2003). Many floats seem to be exchanged from one eddy to the next at short intervals.

The floats looping in rings and cyclones, which are described individually in the appendix, are summarized here in the context of southward advection. First, all 12 floats launched in the Cape Basin either looped in eddies or were advected around the periphery of eddies that were being tracked with looping floats. Floats 383, 385, and 390 were intentionally launched in ring 1, so it is not surprising they looped. What seems surprising is that all the other floats also were advected by eddies. Four floats had multiple contacts with eddies: float 395 was advected around the periphery of rings 1 and 5 and looped in cyclone 3 and ring 7; float 101 was advected around rings 1 and 5 and cyclone 2; float 402 was advected far south by cyclone 1 (along with float 392) and north by cyclone 2; float 397 was advected around ring 1 and looped in ring 5. Much if not most of the southward displacements of floats in the Cape Basin appears to be due to floats being advected southward by eddies—floats 392 and 402 in cyclone 1 and float 395 around ring 5 and in cyclone 3 are the best examples.

Could the southward displacements of the Cape Basin floats have been partially caused by their dispersion up the eddy kinetic gradient, which reaches a peak in the region where Agulhas rings form? Davis (1991) described how particles that pass through a point tend to diffuse by eddy dispersion toward regions of the most vigorous eddy dispersion, resulting in an apparent velocity or bias in that direction, $U_{\text{bias}} = \partial K/\partial X$ where K is the eddy diffusivity. We estimated U_{bias} from $K = \langle \overline{u'^2} \rangle T$ where $\langle \overline{u'^2} \rangle$ is the velocity variance ensemble-averaged over all particles and T is the integral time scale of the Lagrangian autocorrelation function (see Spall et al., 1993) which is around 8 days for the Cape Basin floats. Velocity variance in the meridional direction, which was estimated by grouping KAPEX float velocities in 5° latitudinal bins, increased from around $\overline{v'^2} \sim 40\ \text{cm}^2/\text{s}$ between 25S–30S to $\overline{v'^2} \sim 440\ \text{cm}^2/\text{s}^2$ between 35S and 40S. Using these values, the velocity bias for our Cape Basin floats would be around $v = -2.5$ cm/s. This is approximately the same size as the southward velocity of floats in the Cape Basin, which suggests that southward eddy dispersion could have been important there. However, the whole cluster of six floats translated southward during the first four months, which is more indicative of advection by the mean flow than dispersion. If meridional dispersion were dominant, we would expect some floats to have dispersed north of their launch locations. Only some minor ($\sim$100 km) excursions north of 30S were observed as compared to the much larger southward displacements (Figs. 5a and 6a). In addition, the trajectories of floats that were trapped and looped in eddies look very different from classical eddy dispersion.

After reaching their southernmost points the Cape Basin floats turned and drifted on average northwestward during the remaining part of their mission (Fig. 6b). This is down the gradient of eddy kinetic energy and counter to the bias velocity of floats dispersing from a point in this region. The implication is that during this part of their drift the bias velocity was significantly smaller than the advection velocity by the mean currents. In the future larger numbers of KAPEX and ALACE floats with their more even geographical distribution in the Cape Basin will be used to map the velocity field there. This should reduce the bias velocity from that estimated above using only the floats launched along 30S.

6. Walvis ridge

The Walvis ridge separates the 5000 m deep, energetic, eddy-rich Cape Basin in the east from the 5000 m deep, less energetic Angola Basin to the west. The ridge extends diagonally from the west coast of Africa near 20S 10E southwestward toward 35S 5W. Intermediate Water that flows in the Benguela Current must pass over the ridge which in many places rises above 750 m and looks like it could be a significant barrier (Fig. 7). Two wide deep passes cut the ridge, one between 26.5S and 30.0S where ring 1 crossed over the ridge, and the other north of around 22S where no floats and few rings tracked by altimetry crossed over. The other floats and rings crossed over the ridge between about 26S–34S, many floats between 30S–34S, which has spots shallower than 1000 m. Many rings tracked by altimetry also crossed over the ridge in the shallow region 30S–35S.

The eddies in the Cape Basin appear to be important in advecting floats northwestward across the Walvis Ridge. Figs. 4b and 5a show the northwestward translation of eight floats (including three in ring 1) in four rings that

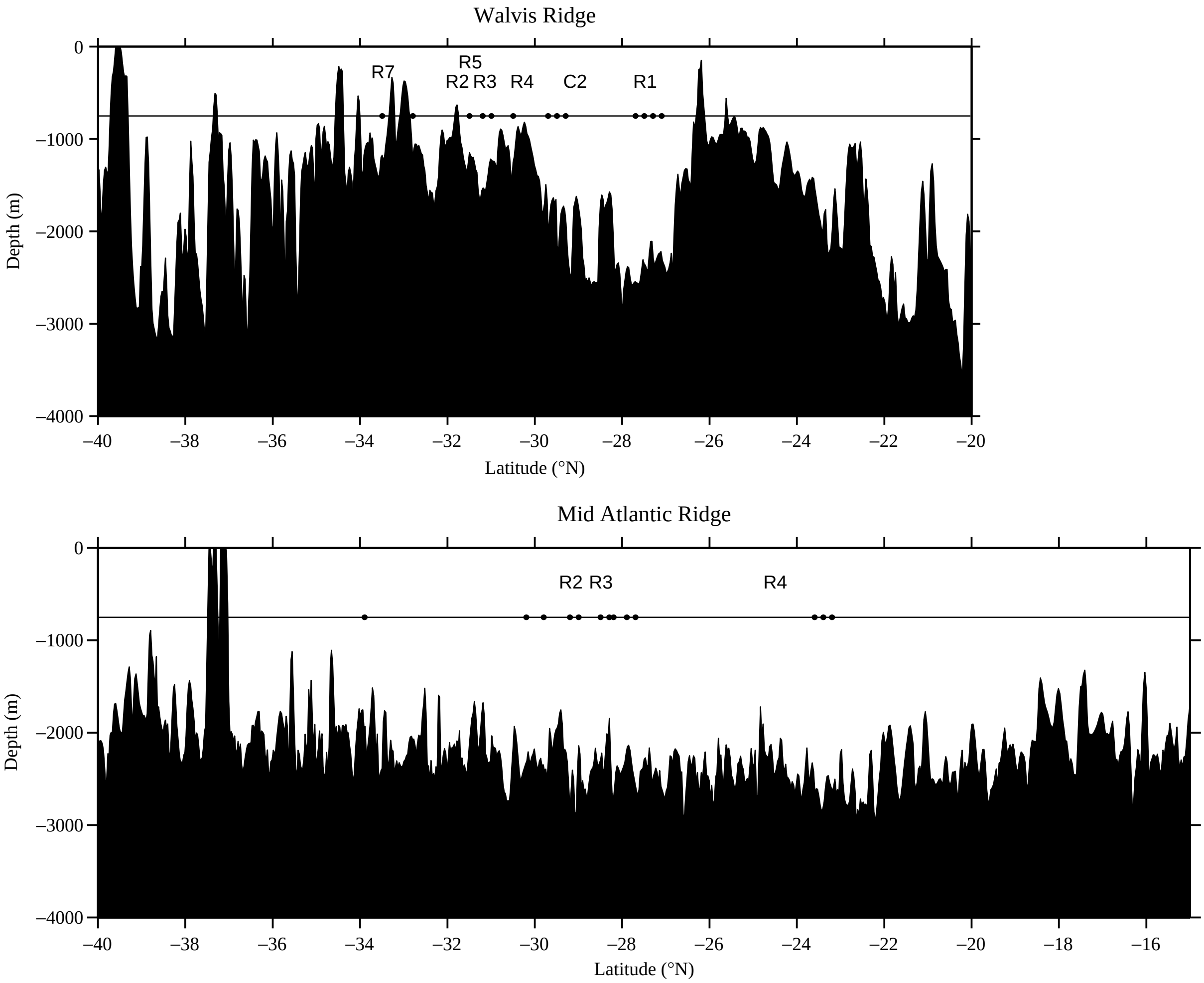


Fig. 7. North–south profiles of sea floor topography showing minimum depths over the Walvis Ridge and the mid-Atlantic Ridge. The light line indicates the level of intermediate water and floats near 750 m. The approximate latitudes where floats drifted westward over the ridges are shown by small dots, and where the rings (R) crossed the ridges by labels R1, R2, etc. The latitudes of rings 2 and 3 over the Walvis Ridge were estimated using satellite altimetry. The largest loops in the rings are around 200 km in diameter or roughly 2 degrees in latitude. The swirl velocity in rings extends well below the 750 m depth. Depth profiles were created by plotting the shallowest depth at each latitude using ETOPO2 data (Smith and Sandwell, 1997) in meridional swaths bounded by 10E and 10W for the Walvis Ridge and 10W and 20W for the mid-Atlantic Ridge.

crossed over the ridge and one cyclone that translated up to the ridge. Of the 9 Cape Basin floats that drifted westward across the ridge (excluding float 392 and ALFOS float 101 which did not provide eddy resolution) all but two (388, 396) were clearly looping in rings or the cyclone near the ridge. The other two (388, 396) looked like they were looping in the periphery of ring 4 when it crossed the ridge and thus were probably advected across by a ring. (The data are not conclusive about this.) Therefore the best chance a Cape Basin float had of crossing the Walvis Ridge was in or associated with an eddy, especially rings since they translated northwestward. The float trajectories imply that most of the flow of intermediate water across the Walvis Ridge was associated with rings. This conclusion is in accord with other KAPEX floats launched south of 30S in the Cape Basin; the only one of these floats to cross over the Walvis Ridge was looping in an Agulhas ring (Boebel et al., 2003).

Only two floats (390 in ring 1, 395 in ring 7) continued to loop in the rings after they crossed the ridge. The other floats all stopped looping, implying that the ridge disrupted the ring swirl velocity at 750 m. Ring 1, which crossed the ridge in the deep (> 1500 m) pass near 27.5S, was disrupted by the ridge in two ways. First the ring translation velocity slowed to around 3 cm/s over and just downstream (within 300 km) of the ridge. Second float 383 was detrained from ring 1 and stopped looping near the ridge, and the loops of float 390 decreased to small diameter (70 km) over the ridge and back to large diameter (200 km) afterward. Rings that crossed the ridge in shallow regions were probably more severely disrupted than ring 1.

The numerous times that floats were entrained into eddies and detrained from them in the Cape Basin suggest that intermediate water does not remain trapped in the eddies very long, but instead is exchanged with water from other eddies and outside of eddies. This is presumably because the rings translate fast, interact intensely with other eddies, split into pieces and, perhaps, generate cyclones. Ring tracking by altimetry shows that most of the decrease in dynamic height in rings occurs while they are in the Cape Basin and that 1/3 of rings totally disintegrate there (Byrne et al., 1995; Schouten et al., 2000). This suggests that much of the intermediate water in rings is expelled from them in this region. Therefore, Agulhas rings that cross the Walvis Ridge transport a mixture of intermediate water from the Agulhas current, from the South Atlantic Current, and from the tropical region of the Atlantic.

Why did virtually all the floats cross over the Walvis Ridge associated with the four rings and one cyclone and none (or very few) outside of eddies? A possible explanation is that the ridge is less of a barrier to water swirling in Agulhas rings than outside of them. This may be because rings consistently translate northwestward over the ridge and their rapid $\sim$15 cm/s swirl speeds at 750 m (partially) trap water in the rings (Flierl, 1981) and advect it over the ridge. Although cyclone 2 was not observed to cross over the ridge, float 402 looping in it did cross the ridge when cyclone 2 collided with the ridge. The implication is that water that had been in cyclone 2 crossed the ridge.

Schouten et al. (2000) estimate that roughly 5 rings form per year and that some of these split generating something like 8 rings per year in the Cape Basin. If all 8 rings cross the Walvis Ridge plus water from two cyclones, this makes 10 eddies per year. The 10 would transport roughly 5 Sv ($1\text{Sv} = 10^6\ \text{m}^3/\text{s}$) of intermediate water, estimated by assuming each eddy is 200 km in diameter (the size of the largest float loops, Table 1) and advects a 500 m thick layer of water. The 5 Sv are only about a third of the 15 Sv of intermediate water estimated (below) for the Benguela extension. This discrepancy suggests that there could be significant mean flow outside of rings crossing the ridge, but this is not obvious in the float trajectories. Another possibility is that the effective trapping diameter of the eddies is larger than the 200 km diameter of largest float loops in accord with the overall size of the rings. The discrepancy might have been caused by the relatively few floats in the Cape Basin having been entrained into an unusually large number of eddies. Perhaps numerical model experiments will help resolve this issue.

7. Benguela current extension

Ten RAFOS floats were tracked starting near 7W. The seven floats launched between 23S–32S all went westward and crossed over the mid-Atlantic Ridge in the Benguela Current extension (Figs. 3, 4). The average velocity of these floats over two years was $\bar{u} = -2.3 \pm 0.2$ cm/s, $\bar{v} = 0.1 \pm 0.1$ cm/s, where the mean and standard errors were estimated from the seven mean velocity values of the individual floats, assuming each to be an independent sample of the flow (Table 3). The northern three floats (410, 391, 404) of this group launched between 23S and 26S are similar in that they translated fairly steadily westward and oscillated meridionally $\sim$100–200 km, with a period of $\sim$120 days. Float 390 in ring 1 entered this group of trajectories near the end of the experiment, and two loops of float 404 in ring 6 were located there too.

The four floats (403, 401, 412, 411) launched farther south along 7W (27S–32S) had somewhat more convoluted trajectories on the eastern and western flanks of the mid-Atlantic Ridge, and the meridional excursions were larger than those of floats located farther north (Fig. 4). Three floats in this southern cluster (401, 411, 403) seemed to slow considerably and become stalled for long periods of time. For example floats 401 and 411 launched near 29S and 32S both remained near 9W during the first year and then drifted westward during the second year. After crossing the mid-Atlantic Ridge float 403 slowed near 29S 20W during the second year. The variations in velocity of the Benguela extension floats are probably due to a combination of westward translating Agulhas rings, westward propagating Rossby waves (Chelton and Schlax, 1996; Le Traon and Minster, 1993; Witter and Gordon, 1999), and interannual variations of the large-scale circulation (Witter and Gordon, 1999), all of which have been observed with altimetry.

Floats 387, 399, 394 and 376 in rings 2 and 3 drifted westward in the southern cluster adding to the band of trajectories between 27S–31S (Fig. 4). These floats were detrained from the rings west of the ridge, one of them (399) reached 32W, farther west than any other float. Four other floats (397, 396, 386, 406) launched along 30S (nominal) drifted westward and their trajectories merged with the 7W trajectories. A gap between the northern and southern groups of trajectories was caused partially by the launch of an ALFOS float (not tracked acoustically) near 26.5S and 7W. Two floats (397, 398) entered the region of the gap at

Table 3
Statistics of floats launched at 7W in the Benguela extension region

Float	Launch latitude (°S)	$\bar{T}$ (°C)	$\bar{P}$ (db)	$\bar{u}$ (cm/s)	$\bar{v}$ (cm/s)	$\overline{u'u'}$ (cm^2/s^2)	$\overline{v'v'}$ (cm^2/s^2)	$\overline{u'v'}$ (cm^2/s^2)	EKE (cm^2/s^2)
405	20.0	4.7	736	0.8±1.2	−0.0±1.2	16.6	15.5	3.7	16.1
409	21.1	5.2	656	0.6±0.9	−0.3±1.1	8.9	12.4	3.3	10.6
393	22.2	4.8	725	0.1±0.9	0.1±0.8	8.2	6.2	0.1	7.2
410	23.3	5.5	686	−2.6±0.6	−0.1±0.7	3.4	5.1	−0.9	4.3
391	24.4	5.1	691	−2.2±0.7	0.3±0.6	6.0	4.4	−1.1	5.2
404	25.5	5.1	757	−2.4±0.9	0.4 ± 1.0	8.7	10.3	−0.2	9.5
403	27.7	5.4	752	−3.0±1.3	−0.1±1.3	2.0	17.7	0.9	10.0
401	28.8	5.6	739	−1.7±1.0	0.2±0.8	9.9	8.0	−2.7	9.0
412	31.0	5.7	719	−2.2±0.8	−0.6±0.9	7.8	9.3	−1.6	8.5
411	32.0	6.2	715	−2.1±1.0	0.4±1.0	10.4	9.9	−0.7	10.1

Notes: These floats were tracked for two years. The gap between floats 393 and 410 marks the boundary between (generally) eastward flow in the north and westward flow in the south in the Benguela extension. The standard errors given for the mean velocities were estimated from $[(2T\overline{u'u'}/N)]^{1/2}$ where $\overline{u'u'}$ is the variance about the mean, $\bar{u}$, (for example), N is the number of daily velocity values and $T = 30$ days is the estimate of the integral time scale of the Lagrangian autocorrelation function of the Benguela extension floats. ALFOS float 102 was deployed near 26.6S 7.0W but was not tracked acoustically (and died after 150 days) so is not included here.

the end of the experiment, so the gap is interpreted to be a gap in data not a gap in the westward flow. Two floats (406, 412) translated southwestward during the last 5–6 months and crossed south of 34S toward the central region of the subtropical gyre near 35S. Three floats (405, 409, 393) launched north of 22S drifted eastward marking the northern boundary of the Benguela extension.

A meridional profile of velocity in the Benguela extension was obtained by grouping and averaging individual float velocities in 1° wide latitude bands extending from 0W–32W (Figs. 8, 9). Floats looping in rings were excluded because they were intentionally seeded in the rings (except for float 394 which was entrained) and because they translated faster than nonlooping floats. The fastest westward velocity was 3.4 ± 0.8 cm/s at 30S. The mean velocity of the 14 bins, which contained mean westward components (22S–35S) was $\bar{u} = -1.8 \pm 0.2$ cm/s, $\bar{v} = -0.1 \pm 0.1$ cm/s, where the standard errors were estimated from the 14 band-averaged velocity components. The mean westward velocity was somewhat smaller than that calculated from the seven 7W floats because a larger set of floats was used including those launched along 30S, because the trajectory of ring 6 was excluded, and because some of the other ring floats were slow after they came out of the rings.

The meridional distribution of the velocities show that the Benguela extension is located from 22S to 35S and flows on average directly westward.

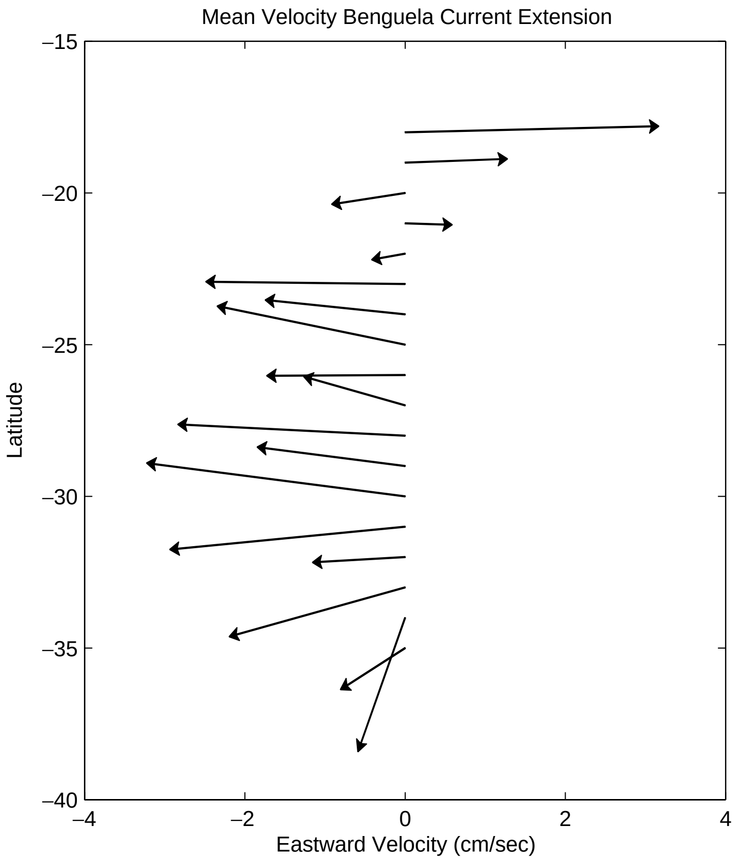


Fig. 8. Mean velocities in the Benguela Current extension region over the mid-Atlantic Ridge. Nonlooping float velocities were grouped and averaged in 1° latitude bands located between 0W and 32W. Looping floats in rings were excluded because they translated significantly faster than floats outside of rings. The Benguela extension is considered to be the region of westward velocities ~2 cm/s extending from 22S–35S.

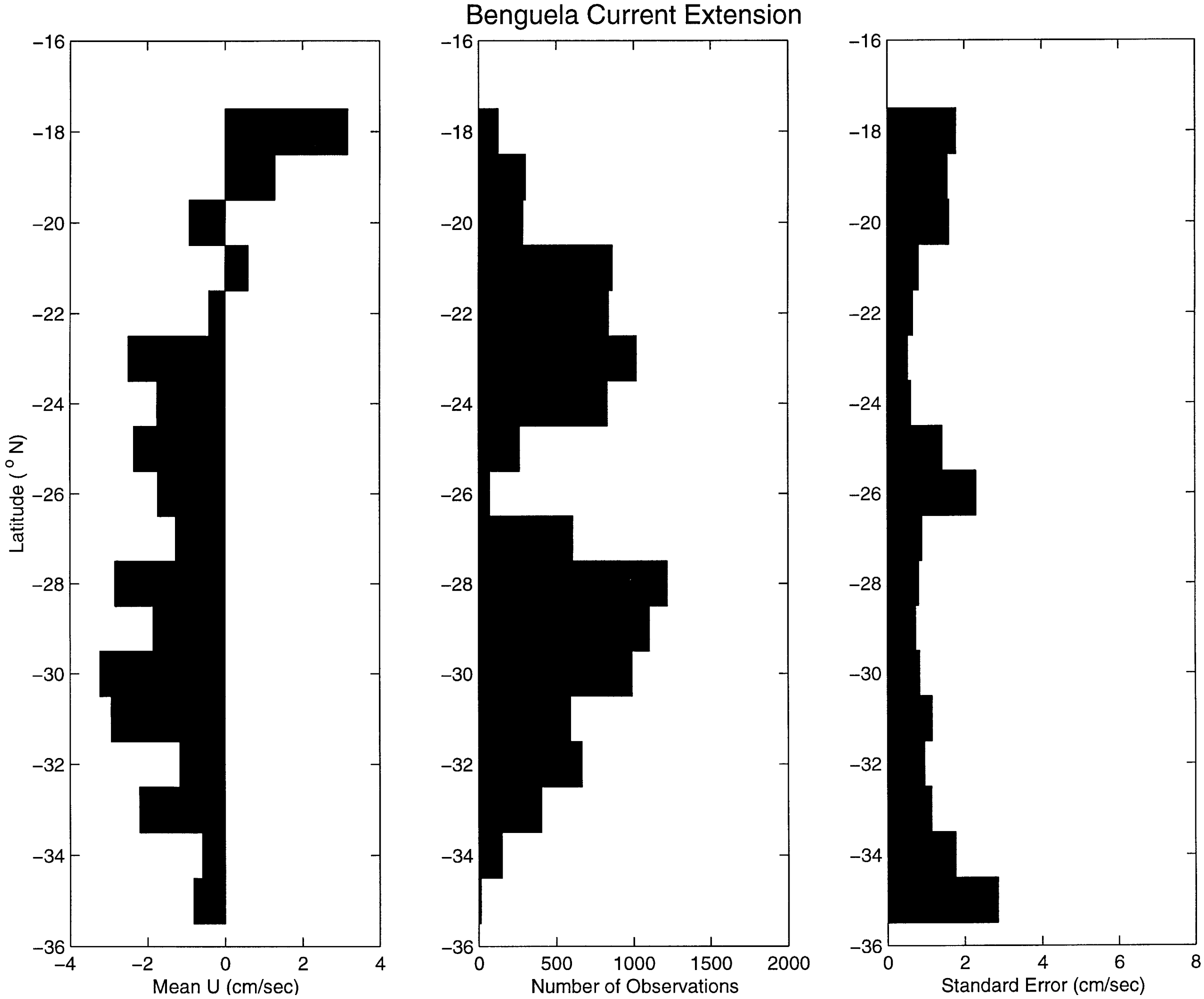


Fig. 9. Meridional profile of mean zonal velocity, number of observations and estimated standard errors in the Benguela Current extension region based on grouping nonlooping float velocities in 1° latitudinal bands (0W–32W). Eddy kinetic energy along the profile is approximately 10 cm^2/s^2. Standard errors in the bands, estimated as in Table 3, are generally smaller than the mean velocities in the Benguela extension, which is considered to be the band of westward velocities extending from 22S to 35S. The mean zonal velocity of the Benguela extension is 1.8 ± 0.2 cm/s obtained by averaging the 14 band-averaged westward velocities (22S–35S). The standard error (± 0.2 cm/s) was estimated by assuming each of the 14 band-averaged velocities was independent.

A divergence of vectors is apparent with those north of the center inclined slightly north of west and those south of the center inclined south of west. This could be due to real divergence of the Benguela extension, with some flow diverging into the gyre interior over the mid-Atlantic Ridge and flow diverging northward before reaching the western boundary. Because the floats along 7W were all launched between 20S and 32S, it is to be expected that some floats would tend to disperse northward and southward away from the cluster center by eddy dispersion. However, the vectors north of the extension center show very little meridional divergence, especially when those north of 22S are included, and the gap in float concentration near 26N remained throughout the experiment. Since eddy kinetic energy is low ~ 10 cm^2/s^2 and nearly constant across the extension, meridional eddy dispersion does not appear to be very important for these floats.

Rings 1–3 translated in a direction north of west in the general area where background floats had a more westward velocity. The two long ring trajectories (rings 2 and 3) had an average velocity of $\bar{u} = -5.5$, $\bar{v} = 1.4$ cm/s (Table 2) compared to the average of the background nonlooping floats in the extension region $\bar{u} = -1.8 \pm 0.2$ cm/s, $\bar{v} = -0.1 \pm 0.1$ cm/s, or average of the seven 7W floats $\bar{u} = -2.3 \pm 0.2$ cm/s, $\bar{v} = 0.1 \pm 0.1$ cm/s. Therefore the rings' velocity relative to the 750 m background velocity field is around $u = -3.5 \pm 0.4$ cm/s, $v = 1.4 \pm 0.2$ cm/s which is interpreted to be the self advection velocity of the two rings. The standard errors were estimated by combining the standard errors of the mean 7W float velocities and the standard errors of the mean ring velocities estimated from rings 1–3. Over the 13-month period that rings 2 and 3 were tracked in the extension region they translated around 450 km northward ($\sim 4^\circ$ of latitude) across the primarily westward Benguela extension. This is around 31% of the width of the extension (22S–35S). The background flow above 750 m could have been faster toward the northwest, and therefore the upper part of the rings could have translated slower with respect to the background velocity field there. However, surface drifters in the Benguela extension region (not shown) drifted primarily westward at 3 cm/s, so the near surface ring water also translated northward relative to the background surface velocity field. The implication is that the rings transported water trapped by their swirl velocity northward across the mean axes of the Benguela extension and released this water when the rings further decayed in the western Atlantic. Some rings tracked by altimetry translated more westward in the extension region, and they would have transported less water northward than rings 1–3 and 6 and many others that translated northwestward in the extension.

7.1. Transport

The transport of intermediate water in the Benguela extension was estimated by multiplying the 1° band-average velocity (nonlooping floats) by the 14° width (22S–35S) of the extension and by the (approximate) 500 m thickness of intermediate water (Schmid et al., 2000). The thickness varies depending on the limits chosen for intermediate water and the geographical location. The estimated transport is 14.1 ± 1.8 Sv. When the band-average velocities were multiplied by the distance between the 27.05 and 27.40 density surfaces as measured by CTD along 7W (Fig. 2), the estimated transport amounts to around 12.8 ± 1.7 Sv. These represent the transport of the background flow field without including the transport carried by rings. The transport of the three rings per year (Schouten et al., 2000) that translated at 5.5 cm/s over the mid-Atlantic Ridge, each one assumed to be 200 km in diameter (based on largest float loops) and carrying a 500 m thick cylinder of intermediate water, is 1.5 Sv. The amount of transport to be added to the background is 2/3 of this and is due to the excess westward ring velocity relative to the background velocity. The combined westward transport of background flow field and three rings per year is 15.0 Sv (of which 1.5 Sv is due to the rings) for the 500 m thick layer or 13.7 Sv for the layer between 27.05 and 27.40 density surfaces.

Additional transport by rings is deposited in the Cape Basin by the 5–6 rings per year that form there (Goni et al., 1997; Schouten et al., 2000). All the rings decay significantly in the Cape Basin; one-third totally dissipate there and never reach the Walvis Ridge (Schouten et al., 2000). Therefore, much of the intermediate water that was originally trapped in rings when they formed left the rings and eventually became background water in the Benguela extension. Thus the contribution to the Benguela extension transport by rings is much larger than the 1.5 Sv estimated for the three rings per year that cross the mid-Atlantic Ridge, perhaps two to three times that amount. Additional transport into the Cape Basin is provided by Agulhas cyclones and other contributions from the Agulhas Current, the total contribution from the Indian Ocean perhaps reaching half the transport of the Benguela extension.

This value 14–15 Sv of westward transport of intermediate water is significant because it is based on long-term direct measurements (and therefore is not dependent on an assumed level of no motion) and because the full width of the Benguela extension was measured reaching from the eastward counterflow on the north to the center of the subtropical gyre on the south. The 15 Sv agrees well with the transport found by Boebel et al. (1999b) farther west by also using floats. They assumed a thickness of 400 m and estimated 12 ± 3 Sv which, adjusting for our 500 m thickness, gives 15 Sv. The western floats clearly divided near the western boundary near 28S, suggesting that around one-third or ~5 Sv of the westward transport turns north in a narrow (~30 km) swift (~30 cm/s) intermediate depth western boundary current (Boebel et al., 1999b; Ollitrault, personal communication). The rest ~10 Sv flow southward in the Brazil Current around the western side of the subtropical gyre. Additional floats are presently being tracked in the western South Atlantic (Ollitrault, personal communication), which will help refine the estimates of transport and pathways there.

7.2. Geostrophic velocity

A vertical profile of zonal geostrophic velocity was calculated for the Benguela extension (Fig. 10) from the CTD data collected during the float deployment cruise. The profile was shifted to match the mean float velocity located near 750 m (Fig. 9). Therefore the profile represents absolute velocity at least to the extent it is legitimate to combine a velocity profile from a CTD section and a two-year-average float velocity. The velocity of the Benguela extension was all westward and had a subsurface maximum of 2.2 cm/s centered near 500 m and a surface minimum of around 0.9 cm/s. The surface geostrophic velocity is smaller than that obtained from surface drifters (~3 cm/s) due to westward Ekman velocity and some drifters looping in westward translating eddies. The geostrophic velocity varied by only 1.3 cm/s over 2000 m, which suggests that the Benguela extension is only weakly baroclinic like the Benguela Current is as seen in the velocity profile across 30S (nominal) (Fig. 10). The small shear in the upper 1000 m suggests that the mean float velocity at 750 m is nearly equal to the average velocity over the upper 1000 m where the Agulhas rings were located. The estimated westward volume transport in the upper 1000 m (22S–33S) is around 25 Sv and between 18S–33S is 29 Sv, if the westward transport above 500 m between 18S and 22S (Fig. 10) is included.

7.3. Mid-Atlantic ridge

The crest of the mid-Atlantic ridge rises up to around 2000 m between the Angola and Brazil Basins both of which are around 5000 m deep (Fig. 7). The floats appeared to speed up slightly as they crossed over the mid-Atlantic ridge. This could be a result of the several floats that slowed or stalled for long periods of time over the flanks of the ridge but not over the ridge crest. The increase of velocity was estimated by calculating the mean velocity of each float over the ridge (11W–16W) and on either side (7W–11W, 16W–26W). The results suggest that the seven 7W floats drifted at 4.0 ± 0.7 cm/s over the ridge and at 2.4 ± 0.3 cm/s on the two sides. Thus the increase of westward velocity was 1.7 ± 0.8 cm/s over the ridge. The mean and standard error were estimated from the mean float velocities over the ridge and the 14 float velocities east and west of the ridge. Rings 2 and 3 also appeared to translate faster over the ridge by around 1.3 ± 0.6 cm/s consistent with the conclusion that they were advected by the mean flow.

The above mean velocities were calculated by equally weighting the seven mean float velocities in each zonal band. This tends to emphasize the increase in velocity because a fast float is counted as being equal to a slow one despite the fast one having fewer daily velocity values in a band (because the fast float crossed over the Ridge in a shorter amount of time). We also grouped all individual float velocities into the three bands over and to the sides of the mid-Atlantic Ridge, which resulted in a mean westward velocity of 2.7 ± 0.6 cm/s over the ridge and 2.3 ± 0.4 cm/s for the region on the sides. This is based on equally weighting each daily float velocity. The velocities are smaller because some slower floats remained in the band over the ridge longer than the faster ones did, which reduced the mean velocity. This second

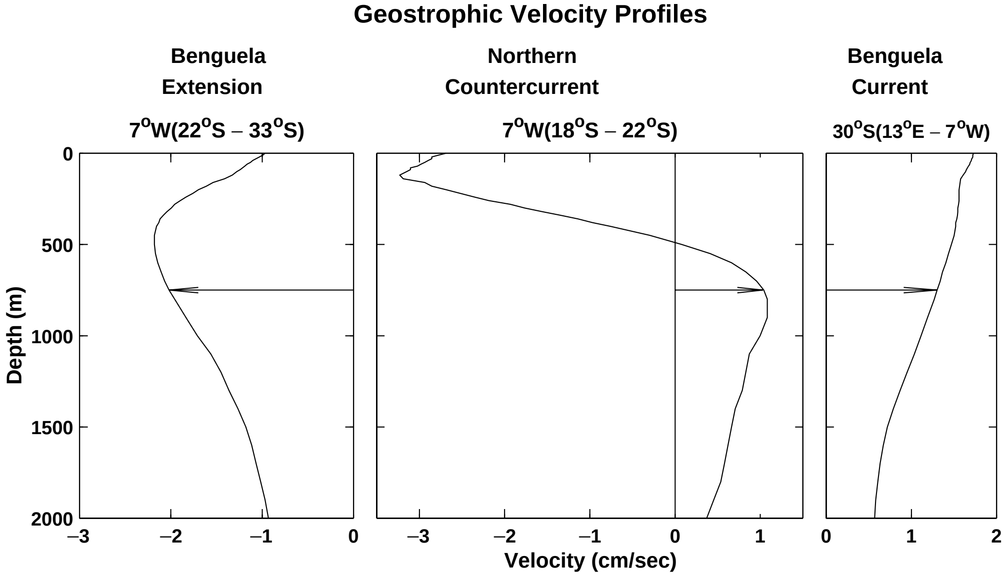


Fig. 10. Profiles of geostrophic velocity calculated for (1) the Benguela extension near 7W (22S–33S), (2) the eastward countercurrent located north of it near 7W (18S–22S), and (3) the Benguela Current across 30S (nominal) from 30.4S 14.2E to 33S 7W. The profiles near 7W were shifted to pass through the mean velocity calculated from the band-averaged float velocities between the CTD stations used to calculate geostrophic velocity. The 30S profile was shifted so that its transport per unit depth (or mean velocity × width) at the level of floats (750 m) matched the transport per unit depth of the Benguela extension (22S–33S). Since some transport in the Benguela extension probably came from north of the 30S (nominal) section, the absolute velocities across 30S could be slightly less than shown. Particularly noticeable is the small baroclinic sheer in the profiles of Benguela Current and its extension.

method also suggests an increase in velocity over the ridge but not a significant one. We think the first method is the most enlightening, especially when one compares the translation velocity of the two rings to the velocity of background floats. In summary, the first method considered the mean velocity of each float in each band as being an independent measurement whereas the second method considered each 30 days of float velocity in each band as independent.

The reason for the increase in speed over the ridge is not known but a hint comes from the two southern floats (411, 412) launched along 7W near 31S–33W. Floats 411 and 412 both appeared to be deflected northward $\sim 2^\circ$–4° over the ridge as compared to their start-stop displacement vectors. The more northern floats did not appear to be deflected northward. Perhaps the northward deflection of southern floats is an indication of meridional convergence and therefore increase of speed of the Benguela extension as it flows over the ridge. The northward deflection is in the same direction as general f/H contours over the ridge. It is not known why only two of seven floats looked like they were deflected and not the others, but the deeper flow field and shear could be different in the two regions. Under the Benguela extension, the mid-Atlantic Ridge crest appears to be mostly deeper than 2000 m, with only a slight northward deepening trend from around 1900 m near 35S to 2400 m near 22S (Fig. 7), hardly enough it would seem to account for the deflection of only the southern two floats. It is also possible that the northward deflection of floats 411 and 412 was due to advection by the eddy field or Rossby waves in the extension region.

8. Eastward current near 20S

North of 22S three floats (405, 409, 393) drifted eastward as shown by displacement vectors (Fig. 3), trajectories (Fig. 4a) and band-averaged velocities (Figs. 8, 9). These different figures show that the eastward current speed increased to the north, reaching 3 cm/s at 18S (Fig. 9). The fastest eastward speeds were measured by float 405 that meandered northward and then eastward in the 17S–19S band (between 4W–8W) before stagnating near 19.5S 1.5W.

Some additional float data at intermediate water depths in the Brazil Basin tend to confirm the eastward current observed by our three northern floats. Boebel et al. (1999b) reported an eastward current ~ 3 cm/s located between 19S–20S and extending from 30W–15W, with fastest speeds located between 28W–18W. More recently a float drifted eastward at ~ 4 cm/s near 19S–20S from 20W–5W, over the mid-Atlantic Ridge and into the region near our eastward velocity (Ollitrault, personal communication). The additional float data provide evidence of a narrow eastward current centered near 19S–20S that extends from the western boundary across the mid-Atlantic Ridge into the Angola Basin to at least 0W. The origin of the current appears to be near the western boundary near the northern side of the Vitoria-Trindade Ridge (Boebel et al., 1999b). All three of our floats in the region 19S–22S 0W–6W stagnated, suggesting that the eastward current stops before reaching the eastern boundary, although the eastward drift of float 405 near 17S–19S could be interpreted as showing that this current continues eastward north of 19S.

The implication from various float trajectories is that at 750 m the Benguela extension is bounded on the north by the eastward current and limited from flowing north of around 20S except along the western boundary. Some Benguela extension water could be recirculated eastward in this current, but the water properties near 20S and 7W are tropical, which suggests that the eastward current carries water from farther north.

The geostrophic velocity profile in the region of the eastward current (18S–22S) shows an eastward subsurface maximum around 1.1 cm/s centered in the intermediate water near 800 m (Fig. 10). Eastward flow extends from 500 to 2000 m with a volume transport of around 4.9 Sv. The eastward transport of intermediate water (500–1000 m) is around 2.0 Sv. Above the intermediate water is a westward current reaching a maximum velocity around 3.2 cm/s near 150 m. The westward transport above 500 m is 4.3 Sv. The baroclinic shear is larger than that in the Benguela Current extension and generally of an opposite sign.

It is possible that the eastward current is related to the Namib Col Current, an eastward flow transporting North Atlantic Deep Water (NADW) across the Angola Basin (Speer et al., 1995; Warren and Speer, 1991). This current extends from 1300 m (the assumed level of zero velocity) to 3000 m and flows across the Angola Basin near 22S through a deep pass (the Namib Col) across the northern Walvis Ridge and into the Cape Basin. The origin of this current also may be in the vicinity of the western boundary (Speer et al., 1995) where NADW seems to leave the western boundary although the flow is complicated in the Brazil Basin (Hogg and Owens, 1999). Warren and Speer (1991) report that the Namib Col Current at 1E is located between 20S–25S based on an oxygen maximum centered between 2000 and 3000 m, and that the flow is eastward in the north (19S–23S) and westward in the south (23S–26S). The eastward and westward deep currents are in rough agreement with the zonal velocity distribution at 750 m from floats (Fig. 9). If the eastward current observed by floats at 750 m is an intermediate water manifestation of the deeper Namib Col Current (as suggested by the geostrophic velocity profile) then its eastward velocity extends above 1300 m and its transport is greater than the previously estimated 2–3 Sv.

After stagnating, the three northern floats oscillated in a northeast–southwest direction with ~ 200 km characteristic displacements and a ~ 120 day period. The Reynolds stress $\overline{u'v'}$ was positive for all three floats. The average $\overline{u'v'}$ was estimated from the five 1° latitude band-averaged values (18S–22S) to be 2.4 ± 0.8 cm^2/s^2 as compared to the marginally negative average, -0.3 ± 0.4 cm^2/s^2, estimated for the Benguela extension to the south. These oscillations are possibly caused by Rossby waves formed in the Angola–Benguela frontal zone located to the north. The evidence for this comes from the similarity of the oscillations with those of SOFAR Floats in an equivalent location north of the Cape

Verde frontal zone in the North Atlantic (Spall, 1992). Spall showed that SOFAR float and model float oscillations were consistent with their source being radiating baroclinic Rossby waves originating in the Cape Verde frontal zone.

9. Summary and conclusions

RAFOS float trajectories provide a new vision of the intermediate water circulation in the Cape Basin and in the Benguela Current extension in the mid-Atlantic. In the Cape Basin six floats drifted southward for various amounts of time before entering the Benguela Current and drifting more westward. Four of these floats drifted south of the latitude of the Cape of Good Hope; two returned northward past their launch locations after 12–17 months, implying low-frequency fluctuations of the meridional velocity in the Cape Basin. Low-oxygen water from the tropical Atlantic was observed near the launch locations of three of these floats, suggesting that this water also was advected southward and into the Benguela Current.

All 12 floats launched in the Cape Basin looped in eddies or were advected around the periphery of eddies; several floats made multiple contacts with eddies, giving the impression the Cape Basin was filled with energetic eddies that were interacting, merging, bifurcating, and translating swiftly. The numerous entrainments and detrainments of floats by eddies suggest that water does not remain trapped in eddies very long, but instead is exchanged with water from other eddies and from outside of eddies in a vigorous mixing regime. Intermediate water from the Indian Ocean transported into the South Atlantic by Agulhas rings, cyclones, filaments, and blobs appears to be vigorously stirred and mixed with South Atlantic Current Water and also water from the tropical Atlantic by the eddy field. Eventually the blended product of the mixing flows westward across the Walvis Ridge in the Benguela Current and its embedded rings. The new view of the Benguela Current in the Cape Basin is of a closely packed field of energetic eddies as compared to some earlier descriptions of it being a broad and sluggish current with a few embedded current rings.

Virtually all the 12 Cape Basin floats drifted across the Walvis Ridge associated with the translation of four Agulhas rings and one cyclone. This suggests that the eddies are an important mechanism in advecting intermediate water across the ridge. These observations are somewhat at odds with the 8 rings (and water from 2 cyclones) that are estimated to cross the ridge per year and their 200 km size, which would seem to account for only about a third of the transport of the Benguela extension. A possible explanation is the addition of a mean westward flow outside of the eddies, but this is not obvious in float trajectories.

The three cyclones tracked by floats in the Cape Basin raise the issue of their formation. Agulhas cyclones are advected by the Agulhas Current into the southern Cape Basin near 38S 15E, but they translated southwestward and are probably not a source of cyclones farther north (Boebel et al., 2003). The cyclones farther north were probably generated by intense Agulhas rings that became unstable and broke into pieces there. Floats in two cyclones started looping near Vema Seamount where numerous rings have been observed by satellite to bifurcate. There is also the possibility of cyclone formation near the eastern boundary (Boebel et al., 2003).

Nonlooping floats in the Benguela Current extension region near the mid-Atlantic Ridge translated generally westward in the band 22S–35S, with mean velocity of 1.8–2.3 cm/s depending on how the data were averaged. Four rings were tracked by floats in this region; the two rings tracked the longest time translated at 5.7 cm/s toward 285°. The implication is that roughly 2.0 cm/s of the westward translation velocity of the rings was due to their advection by the background velocity field, and that roughly 3.9 cm/s toward 291° (two times the background velocity) was due to the self advection of the rings. The eddy kinetic energy of the Benguela extension is around 10 cm^2/s^2 much lower than that associated with rings ($\sim$50–100 cm^2/s^2) and the eddy energy in the Cape Basin, which is above 400 cm^2/s^2 in the Agulhas ring formation region.

Transport of intermediate water in the Benguela extension was estimated to be 15 ± 2 Sv by combining mean float velocities with the 14° width of the extension and 500 m thickness. Approximately 1.5 Sv of this transport is due to the three rings that cross the mid-Atlantic Ridge each year. Geostrophic shear in the Benguela Current and its extension was very small ($1-2$ cm/s) suggesting that this current is only weakly baroclinic. The total westward transport in the Benguela Current above 1000 m and between 18S and 33S was estimated to be 29 Sv.

All Agulhas rings tracked by floats coincided with rings tracked by altimetry, confirming that the two methods are complementary. This suggests that rings previously tracked by altimetry over the mid-Atlantic Ridge could be interpreted to have advected intermediate water trapped within them. In the western Atlantic the altimetric signals of the two rings tracked by floats decayed to near background levels at roughly the same times as the floats stopped looping, implying that the water advected by the rings had been released into the background flow field at that point. These two rings had traveled roughly 4000 km over 2.5 years.

Floats launched inside and outside rings in the Benguela extension seemed to translate faster by around 1.5 cm/s over the mid-Atlantic Ridge compared to the regions on either side of the ridge. Two southern floats appeared to be deflected northward over the ridge (perhaps following f/H contours), which may indicate a convergence in the Benguela extension and possibly explain the faster speeds.

Three floats drifted eastward on the northern side of the Benguela extension near 18S–22S. A few other floats suggest this countercurrent extends continuously from the western boundary of the South Atlantic across the mid-Atlantic Ridge into the Angola Basin where the flow seems to stagnate. After stagnating the three floats oscillated in what looks like Rossby waves, which could have originated in the Benguela–Angola frontal region to the north.

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Appendix A. Details of the Agulhas rings and cyclones

Ring 1

Three floats (390, 385, 383) were launched in ring 1 near 31S 9E (Fig. 4b). Float 383 surfaced early while looping, float 383 was detrained from the ring just after it crossed over the Walvis Ridge, but float 390 remained looping in ring 1 for the full 18 month mission. Float 390 looped 11 times for an average period of 49 days and maximum diameter of 200 km. The track of float 390 suggests that ring 1 initially translated northwestward, slowed somewhat (to around 3 cm/s) as it crossed over the Walvis Ridge (near a deep pass centered near 27.5S) in a more westward direction, then continued west northwestward. Float 390 surfaced just as ring 1 approached the crest of the mid-Atlantic Ridge. Ring 1 was the slowest of the three long-tracked rings with a mean velocity of 4.8 cm/s toward 288° (Table 2), although it speeded up somewhat to 5.2 cm/s during the last 7 months. Backtracking ring 1 using satellite altimetry (Garzoli et al., 1999) suggests that ring 1 formed in February 1997 and that its lifetime up to the time float 390 surfaced was 25 months. Satellite tracking followed this ring for another four months as it translated 6° farther west and over the mid-Atlantic Ridge near 24S to 23S 18W (Schouten et al., 2000; M. Schouten, personal communication). Shortly after launch three floats (101, 395, 392) made partial loops in the periphery of ring 1 at a diameter around 250 km. In October 1997 the center of ring 1 was 250 km from the center of ring 4 and float trajectories suggest the two rings may have been partially connected. The two rings had split apart by November 1997 when three floats (101, 395, 397) passed southward between them.

Six months before our cruise, an earlier KAPEX cruise surveyed ring 1 and launched five floats in it, none of which remained in it for six months. A description of ring 1 and its changes based on these floats and the two shipboard surveys (March and September 1997) is given by Schmid et al. (2003).

Ring 2

Two floats (375, 376) were launched in ring 2 near 31S 3W. Float 375 was never heard by Argos, but float 376 looped for over 13 months before being detrained from the ring. Most of the time float 376 looped at small (<50 km) diameter loops with a typical period of 16 days. The loops increased in diameter to around 150 km during the last few months before detrainment. Ring 2 was the largest of the three rings and the thermocline was the deepest in its center, which agrees with the initial temperature, 8.1°C, and pressure, 800 db, of float 376, which are the warmest and deepest of all the floats. Another float, 394, was entrained into ring 2 shortly after launch and looped for 11 months before being detrained. Float 394 made the largest loops, ~260 km diameter, of all the looping ring floats. Float 403, looped once around ring 2 with a diameter of 280 km just before the other two floats were detrained, and float 399, which had been in ring 3, looped once around ring 2 five months after the floats were detrained. Ring 2 translated very steadily at a mean velocity of 5.4 cm/s toward 282° and crossed over the mid-Atlantic Ridge near 29S. Backtracking by altimetry showed that ring 2 formed in July 1996 and crossed over the Walvis Ridge near 32S (Garzoli et al., 1999). Ring 2 was 27 months old when its floats were detrained. Altimetry tracked this ring another 7 months and 10° farther west to 25S 32W (Schouten et al., 2000; and M. Schouten, personal communication).

Ring 3

Two floats were launched near 30S 6W in ring 3, the smallest of the three rings, and looped for 11 months (387) and 13 months (399) (Fig. 4b). Both floats looped with small diameter (<50 km) loops at the beginning and gradually larger loops up to ~140 km diameter (float 387) after crossing the mid-Atlantic Ridge near 28S. One other float (401) looped once around ring 3 in November 1997 with a diameter of 220 km. Float 399 was detrained in October, 1998, coinciding with the time the last float (376) was detrained from ring 2. Ring 3 was the fastest of the rings with a mean velocity of 5.9 cm/s toward 287°. It was backtracked with altimetry (Garzoli et al., 1999) to its formation in April 1996 and crossed over the Walvis Ridge near 32S. The total tracked lifetime of ring 3 was 30 months. Altimetry was used to track this ring only up to June 1988, four months less than the looping floats (Schouten, personal communication). M. Schouten (personal communication) says this ring had low values of sea-surface height; this might be caused by its relatively small size compared to the other two rings.

Ring 4

Float 406 was entrained into ring 4 shortly after launch and looped three times before being detrained from the ring as it translated over the Walvis Ridge. Floats 388 and 396 look like they made partial loops with a diameter of 200 km in the periphery of ring 4 over the Walvis Ridge. This ring appeared to be partially connected to ring 1 in October 1997 as mentioned above. M. Schouten tracked this ring from near 35S 14E in January 1997 for 27 months as it crossed over the mid-Atlantic Ridge near 27S. The altimetric track ends near 27S 20W in March 1999.

Ring 5

Ring 5 was tracked sequentially by two floats (398, 397) that looped three times (398) and two times (397). Float 398 was detrained as float 397 started looping over the Walvis Ridge. Float 397 stopped looping just after it translated over the Ridge. Three other floats (101, 395, 397) made partial loops in the periphery of ring 5 with a diameter of 250 km while float 398 was looping. Altimetric tracking of ring 5 started near 38S 17E in January 1997 and ended near 23S 32W in March 1999 (M. Schouten, personal communication). Ring 5 crossed over the mid-Atlantic Ridge near 26S.

Ring 6

Float 404 was entrained into ring 6 for two loops as it crossed over the mid-Atlantic Ridge near 24S, almost exactly coinciding with the end of the track of ring 1 but 9 months earlier. Ring 6 was tracked altimetrically from 35S 15E in March 1996 across the mid-Atlantic Ridge near 24S to 22S 23W in March 1999. This ring appears to have had the same origin as ring 3. They interacted near Cape Town, and came together and then separated again near Vema Seamount near 32S 9E (M. Schouten, personal communication).

Ring 7

Float 395 was entrained into ring 7 and looped four times. Float 395 surfaced as it was still looping after the ring had crossed over the Walvis Ridge. Altimetric tracking was difficult because of a low-amplitude signal and extended from only 37S 7E in October 1997 to 34S 4W in October 1999 (M. Schouten, personal communication).

Cyclone 1

Float 392 looped twice in cyclone 1 in October and November 1997 shortly after launch (Fig. 4b). The cyclone appeared to translate a short distance southwestward. However, two other KAPEX floats (176, 184 – not shown) also became entrained into cyclone 1 in October and November and looped in it as it continued 500 km farther southwestward (Fig. 5b) at around 10 cm/s reaching 37S 10E in February 1998 (Boebel et al., 2000). Float 184 looped three times and float 176 four times at a maximum diameter around 140 km. These floats reveal that float 392 remained in the cyclone until the end of December 1997 and was advected far south to around 36.4S by it. Float 402 also was entrained into cyclone 1 in November and advected far south by it to around 36.4S in December.

Cyclone 2

Float 402 was entrained into cyclone 2 in August 1998 and looped 5 times as it first translated northeastward, then turned abruptly westward and translated up to the Walvis Ridge (Fig. 5b). Float 402 stopped looping in May 1999 as the cyclone encountered the Ridge. The mean translation direction of cyclone 2 seems to be at odds with cyclones 1 and 3 and other cyclones tracked with KAPEX floats that translated generally southwestward. Cyclone 2 was the only one that translated up to the Walvis Ridge. A few surface drifters in this region looped and translated westward in cyclones suggesting that this motion is not atypical or at least that there are different kinds of cyclones, some of which can translate westward over the Walvis Ridge. The cyclones simulated by Matano and Beier (2003) were bottom intensified and were not able to translate over the Walvis Ridge.

Two other KAPEX floats (208, 230, not shown) looped in another cyclone that coalesced with cyclone 2 (Boebel et al., 2000). Floats 208 and 230 started to loop near 33S 8E in March 1998. This cyclone passed close to Vema Seamount in May 1998 and merged with cyclone 2 near 31S 11W in August (Fig. 5b). At this point float 208 stopped looping but floats 230 and 402 looped together until float 230 surfaced in December 1998 at the end of its mission. It seems possible that Vema split the two cyclones apart from a common parent cyclone since they seem to originate near the same location and time south of Vema.

Cyclone 3

Float 395 was entrained into cyclone 3 and looped 5 times as it translated southwestward (Fig. 4b). Cyclone 3 also seems to have originated near Vema Seamount near the same time as cyclone 2 although these two initially translated in opposite directions (Fig. 5b). Float 395 stopped looping in cyclone 3 and immediately started looping in ring 7 implying that these two eddies were very close to each other and possibly interacting. At this time, February 1999, the distance between eddy centers was estimated to be 250 km.

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