Observations of the Inter-Ocean Exchange Around South Africa

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There is growing evidence that the inter-ocean exchange south of Africa is an important link in the global overturning circulation of the ocean, the so-called ocean conveyer belt. At this location, warm and salty Indian Ocean waters enter the South Atlantic and are pulled by currents that eventually reach the North Atlantic, where water cools and sinks.

A major contributor to the exchange is the frequent shedding of ring eddies from the termination of the Agulhas Current south of the tip of Africa. This shedding is controlled by developments far upstream in the Indian Ocean, and variations in this 'Agulhas Leakage' can lead to changes in the rate and stability of the Atlantic overturning, with possible associated global climate variations [*Weijer et al.*, 1999]. Regional climate variations in the tropical and subtropical Indian Ocean are known to affect the whole system of the Agulhas Current, including the inter-ocean exchanges. This article reports on some of the seminal results of ongoing multinational, multidisciplinary projects that explore these issues.

In the Mozambique Channel, between Madagascar and southeast Africa, interannual ocean current fluctuations are coupled to the climate modes of the Indian Ocean and to global climate variations, in an as yet unquantified way. The current within the channel flows southward, and is connected upstream to monsoon-driven circulation and downstream to the interocean exchange system around South Africa.

The Long-Term Ocean Climate Observations (LOCO) program—funded by the Netherlands Organization for Scientific Research (NWO-groot), and carried out by the Royal Netherlands Institute for Sea Research (Royal NIOZ), the Institute for Marine and Atmospheric Research Utrecht (IMAU), and the Royal Netherlands Meteorological Institute (KNMI)—is measuring time-varying mass and heat transports through the use of an array of instrumented mooring across the Mozambique Channel's narrowest section, around 17°S (Figures 1 and 2). This array has been deployed in 2000 and will remain in place at least until early 2008.

LOCO is based on two other NWO projects, the Mixing of Agulhas Rings Experiment (MARE, 1999–2004) and the Agulhas Current Sources Experiment (ACSEX, 2000–2001), carried out by researchers from IMAU, Royal NIOZ, KNMI, and the University of Cape Town. In MARE, the relevant processes related to the dissipation of rings from the Agulhas Leakage were investigated. Three cruises were dedicated to the evolution of one ring and included paleoceanographic and numerical model studies. During ACSEX, two cruises concentrated on the upstream developments in the Mozambique Channel and around Madagascar.

Agulhas Leakage and Ring Decay

During MARE, model studies using a Lagrangian method to follow water parcels have suggested that 90 percent of the upper water layers that cross the Atlantic equator northward are drawn from the Indian Ocean via the Agulhas Leakage and that less than 10 percent comes directly from the Pacific via the Drake Passage between Antarctica and South America [*Donners et al.*, 2004].

Part of the Agulhas Leakage water originates distally from the Antarctic Circumpolar Current (ACC). By far, the major proportion of waters involved in the global overturning circulation recirculates in this current. Surface water from the ACC is transported equatorward by the wind, especially in the Pacific Ocean and the East Indian Ocean. From there it finds its way to the Agulhas Current system through subduction and upwelling in various regions. When the Agulhas Current reaches the southern tip of Africa, the majority of this water retroflects, or loops backward, into the Indian Ocean through a not well understood combination of the Earth's rotation, bottom topography, and large-scale wind fields over the southern Indian Ocean. The rest spins off as eddies that move into the South Atlantic.

In January 2000, just before the first MARE cruise, a large ring with an initial diameter of 300 kilometers was shed from this retroflection area. MARE surveys (March and August 2000; February 2001) showed that the ring extended initially to the ocean bottom and had a surface velocity of 120 centimeters per second (cm/s) and a velocity of 10 cm/s at 5000 meters depth [*van Aken et al.*, 2003]. Five months later, the surface velocity had decreased to 80 cm/s and the ring structure had disappeared below 2500 meters.

Forty percent of the ring's decay was related to cooling by air-sea interaction. In a numerical model of the ring, cooling resulted in a shallow overturning circulation, enhancing mass, heat, and salt exchanges across the ring boundary. In addition to cooling, lateral intrusions and the associated heaving of density surfaces caused about 30 percent of the ring's decay. Instability of the ring causes ring water to spiral out of the ring in thin filaments, while surrounding water was entrained into the ring just inward of the filaments. Ring water in deeper layers was not transported further northwestward with the ring, but was left behind [*De Steur et al.*, 2004].

To unravel the sensitivity of past Indian-Atlantic inter-ocean exchange to climate changes, the paleo-record in ocean sediments at the ocean bottom was investigated. The modern MARE observations indicate that Agulhas rings carry a characteristic assemblage of Indian Ocean plankton. These advected Indian Ocean species accumulate in the bottom sediments of the southeastern

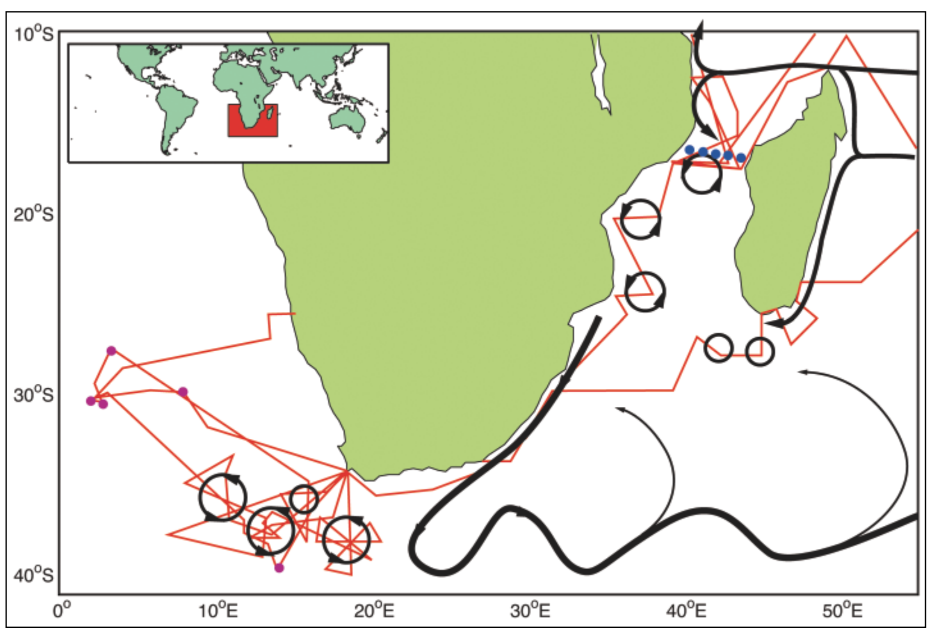

Fig. 1. The tracks of the MARE and ACSEX cruises. Black lines portray the surface ocean circulation; red lines portray cruise tracks. Blue dots indicate the locations of current meter moorings; red dots indicate sediment traps. Cruise tracks indicate the investigations that were carried out on Agulhas rings in the southeastern Atlantic Ocean as well as the hydrographic observations undertaken of eddies in the Mozambique Channel and south of Madagascar.

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Atlantic Ocean. Sediment cores taken just west of the ring-shedding area indicate that leakage was enhanced during present and past interglacial periods and largely reduced or even ceased during glacial periods. Maxima in leakage were recorded during the second half of the major deglaciations (Figure 3). The fossil record of Agulhas Leakage thus indicates that the flow of Indian Ocean water into the Atlantic has played a central role in the timing of interhemispheric climate changes and should be considered an important marine amplifier for the 100,000-year glacial-interglacial cycle [*Peeters et al.*, 2004].

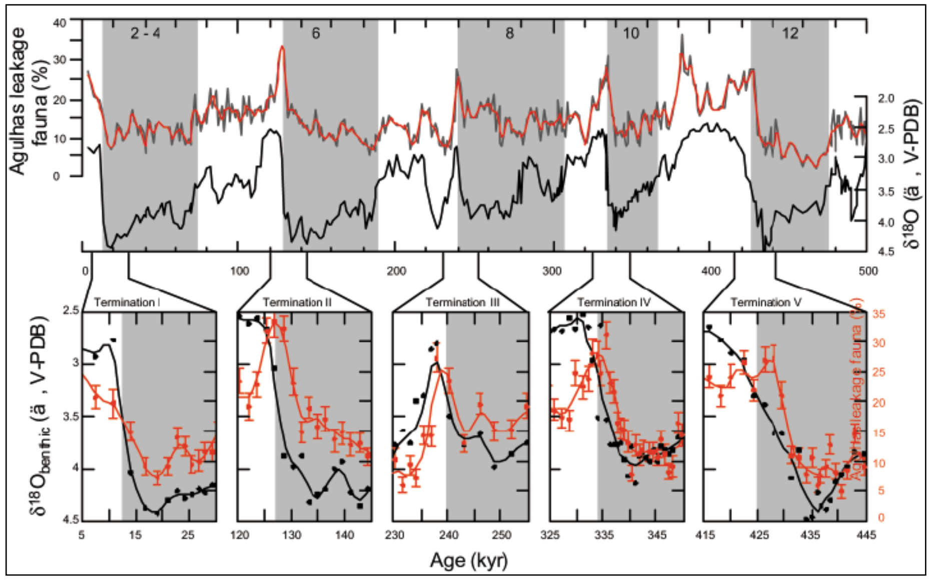

Fig. 3. The history of the Agulhas Leakage as reflected in fauna proxies in sediments (modified after Peeters et al. *[2004]). The top panel shows the oxygen isotope composition of the benthic foraminifer* Cibicides wuellerstorfi, *largely indicating global ice volume (black). The relative abundance of fauna associated with the Agulhas Leakage (red) is the sum of the relative abundance of Indian Ocean species of planktic foraminifera. An increase of Agulhas fauna is taken as evidence for increased Indian-Atlantic transport. The bottom panels are enlargements for the major glacial terminations of the Late Pleistocene (I–V) and show that the onset of the Agulhas Leakage started during late glacial conditions and reached maxima during the second half of the terminations. Maxima in the Agulhas Leakage is thought to have helped boost the ocean and global climate into the interglacial mode of circulation. Numbers along the top of the figure refer to glacial Marine Isotopic Stages.*

Eastward Retroflection and Currents Through the Mozambique Channel

Occasionally, the entire Agulhas Current retroflects much further east than usual, interrupting the interocean flow and the formation of rings. This occurred in 2000 and was studied at sea during one of the ACSEX cruises. The anomalous retroflection involved the current at substantial depths, lasted over nine months, and was connected to the stagnation of ring shedding. The causes for this behavior lie upstream, in the Mozambique Channel, southeast of Madagascar, and in the climate modes of the Indian Ocean.

During the first ACSEX cruise in 2000, the circulation south of the narrows of the Mozambique Channel was dominated by deep-reaching, southward-migrating, anticyclonic eddies [*De Ruijter et al.*, 2002]. There was no continuous boundary current along the western side of the channel that fed directly into the Agulhas, contrary to general belief. Satellite observations of sea-surface temperature and sea-surface height collected from 1992 to 2002 showed that these eddies, formed in the Mozambique Channel, eventually triggered the shedding of Agulhas rings.

Current meters from the LOCO project across the narrows of the channel have confirmed the regular formation of these eddies [*Ridderinkhof and De Ruijter*, 2002] with a poleward volume transport of about 14×10^6 cubic meters per second (m^3/s), which is in line with estimates of its contribution to the global thermohaline circulation. This transport oscillated between 60×10^6 m^3/s southward and 20×10^6 m^3/s northward due to the passage of the eddies. A strong northward-setting undercurrent was discovered, with a mean speed of five cm/s and current maxima at 1500 and 2500 meters. The latter was identified as North Atlantic Deep Water, connecting this deep Indian Ocean flow globally to the polar North Atlantic.

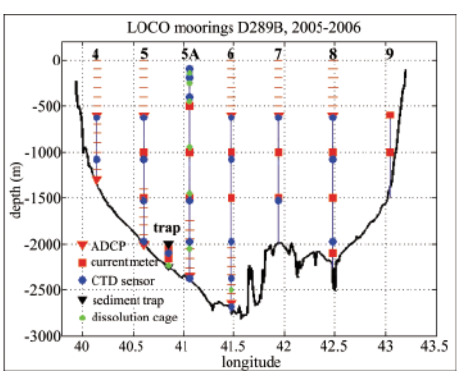

Fig. 2. The LOCO mooring array, located across the narrow section of the Mozambique Channel, will measure the time-varying transports at least until 2008.

East Madagascar Current

Little is known about the termination of the East Madagascar Current, which flows southward along the east coast of Madagascar. The data gathered during ACSEX II in 2001 give no clear evidence of a retroflection of the East Madagascar Current. During the cruise, an equatorward undercurrent was discovered that was connected to the same source as the undercurrent in the Mozambique Channel [*van Aken et al.*, 2004]. The presence of cold upwelled water was observed where the East Madagascar Current starts to diverge from the shelf edge, with higher concentrations of both nutrients and chlorophyll-*a* [*Machu et al.*, 2002].

During ACSEX II, a large vortex pair southwest of Madagascar, fed by the East Madagascar Current, was identified in satellite observations [*De Ruijter et al.*, 2004]. Its cyclonic lobe consisted of shelf and slope water, suggesting that this current was formed at the inshore edge of the East Madagascar Current when it diverges from the coast. Satellite altimetry indicates preferential formation of these vortex pairs when the Indian Ocean Dipole, the major interannual climate mode in the Indian Ocean comparable to El Niño in the Pacific Ocean, is in its negative phase. This negative phase is related to high sea surface temperatures off Sumatra, and low sea surface temperatures in the central and western tropical Indian Ocean. The current was exceptionally strong from July 1999 through 2000, triggering a regular sequence of dipoles leading to the anomalous eastward position of the Agulhas retroflection and the interruption of ring shedding. These observations point to a large-scale connection between tropical Indian Ocean climate modes and inter-ocean exchange south of Africa.

Summary and Future Work

These projects have so far revealed that the Mozambique Current is not continuous but is broken up into eddies, with a deep countercurrent connected to the global-scale circulation. Upwelling of cold nutrient-rich water off southeastern Madagascar was confirmed by hydrographic measurements. These projects have also discovered a correlation between varying inter-ocean exchanges and the past five glacial periods, which is probably controlled by the strength of the Indian Ocean tropical and subtropical climate modes.

Rings from the Agulhas Leakage extend to the ocean bottom, and the processes involved in their spin-down have been elucidated. However, the mechanisms controlling the regularity, coherence, and interannual variability of eddy formation in the system have yet to be confirmed. Preparations by researchers from IMAU, NIOZ, KNMI, Vrije Universiteit (Amsterdam), and others are under way for a new international program that builds on the successes achieved with MARE and ACSEX and is centered around the existing LOCO mooring array in the Mozambique Channel.

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References

De Ruijter, W. P. M., H. Ridderinkhof, J. R. E. Lutjeharms, M. W. Schouten, and C. Veth (2002), Observations of the flow in the Mozambique Channel, *Geophys. Res. Lett.*, *29*(10), 1502, doi:10.1029/2001GL013714.

De Ruijter, W. P. M., H. M. van Aken, E. J. Beier, J. R. E. Lutjeharms, R. P. Matano, and M. W. Schouten (2004), Eddies and dipoles around South Madagascar: Formation, pathways and large-scale impact, *Deep Sea Res., Part I*, *51*, 383–400.

De Steur, L., P. J. van Leeuwen, and S. S. Drijfhout (2004), Tracer leakage from modeled Agulhas rings, *J. Phys. Oceanogr.*, *43*, 1387–1399.

Drijfhout, S. S., J. Donners, and W. P. M. de Ruijter (2005), The origin of Intermediate and Subpolar Mode Waters crossing the Atlantic equator in OCCAM, *Geophys. Res. Lett.*, *32*, L06602, doi:10.1029/2004GL021851.

Machu, E., J. R. E. Lutjeharms, A. M. Webb, and H. van Aken (2002), First hydrographic evidence of the southeast Madagascar upwelling cell, *Geophys. Res. Lett.*, *29*(21), 2009, doi:10.1029/2002GL015381.

Peeters, F. J. C., R. Acheson, G.-J. A. Brummer, W. P. M. de Ruijter, G. M. Ganssen, R. R. Schneider, E. Ufkes, and D. Kroon (2004), Vigorous exchange between the Indian and Atlantic oceans at the end of the past five glacial periods, *Nature*, *430*, 661–665.

Ridderinkhof, H., and W. P. M. de Ruijter (2002), Moored current observations in the Mozambique Channel, *Deep Sea Res., Part II*, *50*, 1933–1955.

van Aken, H., A. K. van Veldhoven, C. Veth, W. P. M. de Ruijter, P. J. van Leeuwen, S. S. Drijfhout, C. P. Whittle, and M. Rouault (2003), Observations of a young Agulhas ring, Astrid, during MARE, the Mixing of Agulhas Rings Experiment, in March 2000, *Deep Sea Res., Part II*, *50*, 167–195.

van Aken, H. M., H. Ridderinkhof, and W. P. M. de Ruijter (2004), Spreading of North Atlantic Deep Water in the southwest Indian Ocean, *Deep Sea Res., Part I*, *51*, 755–776.

Weijer, W., W. P. M. de Ruijter, H. A. Dijkstra, and P. J. van Leeuwen (1999), Impact of interbasin exchange on the Atlantic overturning circulation, *J. Phys. Oceanogr.*, *29*, 2266–2284.

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