KAPEX: an international experiment to study deep water movement around southern Africa

J.R.E. Lutjeharms, O. Boebel and T. Rossby

Over the past decade it has been demonstrated unequivocally that the exchange of water masses between the Indian and the Atlantic oceans, south of Africa, is a key component of the global thermohaline circulation cell. This thermohaline circulation plays a large part in controlling global climate. Numerous South African and international studies have now been completed on these water exchanges, but most have concentrated their efforts on the upper water masses. We describe here an extensive and exciting new venture, called KAPEX, to investigate the movement of water at intermediate depths using sophisticated Lagrangian floats. This research programme is a collaborative effort between research groups from three countries and constitutes the geographically largest oceanographic experiment ever carried out in South African waters. Detailed information on the aims as well as the progress of KAPEX is available on the Internet on the home page http://triton.sea.uct.ac.za

The meridional gaps between the continents of the southern hemisphere and Antarctica have a decisive influence on the large-scale movement of water in the oceans of this hemisphere. The South American continent extends so far south that only a part of the eastward moving waters of the Antarctic Circumpolar Current passes between it and Antarctica. New Zealand lies farther north, at the generic border between the Southern Ocean and the subtropics — the Subtropical Convergence — allowing all of the Antarctic Circumpolar Current to pass by. The southern tip of Africa, on the other hand, is located well north of the Subtropical Convergence, thus allowing not only a totally free flow for the waters of the Antarctic Circumpolar Current, but even the exchange of waters between the two wind-driven subtropical gyres that lie to either side of the subcontinent.

This exchange[1] forms a key component of the global thermohaline circulation cell,[2] by which surface water moves from the tropics in the Pacific and the Indian oceans, past the Cape of Good Hope, and then northward into the South and later the North Atlantic Ocean. In the northern reaches of the North Atlantic this water is cooled, subducts, and flows southward at depth to complete the global circulation cell.

The movement of this subtropical, upper layer water south of Africa is for the greater part from the South Indian Ocean to the South Atlantic. It is believed to consist of two unequal parts, but both derived from the warm, salty Agulhas Current that flows poleward along the east coast of southern Africa. The first part consists of filaments of warm surface water that are sheared from the inshore side of the current and that subsequently are advected into the South Atlantic.[3] These are thought to make but a minor contribution to the interbasin salt flux. It has now been recognised that the largest part of this interbasin exchange by far takes place via large Agulhas rings that are formed when the Agulhas retroflection loop occludes[4] south of Africa.

These rings carry vast amounts of salt and heat into the South Atlantic.[5] They move all the way across the South Atlantic, slowly losing azimuthal velocity and distributing their excess heat and salt in the process.[6] The amounts of mass, heat and salt involved in this ring shedding are not known precisely because a number of controlling factors have not been adequately quantified. The numbers of rings shed per year vary;[7] their individual heat and salt contents may differ substantially and, furthermore, the interactions between the sea and the atmosphere in the source region of the Agulhas rings may have a considerable affect on the heat[8] as well as the salt content[9] of rings. Enormous amounts of heat are lost from these features when the tropical waters that constitute their surface layers are brought into contact with the cold air in the sub-Antarctic, in the Agulhas retroflection region. Considerable losses of moisture, due to evaporation, also occur here, which leads to salinity boosting in the surface waters of the rings.[9]

Most of our current understanding of the exchange processes south of Africa, set out above, depends on hydrographic observations made from research vessels. These cruises have in general been part of research projects that have concentrated on the southern part of the Agulhas Current. With few exceptions, these observations have been at limited depths and few have extended to the sea floor. These include the hydrographic observations from those cruises designed specifically to investigate features of this system, such as the Agulhas Retroflection Cruise[10] and the Subtropical Convergence and Agulhas Retroflection Cruise.[11] As a result, much more is known about the upper 1 500 m of the water column in this region than deeper down.[12] Calculations of geostrophic motion have been carried out with reference to the flow at this depth, while we know very little about the movement at intermediate depth. This ignorance has serious consequences for our general understanding of the water mass exchanges between the adjacent ocean basins.

There are, for instance, suggestions[13] that the South Atlantic Current, that forms the southern limb of the subtropical gyre in that ocean,[14] carries intermediate water into the Agulhas retroflection region, where it contributes to the flow of the Agulhas Return Current.[15] This water is thought then to recirculate in a South West Indian subgyre[16] and thus to contribute to the sources of the Agulhas Current. This hypothesis is an important one and urgently needs to be tested if we are to quantify the interbasin water exchanges correctly. This is exceedingly hard to do without more observations at the appropriate, greater depths. Gathering hydrographic observations would be a substantial, expensive and time-consuming task.

This hypothesis moreover touches on a second aspect of the macroscale circulation near southern Africa, namely, the degree to which water from the South Atlantic Current continues eastward as the Agulhas Return Current or is instead incorporated into the Benguela Current, the easterly component of the subtropical gyre of the South Atlantic Ocean.

A major research effort has investigated this problem during the past five

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years as part of the Benguela Sources and Transport Experiment (BEST).[17–19] Some important findings have been made. It has been shown that near the coast a broad, slow movement of water characterises the Benguela drift. Farther seaward the passage of Agulhas rings at irregular intervals causes major disturbances to the flow.[18] At 30°S the water in the Benguela Current consists of about 50% water with properties that characterise it as having derived directly from the central Atlantic Ocean, about 25% is pure South Indian Ocean water, while the rest consists of a blend of the two.[19]

These BEST investigations have furthermore demonstrated that the flow of the Benguela Current itself is fairly stable and that all interannual variations of this flow are brought about by modification of the source currents. Although it has been shown that the major disturbing agents to the flow, Agulhas rings, extend to intermediate depths and deeper, few data are available at these depths. In fact, it is clear that the pathways, velocity, transport and variability of the Benguela Current remain poorly understood at these intermediate depths, due mostly to a dearth of data.

From the above it should be clear that a much better understanding of the movement of water at intermediate and greater depths is required if we are fully to understand the inter-ocean exchanges of water south of Africa. The rather coarse and unsatisfactory description we can currently give of this flow is portrayed in Fig. 1. It resembles in many respects the surface circulation.[22] In the South Indian Ocean a recirculation cell is believed to form part of the South West Indian Ocean subgyre. The degree to which it incorporates water from the Agulhas Return Current has not been quantified. The Agulhas Current extends to increasingly greater depths as it moves water southward. It is therefore evident at intermediate depths, as is its continuation, the Agulhas Return Current, and its products, the Agulhas rings. The South Atlantic Current, flowing along the Subtropical Convergence, is also seen to extend to these depths and part of it turns equatorward to form the Benguela Current. At these intermediate depths the Benguela Current seems to have an inner part that is fairly stable and a seaward part that has Agulhas rings imbedded in it. It is the components of this overall flow that now urgently need to be better understood.

Lagrangian measurements

These movements of water at intermediate depth could in principle be quantified in a number of different ways. The first, and most expensive, is to carry out research cruises and to gather large amounts of hydrographic data from which the movements of water and the water types involved can be deduced. This would take a considerable time and is not about to happen. The second way involves placing current meter moorings at numerous places to monitor the flow. This can be done using meters with mechanical rotors or moored inverted echo sounders that establish the flow by transmitting sound pulses. For these Eulerian measurements to be adequate to estimate fluxes, there have to be many of them and they need to be placed fairly closely to one another. To cover the whole region depicted in Fig. 1 would be inordinately expensive. During the past few years, however, a new, less expensive way of measuring the flow at intermediate depths has been perfected. This consists of following the water masses, that is, carrying out Lagrangian measurements by placing neutrally buoyant drifters, usually called floats, at predetermined depths.

These floats track the water masses in which they are embedded, measuring pressure, temperature, salinity[23] and even dissolved oxygen as they move along. They continuously establish their geographic location by acoustic means.[24] This navigation is accomplished by simultaneously placing a small number of acoustic moorings on the sea floor near where the drifts are to be measured. These moorings consist of an anchor, a cable long enough so that the buoyant instrument is at the correct depth — like a balloon on a string — and a battery-driven sound source. These sound sources supply the floats with their geographic co-ordinates and can operate for a number of years before their batteries run low. Some of these moorings have anchors with acoustic releases that can be purposefully triggered by a passing research ship at the end of the experiment. The instrument would then rise to the sea surface, leaving the anchor behind. Thus the retrieval of the expensive instrument can be accomplished. In many cases the moorings are in out-of-the-way places where a special cruise would have to be mounted in order to retrieve the instrument. In such cases it becomes less expensive to place the mooring without an acoustic release from the start and to abandon it at the conclusion of the experiment.

A number of floats with different designs are currently available. Each has distinct advantages and limitations. One that has been used with exceptional success to track intermediate waters in the South West Atlantic Ocean[25] over the past few years is the RAFOS float.[24] This instrument can be described as a high-tech message in a bottle. A 2.1-m-long glass tube houses a microcomputer, sensors, a satellite transmitter and a battery pack for power. It is launched from a vessel and sinks to a predetermined depth where it drifts passively for its mission length, which may be up to two years. When the end of its observational life is reached, the float automatically releases an attached weight and rises to the sea surface. Here it transmits, via satellite, all the data collected during the two years to a group of scientists anxiously waiting in some far-off institutes.

Clearly, a large experiment during which the whole region south of Africa could be seeded with RAFOS floats and where a large number of sound sources would allow the tracking of water masses would be ideal. However, such a research project would have to cover not only each corner of the South Atlantic and the South Indian oceans shown in Fig. 1, but should in addition allow one to follow the trajectory of water moving between these two basins. A field programme of this kind would be such a large endeavour that it would require a number of countries and research groups to collaborate very closely and, furthermore, to synchronise a number of separately funded national projects. This has now been achieved and an experiment with these aims called KAPEX[21] is under way as this is being written.

The KAPEX research programme

The KAPEX project (the name comes from Kap der guten Hoffnung Experimente — Kaap die Goeie Hoop Eksperimente — Cape of Good Hope Experiments) brings together research groups from the USA, Germany and South Africa to share their equipment and expertise. The layout of the combined efforts is shown in Fig. 2. The deployment locations as well as the geographic positions of the sound sources will cover the full South East Atlantic Ocean, the western side of the South West Indian Ocean as well as the region

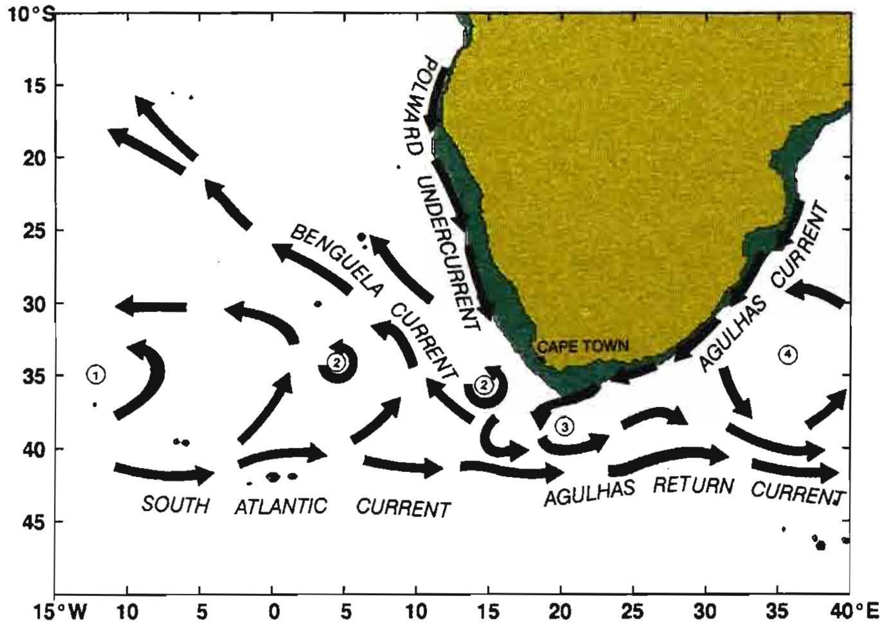

Fig. 1. The assumed average motion of water at intermediate depths around southern Africa. This portrayal is based on an interpretation of historical hydrographic data[20] and is modified from one presented by the KAPEX team.[21] The numbers identify 1, the wind-driven, anticyclonic gyre of the South Atlantic Ocean; 2, Agulhas rings of varying ages that were previously spawned at 3, the Agulhas retroflection; and 4 locates the core of the South West Indian Ocean subgyre.[16]

directly south of South Africa where the inter-basin exchanges of water are believed to take place. Floats launched in the greater Agulhas system east of South Africa will be tracked by reference to sound sources supplied by the University of Rhode Island. If some of these get trapped in Agulhas rings (see Fig. 1) and subsequently move into the South Atlantic, they will be tracked by sound sources from the Institut für Meereskunde (IfM) and further on in their journey into the South Atlantic by sound sources from the Woods Hole Oceanographic Institution and the Lamont-Doherty Earth Observatory of Columbia University. Conversely, floats placed near the junction between the Walvis Ridge (see Fig. 2) and the mid-ocean ridge of the South Atlantic at about 15°W will first be able to orient themselves by sound sources from Woods Hole, then from the IfM and, if they continue into the South Indian Ocean, by sound sources from Rhode Island. The three projects that form the components of KAPEX therefore have linked aims.

Agulhas Current project

The Agulhas Current is the major western boundary current of the southern hemisphere. The greater Agulhas system dominates the water movement in the South West Indian Ocean and the current itself is the driving force for inter-basin exchanges in the upper and thermocline waters. Only rough estimates have to date been made on the proportion of its waters that enters the South Atlantic and that turns back into the South Indian Ocean as the Agulhas Return Current. How much of this latter current's waters turn northwards to become part of a recirculation is only poorly known.[15] We also have no idea if this leakage from the Agulhas Return Current is site specific. We furthermore need to learn more about the depth to which Agulhas rings trap water as they are advected into the South Atlantic.

The component of KAPEX that will

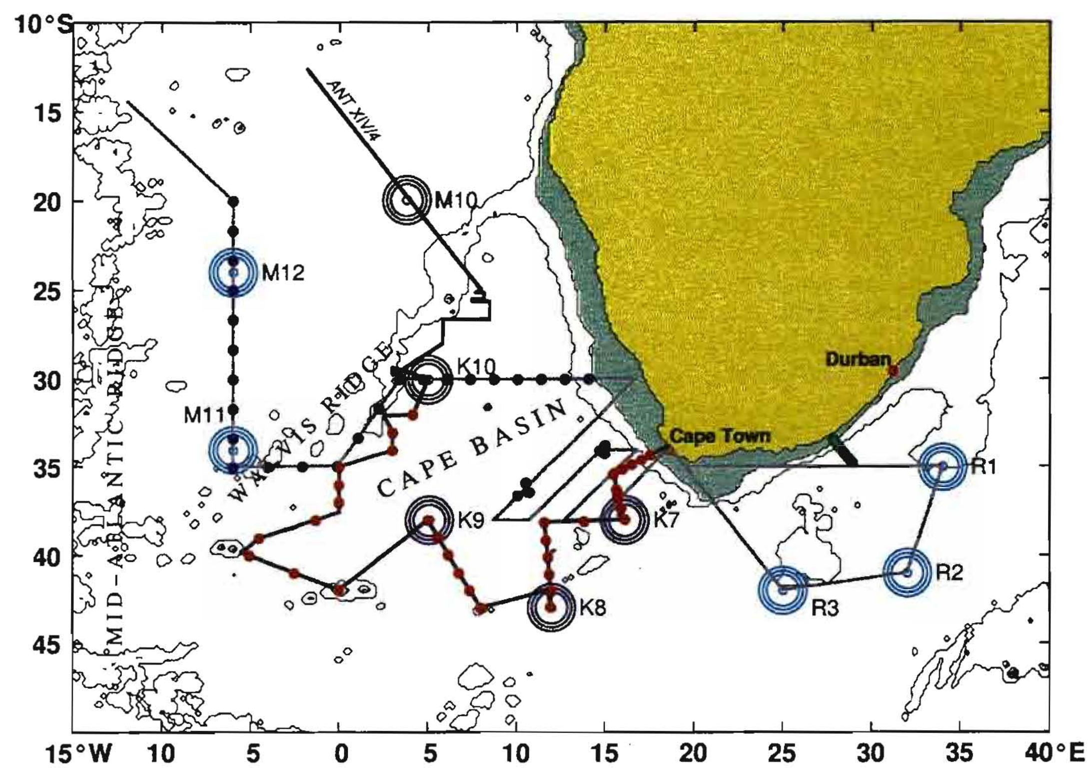

Fig. 2. The deployment plan for the KAPEX field experiment.[21] Concentric circles show the positions where subsurface sound sources are to be placed. R1 to R3 are from the University of Rhode Island; K7 to K10 from the Institut für Meereskunde in Kiel, and are already in place; M10 to M12 are from a combined effort by the Lamont-Doherty Earth Observatory/NOAA and the Woods Hole Oceanographic Institution. Red dots show the positions where RAFOS floats were launched in March and April 1997 from the German research ship *Polarstern*. A grey line with blue dots indicates the planned cruise track of the US research vessel *Seward Johnson* and the planned positions where a further collection of floats is to be placed. A green line off the south-east coast of South Africa shows where RAFOS floats are to be launched at regular intervals of three to four months for the next year. The green area represents the region where the ocean is shallower than 1000 m; the black line indicates an ocean depth of 3000 m.

address these and other questions will be carried out by Tom Rossby from Rhode Island, Olaf Boebel and Johann Lutjeharms from the University of Cape Town, in collaboration with Mike Roberts from the South African Sea Fisheries Research Institute. Three sound sources will be placed in the South West Indian Ocean (see Fig. 2) and floats will be launched at regular intervals off Port Alfred. In addition, regular POGO launches will be carried out across the Agulhas Current. This instrument measures directly the flux of water and from these regular observations the variability in the fluxes of the Agulhas Current will be accurately determined. Observations of temperature and current speed during the cruise in August 1997, when the sound sources are to be deployed, will furthermore establish the possible presence of deep-sea eddies,[26] investigate the Port Alfred upwelling cell[27] and study the movement of bottom water on the Agulhas Bank.[28]

The South Atlantic Current

The South Atlantic Current forms the southern limb of the wind-driven, anticyclonic gyre of the South Atlantic. The flow of this current is concentrated just north of the Subtropical Convergence. In other subtropical gyres of this kind, such as those found in the North Atlantic or in the South Pacific, such polar boundary currents would be constrained by the adjacent continents and be forced eventually to bend equatorwards. Because the southern tip of Africa lies relatively far to the north, this does not necessarily hold true in the South Atlantic where, conceivably, the South Atlantic Current could continue its unobstructed course eastward to merge with the Agulhas Return Current in the South West Indian Ocean. The ratio of water from the South Atlantic Current that continues eastward to that which becomes part of the Benguela Current is unknown. Lagrangian observations would be particularly useful to identify those Atlantic waters at intermediate depths that move into the South Indian and subsequently become part of the South West Indian subgyre.[13,14] The component of KAPEX which will study this flow has already been deployed.

During March and April of this year five moorings were placed in the Cape and Angola basins (see Fig. 1) from the German research vessel *Polarstern* by scientists from the IfM and UCT. This study is the overall responsibility of Walter Zenk and Claudia Schmid from Kiel, Germany. A total of 35 RAFOS floats were launched at strategic locations thought to capture the various flows best. Hydrographic measurements were made along the full cruise track. This, together with surface current observations, allowed us to identify a newly shed Agulhas ring and to seed it with a number of RAFOS floats. This will be the first time that the circulation within a ring of this kind is studied at these depths. If the floats are retained within the ring they will show how the ring spins down with time and the rate at which the intermediate water is mixed with the ambient water masses. The hydrographic observations clearly showed the Indian Ocean origin of the intermediate water mass in this ring. The zigzag pattern of the cruise track (see Fig. 2) was purposefully designed to study the Subtropical Convergence in a region where relatively little is known about it.[29,30]

The Benguela drift

The wind-driven Benguela Current carries intermediate water of both Atlantic and Indian Ocean origin equatorward.[31] The proportions are poorly known, although some rough first estimates have been made.[19] The effect of Agulhas rings on the intermediate flow, the possible influence of the Walvis Ridge and the Mid-Atlantic Ridge on the water trajectories, and a number of other factors remain shrouded in ignorance. These vexing issues are to be studied by a KAPEX project component initiated by Phil Richardson of Woods Hole and Sylvia Garzoli of NOAA (the US National Oceanographic and Atmospheric Administration), in collaboration with Chris Duncombe Rae from the Sea Fisheries Research Institute in Cape Town.

During September 1997 they plan to seed the Benguela Current with 30 RAFOS floats from the research vessel *Seward Johnson* in the positions shown in Fig. 2. An extensive hydrographic survey south-west of Cape Town will attempt to net at least three Agulhas rings and to seed each with floats. A search will also be conducted for rings at, as well as upstream of, the Walvis Ridge. It is believed that Agulhas rings slow down as they cross this ridge and that their structure may be significantly modified during the crossing.[32] Placing floats in these rings is aimed at observing these changes for the first time. Two further sound source moorings will also be placed west of the Walvis Ridge (Fig. 2) during this cruise. This will complete the sound source array and the seeding of floats in the South Atlantic for KAPEX. Additional floats will be placed in the Agulhas Current later and some of these may in time also move through the array in the Cape and Angola basin, to the north. In this way a special time series may be generated for flow in the South East Atlantic Ocean over the period of two years that this experiment is planned to last.

Conclusions

KAPEX is a geographically large, logistically complex and scientifically ambitious oceanographic project. Success in achieving all its aims is not guaranteed. This is particularly so because many of the research questions posed have had to be vaguely formulated due to our ignorance of the general water movements at intermediate depths in this region. When so little is known one can be sure that a number of results are going to be total surprises, increasing the excitement with which the float data are being awaited. Meanwhile, the hydrographic measurements made during the deployment cruises have already added significantly to the meagre data set for the region and enhanced our understanding of some of the oceanographic features present.

In examining this project plan the close international and inter-institutional collaboration is particularly striking. Acoustic sound sources are being shared between groups and the best possible use of the available equipment is being made. This synergistic approach is decidedly to the benefit of all and especially to gaining a better understanding of so complex a circulation system. South African scientists are making only a modest financial contribution to the whole endeavour. By acting as a catalyst that has facilitated the synchronisation of what otherwise might have been a set of uncoordinated, individual projects, we believe they have made a substantial contribution.

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