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Introduction to the "Inter-ocean exchange around southern Africa"

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Abstract

This issue of Deep-Sea Research II contains 12 papers that describe results from field experiments and modeling studies concerning the Indian–Atlantic exchange of water around the Cape of Good Hope. A central theme is the important role of the mesoscale features, such as eddies and filaments, in the leakage of Indian water into the Atlantic. The papers describe new direct-velocity measurements and model simulations, which reveal information about circulation patterns and physical processes that control the inter-ocean exchange. For the first time a large array of subsurface acoustic floats was tracked at the intermediate water level. The float trajectories reveal that the Cape Basin off Cape Town is virtually filled with Agulhas Rings and cyclonic eddies, which interact intensely with each other, change shape, bifurcate, and merge. These energetic eddies dominate the velocity field in the source region of the Benguela Current; they stir the various source waters and advect the blended product westward over the Walvis Ridge. These seminal results have important and lasting implications for our conceptions of the processes involved in inter-ocean exchanges around southern Africa.

1. Introduction to the problem

Inter-ocean exchange of heat and salt around southern Africa is thought to be a key link in the maintenance of the global overturning circulation of the ocean (Gordon et al., 1992; Lutjeharms, 1996; de Ruijter et al., 1999; Sloyan and Rintoul, 2001). Most of the Indian Ocean leakage into the South Atlantic takes place near the Agulhas Current Retroflection where large current rings pinch off and translate into the Atlantic (Duncombe Rae, 1991; Lutjeharms, 1996; de Ruijter et al., 1999). These Agulhas Rings and other Agulhas eddies and current filaments (Lutjeharms and Cooper, 1996) merge with South Atlantic Current water in the Benguela Current, forming the source of the warm upper-layer water that flows northward through the Atlantic in compensation for the colder southward flowing North Atlantic Deep Water. Indian Ocean leakage water tends to be warmer and saltier than South Atlantic water of Drake Passage origin and therefore contributes to larger northward heat and salt fluxes (Gordon et al., 1992; Schmid et al., 2000; Sloyan and Rintoul, 2001). However, a paucity of direct current measurements plus the complexity

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of currents around South Africa have made it difficult to estimate the circulation patterns and inter-ocean fluxes especially in the intermediate water, which is an important part of the Atlantic overturning circulation. The significance of Indian Ocean leakage to the overturning circulation, to the northward flux of heat and to climate motivated the studies reported here. The papers in this special issue of Deep-Sea Research II use new subsurface float and other measurements and modeling studies to investigate the low frequency currents, the role of eddies, and the physical processes that control the amount of Indian Ocean water that leaks into the South Atlantic.

2. Historical context

The first documented encounters with the Agulhas Current were those of early Portuguese mariners seeking an ocean route to India at the end of the fifteenth century (Pearce, 1980; Axelson, 1973a). During these early voyages the southernmost point of Africa received its name, Cabo das Agulhas or Cape Agulhas[1] as it is now known. Because the magnetic compass needles pointed true north there indicating zero magnetic variation, the cape was named Cape of the Needles (Axelson, 1973b; see also http://www.lagulhas.co.za for variations of the name). Within about 80 years of its discovery, the Agulhas Current was sufficiently well known that mariners took advantage of it when sailing westward around Africa but passed to the south of it into the region of the Agulhas Return Current when sailing eastward (Pearce, 1980).

The Agulhas Current was first measured quantitatively by the set and drift of commercial ships as they rounded southern Africa. The first chart of surface currents for this region was published by Rennell (Rennell, 1778) who showed the Agulhas to flow completely around southern Africa and into the South Atlantic (Lutjeharms et al., 1992; Peterson et al., 1996). The first comprehensive description of currents in the South Atlantic was by Rennell (Rennell, 1832; published posthumously). He had concluded (though did not chart) that the greater part of the Agulhas returned back into the Indian Ocean, which is probably the first description of the Agulhas Retroflection (Peterson et al., 1996).

Rennell stated "It was formerly thought by most persons, that the entire body of Lagullas Stream passed round or over the banks to the westward, into the Southern Atlantic; but it now appears evident that the greater part returns back into the Indian Ocean, toward the opposite quarter from whence it came; merging into the well known easterly current that issues from the South-Atlantic, and passes to the southward of the Bank of Lagullas and the string of the Lagullas current, in its way round the bank from the Indian Ocean; both occasioning great eddies and irregularities near their respective borders." Although "great eddies" could have been a reference to Agulhas Rings, it was probably to smaller eddies and areas of current shear located along the "borders" or edges of the main currents.

A later compilation and chart of ship drift measurements (Van Gogh, 1857) gave a remarkably good picture of the Agulhas Current with its termination at the retroflection, its return eastward into the Indian Ocean, and little leakage into the South Atlantic (Lutjeharms et al., 1992). Apparently this chart was not widely reproduced and many subsequent current charts continued to show a major part of the Agulhas flowing directly into the South Atlantic.

The first fairly detailed description of the southern Agulhas using deep hydrographic stations was by Dietrich (1935). He concluded that three-quarters of the Agulhas transport returned to the Indian Ocean via a number of large, stationary eddies (Lutjeharms et al., 1992). However, a major part of the Agulhas was shown to round the Agulhas Bank and flow northwestward as indicated by the dynamic topography at 200 m relative to 1000 dB. This concept of the Agulhas

[1] It was probably Bartholomeu Dias, the first Portuguese explorer to round southern Africa (1487–1488), who originally named this cape Cabo de São Brandão, but he failed to recognize it as the southernmost extremity of Africa (Ravenstein, 1900; Axelson, 1973b). The 1502 Alberto Cantino chart, which summarizes the early Portuguese cartography of Africa labels "G. das Agullas" where modern Struis Bay is located just east of Cape Agulhas (Ravenstein, 1900).

Current branching into the Atlantic became a common perception (Lutjeharms et al., 1992).

In 1969 a major three-ship research experiment, that for the first time covered the full Agulhas Current with modern and closely spaced oceanographic stations (Bang, 1970), laid the foundation for the rediscovery of the Agulhas Retroflection (Lutjeharms et al., 1992). Using the data, Bang (1970) conceived the idea of the tight Agulhas recurvature and was the first to name it the "Agulhas Current Retroflexion." Bang's description established the concept of the Agulhas being a narrow current tightly recurving southward with no direct leakage into the Atlantic. He found that the retroflection region was populated by intrusions or "tongues of warmer water thrusting into the South Atlantic," and he continued "It is likely nevertheless that some geostrophic component exists so that, should the tongues separate to form individual patches of Agulhas Water, some rotation may be expected. The water movements deduced by Shannon (1966) make it clear that the northward branching intrusion is likely to move northwards as an anomalous element in the Benguela Current." Harris and van Foreest (1978) analyzed vertical sections from the same cruises and showed a deep-reaching eddy with the characteristics of an Agulhas Ring and located west of Cape Town near 35°S 15°W where many subsequent rings have been found (Duncombe Rae, 1991). Even slightly before this, Duncan (1968) detected a large Agulhas Ring near 40°S 15°E although the station spacing was coarse. Duncan suggested that "the eddy may have been caused by the Agulhas Current impinging on the West Wind Drift or by inherent instability in the Agulhas Current once it departed from the continental slope…". These observations from the 1960s suggested the possibility that Agulhas water could enter the Atlantic not as a branch of the main current but as large discrete current eddies or rings, very close to what we now believe to be true, although other Agulhas eddies and current filaments also contribute to the leakage.

In the 1970s satellite infrared images began to detail the ribbon-like nature of the Agulhas and its meanders and eddies (Harris et al., 1978). A collection of infrared images was used by Lutjeharms (1981a,b) to reveal the pinching off of the retroflection to form an Agulhas Ring. An early schematic showing the southern Agulhas Current, meanders, rings and eddies was published by Lutjeharms (1981a) and is shown here as Fig. 1. In 1983 a detailed hydrographic study was made in the vicinity of the retroflection, which revealed two rings and the shedding of a ring at sea for the first time (Lutjeharms and Gordon, 1987; Gordon, 1985, 1986; Gordon et al., 1987; Olson and Evans, 1986). These measurements were used to estimate the Indian to Atlantic flux of water and heat (Gordon, 1985, 1986; Olson and Evans, 1986; Gordon et al., 1987).

Large offshore Agulhas meanders have been occasionally observed to propagate southwestward along the Agulhas (Lutjeharms and Roberts, 1988). These Natal Pulses contain a cyclonic cold core eddy that can be seen with satellite infrared images and altimetry. The passage of nearly every Natal Pulse is followed by the spawning of an Agulhas Ring (Van Leeuwen et al., 2000). Additional offshore meanders and cyclones have been observed in the southern Agulhas near the Agulhas Bank (Lutjeharms, 1981a).

Since 1983 many Agulhas Rings have been measured at sea as described by Duncombe Rae (1991), Lutjeharms (1996), Arhan et al. (1999), de Ruijter et al. (1999), Garzoli et al. (1999), and McDonagh et al. (1999). Beginning with the work of Gordon and Haxby (1990) the sea-surface height anomalies associated with rings have been tracked by satellite altimetry across the Walvis and mid-Atlantic Ridges far into the western Atlantic (Feron et al., 1992; Van Ballegooyen et al., 1994; Byrne et al., 1995; Goñi et al., 1997; Schouten et al., 2000). The altimetric tracking of rings provided new descriptions of their complex life histories in the Cape Basin and their ultimate fate.

Present estimates are that roughly six rings form per year, and their associated inter-ocean volume transport is between 0.5 and 1.5 Sv per ring. They decay to less than half their amplitude within 1000 km of the retroflection. Some can translate into the western Atlantic although others are dissipated in the Cape Basin. Most of their properties mix into the water of the Benguela region and into the upper warm limb of the

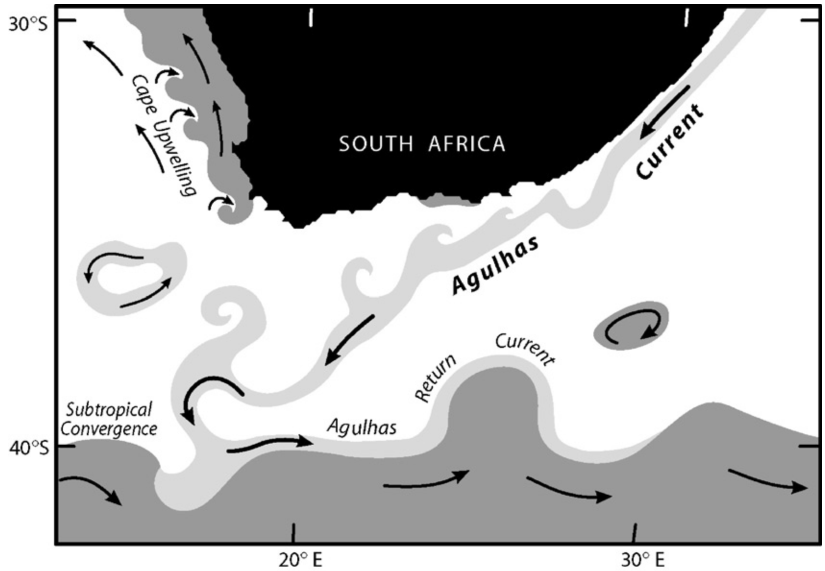

Fig. 1. An early conceptual diagram of the southern Agulhas Current system based largely on satellite infrared images (adapted from Lutjeharms, 1981a,b). This diagram summarizes many circulation features such as the narrow Agulhas, its meanders, tight retroflection, and eddies.

Atlantic overturning circulation (de Ruijter et al., 1999). Recent studies suggest that Agulhas Water (primarily via rings) and Antarctic Intermediate Water are almost equally important sources for the Benguela Current and the overturning circulation (Gordon et al., 1992; Sloyan and Rintoul, 2001). A true quantification of the fluxes of Antarctic Intermediate Water therefore was recognized as important but difficult to achieve. This led to KAPEX.

3. KAPEX–RAFOS float experiments near the Cape of Good Hope

The Cape of Good Hope Experiments (KAPEX)[2] was the geographically largest international oceanographic observational project ever carried out around southern Africa (Lutjeharms et al., 1997; Boebel et al., 1998). It forms the observational foundation for most of the papers in this issue of Deep-Sea Research. A brief overview of the float program is given below because of the importance of the new Lagrangian measurements and because individual papers tend to discuss only subsets of the collection of float trajectories.

The implementation plan for World Ocean Circulation Experiment (WOCE) called for a direct measurement of ocean currents at a reference layer in order to estimate the absolute velocity field from the large-scale hydrographic sections. On a global scale a 1000-m level was proposed because seasonal fluctuations would be small and topographic constraints would be negligible in comparison to the abyss (Davis and Zenk, 2001). In the South Atlantic the core layer of the low-salinity Antarctic Intermediate Water was chosen as the reference level. In order to directly measure the velocity at this level, a major RAFOS (RAFOS is SOFAR spelled backwards, and SOFAR stands for Sound Fixing and Ranging—see Rossby et al., 1986) float experiment was

[2] The Cape of Good Hope or Cabo da Boa Esperança, as it was named by Bartholomeu Dias in 1488 (Axelson, 1973a), is the southwesternmost cape of Africa. Dias believed that this cape was the southern extremity of Africa and many early charts of Africa use this Portuguese name to indicate in a general sense the southern tip of Africa. The name "Cape of Good Hope" is still often used today for that purpose, despite Cape Agulhas being 50 km farther south.

carried out in the western South Atlantic by French and German scientists (Boebel et al., 1999) with additional floats tracked at 2000 and 4000 m by US scientists (Hogg and Owens, 1999). A recent review (Boebel et al., 1999) describes the circulation of the intermediate layer circulation in the western South Atlantic based on the new float data.

During WOCE it became clear that an important part of the general circulation—the circulation of intermediate water around southern Africa and in the eastern South Atlantic—had been omitted from the WOCE float program leaving a huge gap of float coverage and a lack of direct current measurements there. In order to remedy this shortfall a major effort was called for. The serendipitous manner in which this was achieved is perhaps characteristic of how many successful research programs come about. Walter Zenk at the Insitut für Meereskunde in Kiel and the German float group there had been tracking floats in the western South Atlantic and proposed to follow up their measurements in the South Atlantic Current by shifting attention to the eastern part of the basin-wide anticyclone in the Cape Basin. Tom Rossby at the University of Rhode Island and Johann Lutjeharms at the University of Cape Town proposed a float program in the Agulhas Current proper with the intent of directly measuring its contribution to the South Atlantic. Phil Richardson at Woods Hole and Silvia Garzoli at NOAA in Miami proposed a float experiment in the Benguela Current on the foundation of the successful BEST (BEnguela Sources and Transports) program in the same region (Garzoli et al., 1994). It was foreseen that each of these individual experiments would be expensive and therefore difficult to get funded unless the groups could share in maintaining an acoustic sound source array. Through informal discussions at various meetings starting in 1994, the research groups from Germany, South Africa and the US teamed

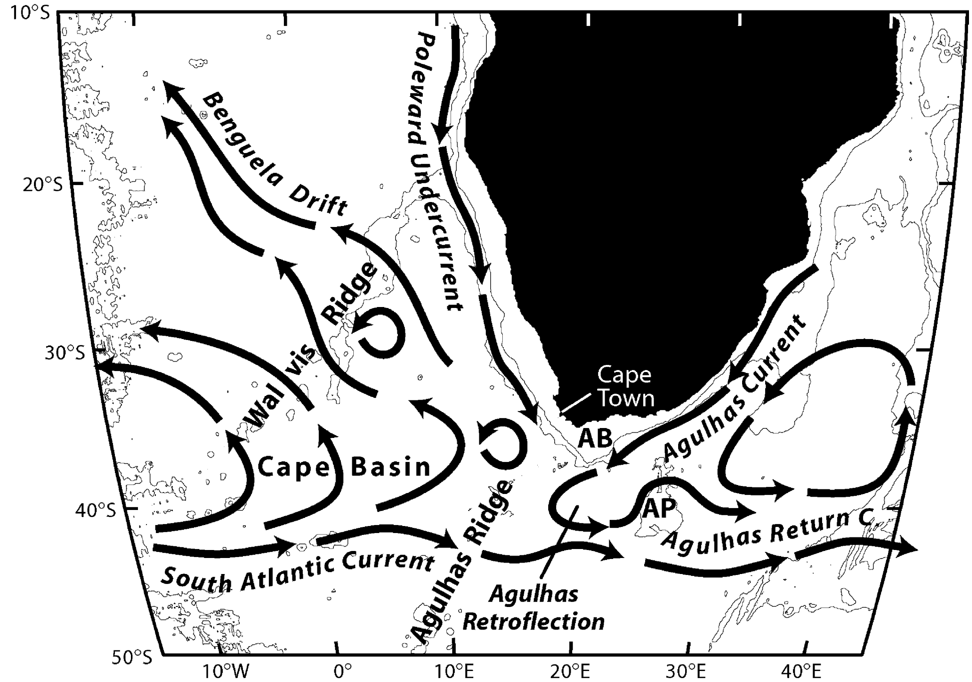

Fig. 2. A conceptual diagram of the circulation of intermediate water in the eastern South Atlantic and around southern Africa (adapted from Boebel et al., 1998 and based on the work of Shannon and Nelson, 1996; Reid, 1989; and others). AB refers to the Agulhas Bank, and AP to the Agulhas Plateau.

up, merging the sources into an extensive array that could be shared by all in a synergetic and cost-effective manner. The three components were combined into a coherent study baptized the Cape of Good Hope Experiments (KAPEX). It soon became clear that a central coordinator would be essential, and when a grant was awarded to Olaf Boebel to work with Johann Lutjeharms at the University of Cape Town, the whole project came together in a most exciting way. Informal planning meetings of the KAPEX team were held in Bremen, Germany; Rondebosch, South Africa; Brest, France; Liège, Belgium; Woods Hole, USA, and Mar del Plata, Argentina, whenever and wherever a sufficient number of participants was available.

The KAPEX program consisted of three overlapping RAFOS float experiments focused on the Agulhas Current, the South Atlantic Current, and the Benguela Current (Figs. 2 and 3). The first, conducted by Olaf Boebel, Tom Rossby, and Johann Lutjeharms, deployed three groups of floats in the Agulhas Current upstream of its retroflection. Isopycnal RAFOS floats were tracked on the 26.8 and 27.2 sigma theta surfaces (see Lutjeharms et al., 2003). The second experiment, conducted by Olaf Boebel, Claudia Schmid, and Walter Zenk, tracked isobaric RAFOS floats in the intermediate water of the South Atlantic Current where it enters into the Benguela Current in the Cape Basin (see paper by Boebel et al., 2003a). The third experiment, conducted by Silvia Garzoli and Phil Richardson, launched isobaric RAFOS floats in the Benguela Current and its extension downstream of the Walvis Ridge (Richardson and Garzoli, 2003).

The floats were tracked acoustically by means of an array of 11 moored sound sources maintained

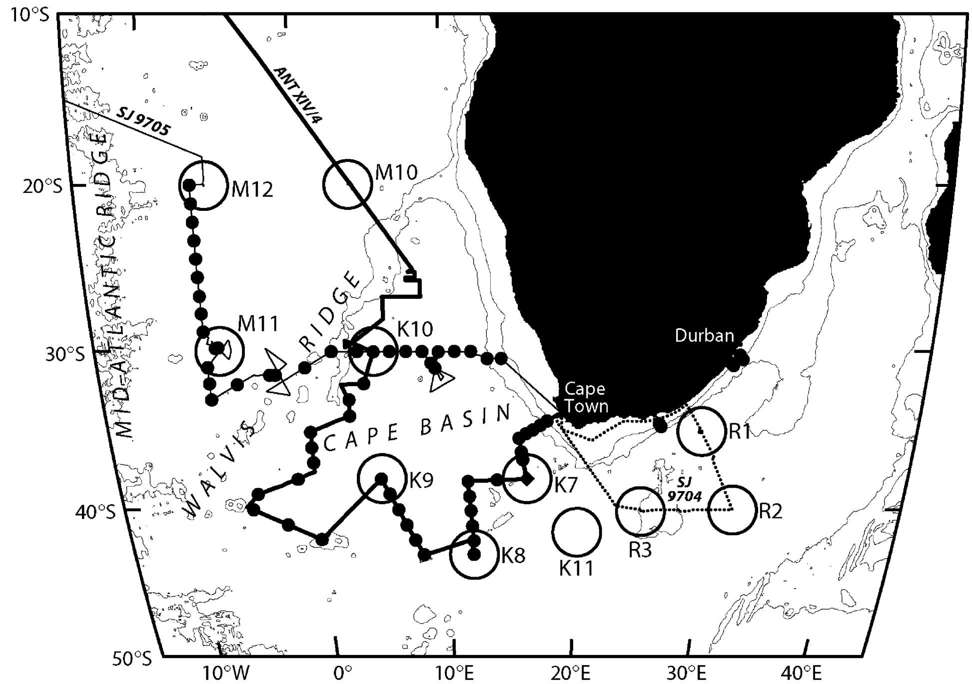

Fig. 3. The experimental plan of KAPEX showing the cruise track lines, the float launch locations as small dots, and the sound source moorings as larger circles (an M is a WHOI source, a K is a Kiel source and an R is a URI source). The major part of the field program occurred during March–September 1997, but some floats were launched in the Agulhas later during 1997 and during 1998. ANT XIV/4 refers to a cruise on the R.V. *Polarstern* during March and April 1997. SJ9704 and SJ9705 refer to R.V. *Seward Johnson* cruises in August and September 1997. Sound source K11 was launched from the R.V. *Polarstern* in March 1999. The 1000 and 3000-m isobaths are added (adapted from Boebel et al., 1998).

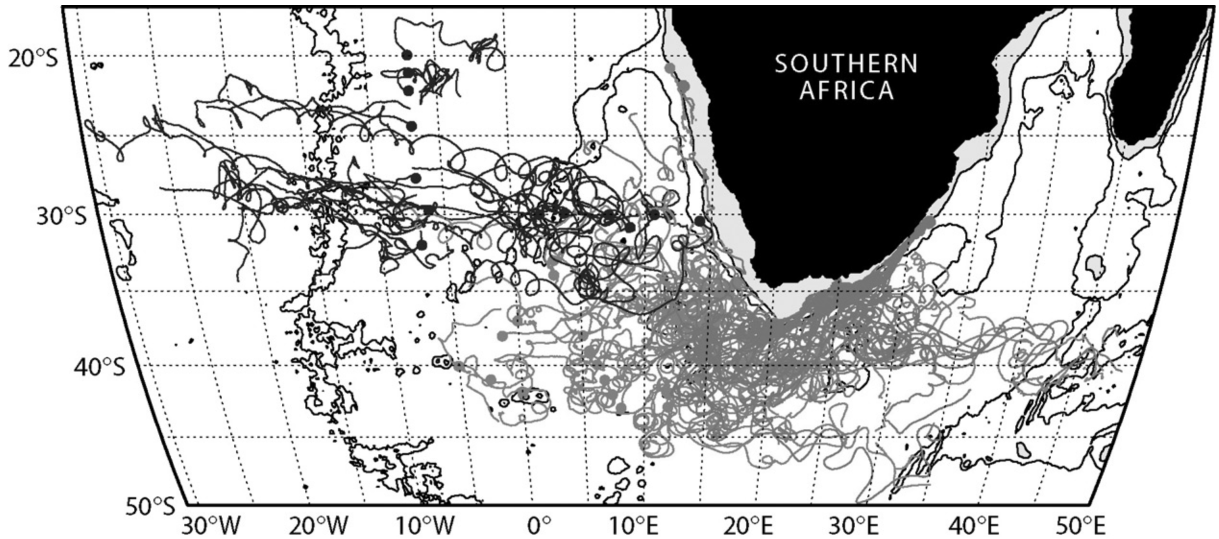

Fig. 4. Summary plot of 105 KAPEX float trajectories obtained during 1997–1999. Most trajectories were located near the level of the intermediate water. Green trajectories are of isopyncal (URI) floats launched (primarily) in the Agulhas Current, red trajectories are of isobaric (IfM-Kiel) floats launched (primarily) in the southern Cape Basin, and blue trajectories are isobaric (WHOI) floats launched near 30°S in the Cape Basin and near 7°W, west of the Walvis Ridge.

by the KAPEX group (Fig. 3). Overall, 105 eddy-resolving float trajectories were obtained during 1997–1999 (Fig. 4). Data reports describing details of the floats, sound sources, tracking and individual trajectories are given by Boebel et al. (2000a) and Richardson et al. (2003). The tangle of trajectories (Fig. 4) illustrates the complicated time-dependent flow regime in the Cape Basin where many floats looped in and around energetic eddies.

In order to help plan the KAPEX float deployments, a schematic diagram was drawn summarizing the general circulation of intermediate water (Fig. 2). It showed our perception that Indian Ocean leakage occurs primarily by Agulhas Rings and that the Benguela Current is a relatively broad and sluggish flow populated by occasional Agulhas Rings. Although we realized that the schematic was overly simplistic, we felt it would serve as a model with which we could compare the resulting float trajectories.

The new float trajectories, other recent data, and model simulations reported here emphasize that the Cape Basin is a highly turbulent regime packed with numerous energetic Agulhas Rings and cyclonic eddies, especially the southeastern Cape Cauldron (Boebel et al., 2003a). Floats in the intermediate water of the Cape Basin usually did not remain in the rings and cyclones for very long, implying strong mixing between the rings, cyclones, and background water from the South Atlantic Current and tropical Atlantic. The earlier concept of a sluggish Benguela Current populated by a few rings is no longer tenable except perhaps downstream, near and west of the Walvis Ridge. A new schematic was drawn based on the analyses of float and other data to reflect some of the recent findings (Fig. 5). Although it, too, is overly simplistic, the new schematic visually illustrates some of the complexity of the inter-ocean exchange near the Cape of Good Hope.

We plan further analyses of the RAFOS float data and complementary non-acoustic Autonomous LAgrangian Circulation Explorer (ALACE) float data measured by Russ Davis, with the overall goal of objectively mapping the low frequency circulation of the South Atlantic at the intermediate water level (see Boebel et al., 1999, 2000b). Additional field work and modeling studies are underway, e.g., Mixing of Agulhas

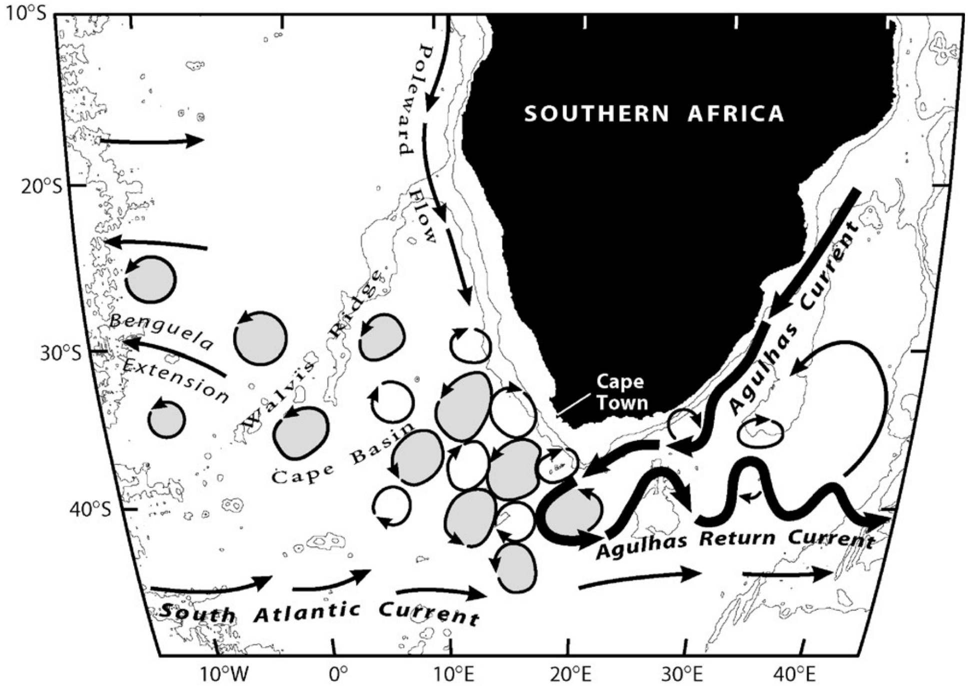

Fig. 5. Schematic map of the circulation of the intermediate water based on the float trajectories and results described in the papers published in this issue of Deep-Sea Research II. The Cape Basin is populated by numerous Agulhas Rings (rotating counterclockwise) and cyclonic eddies (rotating clockwise). Agulhas Rings tend to translate northwestward in the Atlantic at around 5 km/day and cyclones southwestward. Interactions among rings and cyclones are frequent in the Cape Basin as observed with floats and altimetry. The eastward arrow near 18°S is based on float trajectories there.

Rings Experiment (MARE) by de Ruijter et al. (see http://kellia.nioz.nl/projects/mare), Agulhas-South Atlantic Thermohaline Transport Experiment (ASTTEX) by Byrne et al. (see http://gyre.umeoce.maine.edu/ASTTEX/), and there are plans for further collaborative analyses of in situ data and model simulations with the goals of evaluating and improving models and gaining a better understanding of the physical processes that control inter-ocean exchange.

4. Introduction to the papers

A major accomplishment reported here for the first time is the tracking around southern Africa of a large array of RAFOS floats centered near the level of intermediate water. The float trajectories provide a new visualization of the complicated current field and a direct measure of the flow of Indian Ocean water around Africa into the South Atlantic. Movies of float trajectories superimposed on maps of sea surface steric height anomalies from altimetric measurements were made by Olaf Boebel. The animations portray a rich description of the time evolution of current meanders and the formation and evolution of eddies and other features and is available in an electronic annex to this issue of Deep-Sea Research II. Analyses of the float trajectories and other data (altimetry, hydrography, etc.) are presented in the first six papers of this issue. Two additional papers concerning the analysis of other new observations follow these. The first by Van Aken et al. (2003) describes initial results of the new Dutch field program MARE (see Lutjeharms et al., 2000), which measured ring Astrid during the first MARE cruise. The second by You et al. (2003) is a mapping and synthesis of historical and recent hydrographic measurements.

The final four papers report results of numerical model studies. The first three of these discuss Indian to Atlantic fluxes using simulations from eddy-permitting models. Fluxes are subdivided into mean and transient parts. The first two papers further discuss the rings and cyclones responsible for most of the inter-ocean flux. The fourth paper models the early decay of Agulhas Ring Astrid, which was measured during MARE.

A very brief summary of the individual papers in this issue is given below:

"Agulhas Cyclones" by Lutjeharms et al. (2003) describes float and other data in the Agulhas Current and in cyclonic eddies associated with southward Agulhas meanders. Floats looping in these cyclonic eddies translated southwestward into the South Atlantic. The cyclones appear to trigger the pinching off of Agulhas Rings.

"Path and variability of the Agulhas Return Current" by Boebel et al. (2003b) uses floats and altimetry to describe the Agulhas Return Current including its transport, mean path, variability and cyclones, which form from northward meanders. These cyclones translate westward. They occasionally seem to amplify smaller inshore cyclones generating favorable conditions for the shedding of an Agulhas Ring.

"The Cape Cauldron: A regime of turbulent inter-ocean exchange" by Boebel et al. (2003a) describes floats and altimetry in the southern Cape Basin, the Cape Cauldron. Floats rapidly switch between cyclonic and anticyclonic features and show that it is filled with a highly energetic field of cyclonic and anticyclonic eddies. Here, Agulhas Rings were observed to merge and split, to reconnect to the retroflection, and to assume shapes other than circular.

"Characteristics of Intermediate Water flow in the Benguela Current as measured with RAFOS floats" by Richardson and Garzoli (2003) describes float trajectories in the Cape Basin and also in the Benguela extension. Seven rings and three cyclones were tracked with looping floats, three rings for longer than a year. The eddy-rich flow field in the Cape Basin is much more complex than the simpler westward flow in the Benguela extension.

"A comparison of in-situ float velocities with altimeter derived geostrophic velocities" by Boebel and Barron (2003) inter-compares geostrophic surface velocities derived from altimetric Modular Ocean Data Assimilation System (MODAS) steric sea-surface height fields to recent Acoustic Doppler Current Profiler (ADCP) and RAFOS float measurements. It is concluded that MODAS fields give a realistic measure of cyclonic and anticyclonic features and their advection in the Agulhas and Cape Basin.

"Early evolution of an Agulhas Ring" by Schmid et al. (2003) describes details of an Agulhas Ring located in the southern Cape Basin as revealed by two cruises, several floats, and altimetry. Mixing of intermediate water in the ring as well as exchanges with ambient water were vigorous and complex processes leading to rapid dissipation well before the ring reached the Walvis Ridge.

"Observations of a young Agulhas ring, Astrid, during MARE in March 2000" by Van Aken et al. (2003) describes initial results of a new field program, MARE, which measured the details of a newly formed large Agulhas Ring. Surface to bottom velocity profiles made with a lowered ADCP showed the ring to have a significant barotropic velocity component with deep (2000–4000 m) swirl velocities of around 15 cm/s.

In "Quantification of the inter-ocean exchange of intermediate water masses around southern Africa" You et al. (2003) analyze hydrographic data mapped onto five neutral density surfaces spanning the intermediate water. The authors conclude that Antarctic Intermediate Water from the Drake Passage, one-seventh of which first passes into the Indian Ocean, accounts for 80% of the Benguela Current intermediate water transport; the origins of the rest of the transport are the southern Indian Ocean, Red Sea, Persian Gulf, and Indonesian Seas.

In "A Kinematic Analysis of the Indian/Atlantic Interocean Exchange" Matano and Beier (2003) discuss the coexistence of surface-intensified rings and associated bottom-intensified cyclones, which occur as dipole structures. The cyclones are blocked by the Walvis Ridge and disperse after impinging on it. Westward fluxes are mostly associated with the climatological mean circulation, which is intensely driven by Agulhas Rings.

"Agulhas eddy fluxes in a $1/6^{\circ}$ Atlantic model" by Treguier et al. (2003) also describes rings and cyclones although the cyclones are not coherent eddies but mostly elongated structures associated with rings. The authors estimate fluxes due to the trapped fluid in the rings, which emphasizes their role in inter-ocean exchange. Eddy–eddy interactions, which are intense in the Cape Basin, lead to turbulent ring trajectories there.

"Inter-ocean fluxes south of Africa in an eddy-permitting model" by Reason et al. (2003) describes the Agulhas region and inter-ocean exchange in terms of its mean and time variability on mesoscale, seasonal and interannual time scales. Considerable attention is paid to model variability that refers to only that generated internally through ocean processes since the monthly forcing is repeated each year.

"Modeling the initial, fast Sea Surface Height decay of Agulhas ring 'Astrid' " by Drijfhout et al. (2003) modeled the initial rapid decay of rings and found that they are unstable to an $m = 2$ mode that leads to ring splitting. The instability appears to be associated with mixing of fluid that occurs preferentially through the lobes at the extremes of the elongated rings. This study shows how ring water can become detrained into the background.

Acknowledgements

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