JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 105, NO. C9, PAGES 21,913–21,925, SEPTEMBER 15, 2000

Translation, decay and splitting of Agulhas rings in the southeastern Atlantic Ocean

Mathijs W. Schouten, Will P.M. de Ruijter and Peter Jan van Leeuwen
Institute of Marine and Atmospheric Research, Utrecht, Netherlands

Johann R.E. Lutjeharms
Department of Oceanography, University of Cape Town, Rondebosch, South Africa

Abstract. All Agulhas rings that were spawned at the Agulhas retroflection between 1993 and 1996 (a total of 21 rings) have been monitored using TOPEX/Poseidon satellite altimetry and followed as they moved through the southeastern Atlantic Ocean, decayed, interacted with bottom topography and each other, or dissipated completely. Rings preferentially crossed the Walvis Ridge at its deepest parts. After having crossed this ridge they have lower translational speeds, and their decay rate decreases markedly. Half the decay of long-lived rings takes place in the first 5 months of their lifetimes. In addition to the strong decay of rings in the Cape Basin, about one third of the observed rings do not seem to leave this region at all but totally disintegrate here. The interaction of rings with bottom topography, in particular with the Vema Seamount, is shown frequently to cause splitting of rings. This will enhance mixing of the rings' Indian Ocean water into that of the southern Atlantic. This localized mixing may well provide a considerable source of warm and salty Indian Ocean water into the Atlantic overturning circulation.

1. Introduction

The Agulhas Current is the western boundary current to several nested anticyclonic gyres in the South Indian Ocean. On the basin scale it is constituted by the wind-driven subtropical gyre of this ocean. On a smaller scale it is fed by a distinct subgyre concentrated in the southwestern part of the Indian Ocean [*Stramma and Lutjeharms*, 1997], which encloses an even tighter eddy-driven recirculation cell [*Feron et al.*, 1998]. Major contributions to the Agulhas Current's volume transport come from these subgyres. For instance, the Agulhas transport has been estimated to increase from 65 Sv (1 Sv = $10^6\,\mathrm{m^3\,s^{-1}}$) at 32°S to 95 Sv at the southern tip of Africa [*Gordon et al.*, 1987].

Having become detached from the African continent around 35°S, the Agulhas Current continues as a free jet in a west-southwesterly direction. Around 20°E it makes a strong anticyclonic turn back into the Indian Ocean, while conserving its potential vorticity [*De Ruijter and Boudra*, 1985; *Ou and de Ruijter*, 1986]. The location of this retroflection loop is highly variable, as monitored by infrared imagery [*Lutjeharms and van Ballegooyen*, 1988] and by radar altimetry [*Feron et al.*, 1992; *Wakker et al.*, 1990]. Intermittently, the westward progradation of the retroflection loop is terminated by the shedding of a large Agulhas ring when the current loops back upon itself. This event may be triggered by meanders in the Agulhas Current, causing the shortcut between the current itself and the Agulhas Return Current [*Lutjeharms and van Ballegooyen*, 1988; van Leeuwen et al., 2000].

The rings shed from the Agulhas Current consist of relatively warm and salty Indian Ocean water [*Olson and Evans*, 1986; *Gordon et al.*, 1987] compared to the ambient South Atlantic waters. Together with direct Agulhas leakage [*Gordon*, 1985], they constitute a distinctive source of energy and salt for the Atlantic. This feeds a net equatorward transport of these quantities in the South Atlantic and may establish a key link in the global thermohaline circulation (THC) [*Gordon*, 1986; *Weijer*, 2000]. From hydrographic and tracer data, obtained on a number of cruises, estimates of direct Agulhas Current leakage range between 2 and 10 Sv [*Lutjeharms*, 1996]. Estimates of the interocean volume transport by Agulhas rings range between 0.5 and 1.5 Sv per ring, salt flux estimates range between 0.7×10^5 kg/s and 6.3×10^5 kg/s, and heat flux estimates between 10^{-3} and $2.5 \cdot 10^{-2}$ PW (1 PW = 10^{15} W) per ring, depending on ring size and whether the anomalies are calculated with respect to their direct

Paper number 1999JC000046.
0148-0227/00/1999JC000046$09.00

surroundings [*De Ruijter et al.*, 1999; *van Ballegooyen et al.*, 1994]. However, if the Indian Ocean water input is (partially) compensated by North Atlantic Deep Water (NADW), then the heat flux estimates increase by an order of magnitude. Assuming complete compensation by NADW for a total volume flux of 14 Sv, *Gordon* [1985] has obtained a heat flux estimate of 0.5 PW. Based on six rings shed per year (see also below) they contribute about one third to the total estimated fluxes. These numbers are of comparable magnitude to estimates of the equatorward heat flux across 30°S [*Fu*, 1981; *Schlitzer*, 1996]. This has contributed to the development [*Gordon*, 1985; *Broecker*, 1991] of the concept of a global thermohaline overturning circulation in which a key role is played by Agulhas leakage.

Because of strong air-sea interaction, the positive sea surface temperature anomalies of Agulhas rings tend to disappear quickly [*Olson et al.*, 1992]. Rings can therefore be identified from thermal infrared images only for a very limited part of their lifetime. The signature of Agulhas rings in sea surface height (SSH) stays visible far longer, making satellite altimeter measurements very useful for monitoring the behavior of Agulhas rings over longer periods [*van Ballegooyen et al.*, 1994; *Gründlingh*, 1995; *Gordon and Haxby*, 1990; *Goñi et al.*, 1997].

The process of ring shedding by the Agulhas Current is highly variable [*Feron et al.*, 1992; *Goñi et al.*, 1997]. Estimates based on the 3 year Geosat period between 1987 and 1989 agree on five to seven rings being spawned per year [*Gordon and Haxby*, 1990; *Feron et al.*, 1992; *van Ballegooyen et al.*, 1994; *Byrne et al.*, 1995]. From the TOPEX/Poseidon data set (starting in November 1992), *Gründlingh* [1995] has estimated that five rings were shed in 1992 and that at least five were shed in 1991. *Goñi et al.* [1997] have given estimates of five, four, and six rings shed in 1993, 1994, and 1995, respectively. The speeds at which the rings travel in a west-northwestward direction lie between 5 and 15 kmd^{-1} [*Byrne et al.*, 1995]. They seem to slow down when getting closer to major bottom topographic features such as the Walvis Ridge. This slowing down is also expected from model results [*Kamenkovich et al.*, 1996].

After being spawned most Agulhas rings translate in a northwestward direction, changing to a more western course between 25° and 35°S. Most rings stay south of 20°S and also north of the subtropical convergence [*Gründlingh*, 1995; *Goñi et al.*, 1997]. *Garzoli and Gordon* [1996] have defined an "Agulhas Eddy Corridor" confining rings to their northwestward direction until 30°S and diverging north of that. *Goñi et al.* [1997] have placed the "Ring Corridor" more to the south, indicating the change of the rings' paths to more westward directions around 5° east. Their corridor is consistent with a maximum in the eddy kinetic energy of the area, which stems almost completely from Agulhas ring activity.

So far, studies on the fate and decay of Agulhas rings have focused on long-lived ones [*Byrne et al.*, 1995]. These rings penetrate the interior of the South Atlantic subtropical gyre and their water may thus conceivably recirculate in the subtropical "supergyre" that connects the South Atlantic and Indian Oceans [*De Ruijter*, 1982; *Schmidtz*, 1995]. As such, they may not contribute directly or immediately to the warm water limb of the Atlantic Ocean overturning circulation. Such an immediate contribution is expected to result predominantly from their decay in the Benguela Current region, i.e. in the Cape Basin off southwestern Africa, between the continent and the Walvis Ridge. A class of rings that seems to have gone unnoticed thus far consists of those that do not make it across the Walvis Ridge and that decay completely in the Cape Basin. Such rings may mix completely into the overturning circulation, providing it with a significant direct source of extra heat and salt. Therefore, in this paper the earlier analyses using satellite altimeter data [*Gründlingh*, 1995; *Byrne et al.*, 1995; *Goñi et al.*, 1997] are extended by an analysis of 5 years of data from the TOPEX/Poseidon altimeter, collected between 1993 and 1998. Focus is on the translation, decay and splitting of all identified rings and on estimating the number and size of rings that disappear from the altimetric signal. All Agulhas rings formed between January 1993 and December 1996 have been followed on their way through the South Atlantic Ocean.

2. Data and Methods

The TOPEX/Poseidon altimeters cover the World oceans between 65°N and 65°S every 10 days, with a spatial resolution of $\sim$ 7 km along track but with an intertrack spacing of $\sim$300 km at the equator. A coverage at this resolution means that mesoscale features with a diameter of 250 km, moving though the ocean, may temporarily not be resolved and may thus disappear from view. The precise locations of, for instance, Agulhas rings can therefore not be known all the time. Nevertheless, by interpolating between members of a series of mappings, one can usually get a reliable estimate of their trajectories. Only measurements that show some consistency in the height anomaly of the rings, or in their horizontal dimensions, have been considered reliable in this analysis. It is therefore expected that most of the time the measured position is within 50 km, or half a degree, of the actual center of the ring. A sudden drop in both height and diameter of a ring has been regarded as a "hole-in-the-net" incident where resolution of the feature has been partially lost.

All available data provided in the TOPEX/Po-seidon altimeter path-finder data set for the mentioned period have been used. The area under investigation includes the South Atlantic Ocean between 45° and 20°S. A mean ocean surface was computed from the measurements between November 1992 and November 1996 and subtracted from the measurements. This defines, but may underestimate, the intensity of the anomalies. All conventional corrections (instrumental, atmospheric, tidal and inverse barometer) have been applied to the measurements. The data processing used to create the path-finder dataset can be found on the WWW: http://neptune.gsfc.nasa.gov/~krachlin/opf/algorithms.html. For each 10 day cycle the data have been taken together and a surface has been fitted through them. These surfaces do not completely represent the state of the ocean at one instant but suffer some time distortion resulting from the 10 day cycle needed to collect all the data. Removing this time distortion adds little, but removes a substantial part of the variability and thus visibility of the rings [*Gründlingh*, 1995].

Only anomalies generated at the known location [*Lutjeharms and van Ballegooyen*, 1988] of the Agulhas retroflection were slected as ring candidates. The tracks of these Agulhas rings were then determined from consecutive maps, as described above. For a number of rings the individual satellite tracks have, furthermore, been examined in detail to obtain the actual measured SSH anomalies in every cycle.

We have determined the first time an anomaly is visible as a distinct entity on the altimetric maps and considered this as the moment of spawning. As the rings are shed in arguably the most variable area of the world ocean, the Agulhas retroflection, this is no easy task and is never quite objective. To detect the events in a more objective manner, the correlation method proposed by *Feron et al.* [1992] has been used. In this method an analysis is carried out of a time series to establish the decorrelation time of altimetrically derived SSH anomaly fields. The fields are obtained by a Gaussian interpolation in both time and space of the described altimeter data onto a regular 1° by 1° by 10 days grid. Decorrelation scales of 1.4° in space and 3.5 days in time were used. The correlation between each field and its successors is computed, and the time when this correlation drops below 0.5 for the first time is defined as the decorrelation time. The rate of change of the decorrelation time contains information about sudden changes in the SSH fields. A jump in decorrelation time is associated with a ring shedding event [*Feron et al.*, 1992].

Clearly, the crucial assumption being made here is that SSH anomalies in the southeastern Atlantic Ocean that are explicitly initiated at the Agulhas retroflection are indeed Agulhas rings and nothing else. Since this project did not contain a seagoing component, we were unable directly to verify most of the anomalies as rings. However, there exists ample evidence that the Benguela Current in this region is a broad and sluggish background drift with little inherent variability itself [*Garzoli and Gordon*, 1996; *Garzoli et al.*, 1996]. The preponderance of variability in the Cape Basin has therefore been demonstrated to arise from passing Agulhas rings only. A number of the type of anomalies we indentify here as Agulhas rings have been investigated hydrographically by others [*Arhan et al.*, 1999; *Goñi et al.*, 1997; *van Ballegooyen et al.*, 1994]) and have been demonstrated to be rings. Three of the set of features specifically used in our study were fortuitously surveyed at sea and unambiguously shown to be rings by it Arhan et al. [1999]. Two more were thoroughly measured by a range of observational methods, and described by *Garzoli et al.* [1999]. Another two that are not included in this investigation as they were shed before the start of the TOPEX/Poseidon period have been measured at sea and identified as Agulhas rings by *Garzoli and Gordon* [1996]. These are also described by *Clement and Gordon* [1995]. A number of these type of anomalies have, furthermore, been verified by their characteristic thermal expressions at the sea surface from infrared observations [*Gründlingh*, 1995] or have been correlated with current meter measurements [*Garzoli et al.*, 1997]. This large number of authentications gives us strong confidence that all the SSH anomalies we follow in this investigation have a very high likelihood of being Agulhas rings.

3. Agulhas Rings

3.1. Ring Shedding

By the methods described in section 2 we estimate that 21 rings were shed at the Agulhas retroflection between November 1992 and December 1996. The time series obtained by the decorrelation method were used to verify each visually identified ring-shedding event. These spawning events occured irregularly, but the average number of five rings per year seems to be a fairly steady value. We determine that in 1993, 1994, 1995 and 1996, 4, 6, 5, and 5 Agulhas rings were shed, respectively. These numbers agree very well to the results of *Goni et al.* [1997]. Small differences are caused by the subjective way of defining when exactly a ring is pinched off: visual inspection of snapshots of SSH or SSH-derived quantities such as the depth of the10°C isotherm does not enable the exact timing of the events within a month or so. To reduce the subjectivity involved in the visual inspection, the decorrelation method can be used for the timing of ring-shedding events. Three periods of over 4 months without any ring shedding were observed: in the second half of 1993, between August 1995 and January 1996, and again between February and June 1996, as illustrated in Figure 1. A relative change in decorrelation time of 30%with respect to the previous observation is chosen to distinguish peaks. All jumps in decorrelation time thus defined may be associated with a ring-shedding event. The peak at the end of 1993, which comes half a year after the shedding of three rings without a corresponding jump in decorrelation time, is an exception. The data suggest that during the second half of 1993 more rings were shed but were reabsorbed by the retroflecting current shortly afterward. This would cause the

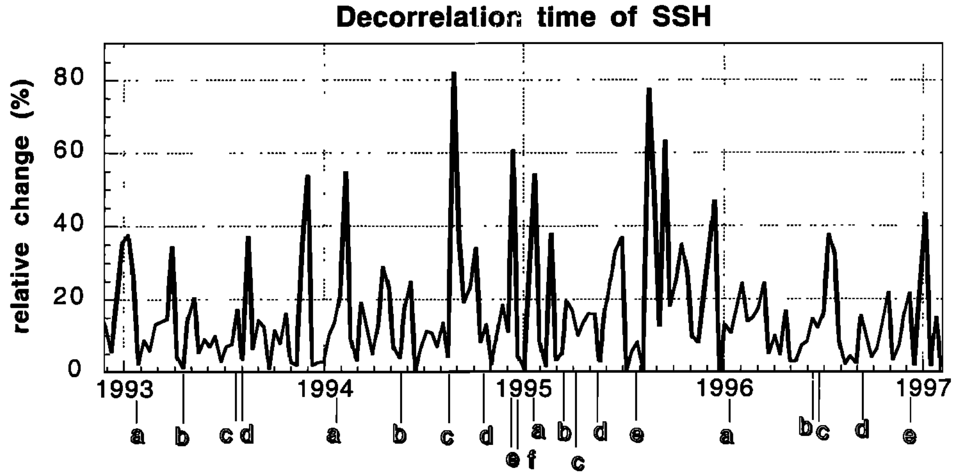

Figure 1. The relative change in decorrelation time between altimetry-derived SSH anomaly fields around South Africa. A maximum means that there is a sudden change in the SSH field, which is associated with a ring shedding event [*Feron et al.*, 1992]. This holds for almost all of the higher peaks. Below the horizontal axis the ring shedding events are indicated at the time they can be visually identified in the series of SSH maps.

decorrelation time to stay short as there is still a lot of mesoscale activity. The area used to evaluate correlations was fairly large (between 0°–30°E and 50°–20°S). It is therefore remarkable that the ring-shedding events seem to dominate the described signal for such a large area. This phenomenon is currently subject to further investigation.

On four occasions, two Agulhas rings were shed almost simultaneously or within 3 weeks. On three of these occasions the rings left the region in completely different directions (93C/93D, 94E/94F and 95B/95C in figure 2). It could therefore seem that the trajectories the rings take after spawning are indeterminate, but an analysis of their paths shows that this is not the case.

3.2. Ring Paths

All rings formed between November 1992 and December 1996 have been tracked as long as their SSH signatures permitted. The tracks of all 39 rings are given in Figure 2 (besides the 21 rings discussed before, 5 older rings are tracked, as well as 13 rings that are split off from other ones, as will be discussed in section 4). A tendency to avoid the shallow parts of the Walvis Ridge as noted by *Byrne et al.* [1995] is suggested by the tracks given in Figure 2, although rings with a very steady west-northwestward movement are not observed to have this tendency. A number of rings (93C4, 93C, 94B2, 94D, 94F and 96A; Figure 2) show a tendency for a greater meridional component in their movement on reaching the Walvis Ridge.

The corridor for rings suggested by *Goñi et al.* [1997], following the isolines of eddy kinetic energy, is partially confirmed by our data. The main routes of Agulhas rings are within this corridor, but a substantial number of rings nevertheless travels north of this corridor. Out of 39 observed rings, 12 are not confined by the corridor. Of these, 7 belong to the class of dissipating rings discussed below. The Agulhas Eddy Corridor drawn by *Garzoli and Gordon* [1996] lies considerably too far to the north. No rings would be allowed to cross south of 30°S, which is, in fact, done by two thirds of the rings that cross the Walvis Ridge.

From the conservation of potential vorticity one would expect a northward topographic steering when a ring encounters a ridge on the seafloor. We do observe this effect in a number of cases (rings 93C, 93C4, 94A3, 94D, 94E, 96A4 and 96B; Figure 2) but clearly not in all. A possible explanation for this difference is given by the modeling results of *Beismann et al.* [1999]. In their qausigeostrophic two layer model, rings that reach the ridge early in their lifetimes show the effect of northward translation on passing the ridge, whereas rings that have spent more time in the Cape Basin do not. The cause of this difference is the loss of barotropic structure that occurs with age. The older, more baroclinic rings are unable to feel bottom topography in the model. This explanation is not confirmed by our observations, as also older rings (like rings 93C4 and 94A3 over a year after shedding) show the northward movement along the slope of the ridge. Also, some younger rings (like 94B and 94B2 at ages of only half a year) pass the ridge without a clear disturbace to their paths.

The average translational speed of all the rings investigated fluctuates steadily around 4.8 $\mathrm{km d^{-1}}$. We found no evidence for seasonal or interannual variations in this speed of Agulhas rings. Our estimates confirm those established by *Goñi et al.* [1997]. However, average speeds vary by geographic location. Highest speeds occur in the eastern part of the basin, in the region east

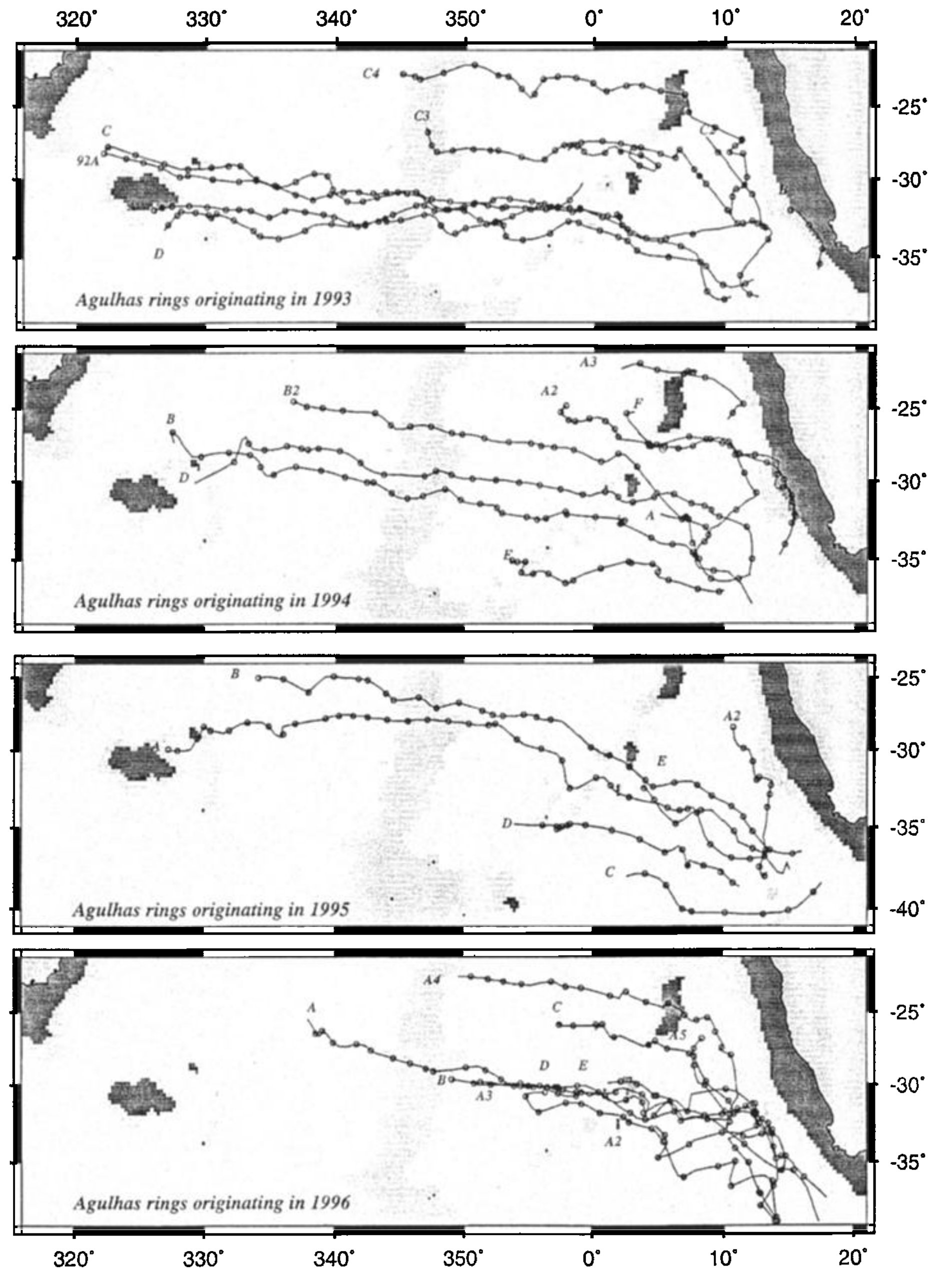

Figure 2. The paths of all observed Agulhas rings for the years 1993, 1994, 1995 and 1996. Ring 92A has been included in 1993's plot. The rings that were shed from the Agulhas retroflection have been named by their year and a letter, and the split off parts have been named by the name of their parent and a number (93C-2 is split from original ring 93C). The shaded contours are those for the 3500 and 2500 m isobaths. Dots indicate locations 1 month apart.

of the Walvis Ridge. For this region the mean speed for all rings is 5.2 kmd^{-1} (with a standard deviation of 3.6 kmd^{-1}). On passing the Walvis Ridge the mean speed drops to 4.6 kmd^{-1} ($\pm$3.1). This drop has usually been attributed to the direct effect of this strong topographic feature [*Byrne et al.*, 1995; *Gründlingh*, 1995], but that is not confirmed by our observations. We find that the mean speed stays low and even drops farther, to 4.3 kmd^{-1} ($\pm$2.2), for the region between the Walvis Ridge and the Mid-Atlantic Ridge. A more credible explanation for the higher speeds east of the Walvis Ridge is that the background flow in that region is stronger than elsewhere.

The influence of the background flow is also clear when one compares the mean speed of the rings on both sides of the 31°S parallel. South of it, in the heart of the wind-driven gyre, the mean translation speed is 3.5 km/day ($\pm$1.8). To the north, where the speed of the rings is enhanced by westward advection, the mean translation velocity is 4.9 kmd^{-1} ($\pm$2.5). If we assume the background zonal flow south of 31°S to be close to zero, which is supported by the results of drifter tracking [*Piola et al.*, 1987], and assume that the mean intrinsic drift of the rings north and south of the parallel is the same, we can derive a mean background flow of ~1.7 cms^{-1} for the region roughly between 31° and 25°S. An attempt has been made also to examine whether there is a relationship between translation speed and diameter of the rings, but because of the difficulty of measuring diameters accurately, it turns out that the signal to noise ratio is too small to draw any conclusions. The same holds for a comparison of the size, the shape, and the effect of bottom topography.

3.3. Ring Decay

The upper age at which rings are still reliably identifiable in this data set is ~ 2.5 – 3.5 years. By then the rings that travel near the 30°S parallel have almost reached the other side of the basin and are lost in the mesoscale variability associated with the Brazil Current. The rings taking the more northerly route are also lost after ~2.5 years. They will then have traveled a distance about as far as their more southern counterparts but have spent a larger part of their time in getting north. However, most rings could only be tracked for periods much shorter than 2.5 years. A substantial number of rings can be tracked for only ~ 7 months, and the split-off rings to be discussed below could be tracked for ~2 years if they were not dissipated before they reached the Walvis Ridge. (The rings shed or split off in 1996 are not included in these numbers, as they were not tracked after December 1997).

The decay rate of Agulhas rings has been considered to be exponential in a number of studies. *Byrne et al.* [1995], *Gründlingh* [1995], and others have made estimates of the *e*-folding distance for Agulhas ring decay. However, *van Ballegooyen et al.* [1994] have noticed that the strong decline of the SSH anomaly stopped for at least one ring after having crossed the Walvis Ridge. This latter behavior is confirmed by our results based on the close examination of 11 rings that can be tracked from their shedding at the Agulhas retroflection and that do not totally dissipate in the Cape Basin (Figure 3).

The first 5 months show a strong decay of ~5 cm per month on average. From ten months onwards the rings keep their surface height anomalies of, on average, just below 20 cm (Figure 3). In the first period after having been spawned the rings are subject to a combination of physical mechanisms, leading to strong decay. Their warm core of Indian Ocean water is strongly cooled by air-sea interaction. A large evaporative buoyancy flux adds to the increase of upper layer density. In particular, during winter this lead to vigorous convection down to over 300 m [*Duncombe Rae et al.*, 1996; *Olson et al.*, 1992]. In the next spring, subduction and associated lateral spreading [*Dewar*, 1987] leads to mixing of the ring's water into its surroundings. Observed temperature and salinity characteristics on isopycnal surfaces suggest that double diffusive interleaving is also a

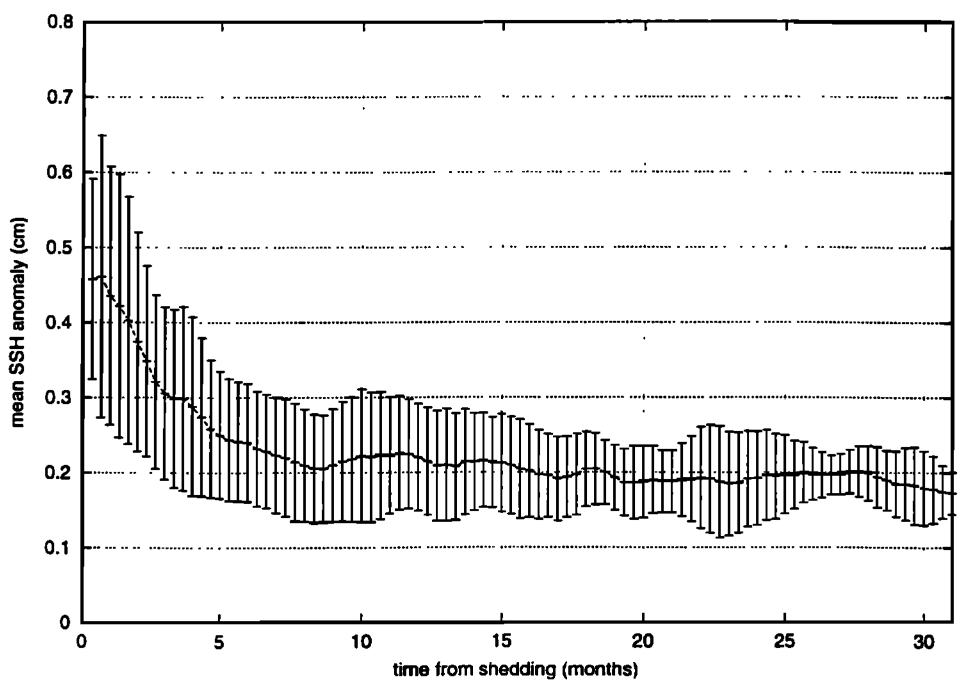

Figure 3. Mean SSH anomaly (and bars of 1 standard deviation) of Agulhas rings plotted against their age. The first 5 months can be characterized by a very strong decay in the Cape Basin. After 10 months the rings hardly decay anymore.

very active process by which ring properties are mixed into the environment [*Arhan et al.*, 1999]. On top of this, rings may be strongly deformed by their interaction with each other, by the shear in the background Benguela Current, and by their interaction with the bottom topography (as shown below and in section 4). Together with the small scale mixing processes this may lead to a large shear diffusion and associated decay of the rings. The Benguela region seems to act as a big blender by all the above processes.

In the next period the rings cross the Walvis Ridge, and after 10 months most rings have reached the relatively invarient regions west of the Walvis Ridge. Here there seems to be less distortion of the rings by background currents, interactions between rings, and bottom topography. Only the small-scale processes are still at work, leading to only a very slow decay (Figure 3).

The effect of the Walvis Ridge on the SSH expression of Agulhas rings has been mentioned by *Kamenkovich et al.* [1996]. They expected a measurable increase of the SSH elevation of up to 10 cm when the ring is approaching the higher parts of the ridge, followed by a decrease when leaving the ridge again. This is not inconsistent with our results, although the theory is not applicable to all rings measured by altimetry. Of 15 rings crossing the ridge over the shallower parts ($\leq$ 3000 m deep), 9 rings show the mentioned increasing SSH anomaly, whereas 6 do not. This is not clearly connected to the age of the rings, although the increase does always take place when the Walvis Ridge is reached at the end of the period of strong decay (the first 3-5 months). The rings that have already reached the more or less stable value of $\sim$ 20 cm before they arrive at the Walvis Ridge do not always show the expected behavior. This favors the assumption that the barotropic component of the rings is dissipated in the Cape Basin, taking away the rings's ability to feel directly the bottom topography. On crossing the Walvis Ridge the remaining deeper parts may be dissipated, explaining the end of the period of strong decay that is often marked by the passage of the Walvis Ridge. But, as the effect of the Walvis Ridge on the routes of the rings are not clearly related to the age of the rings, we cannot endorse this assumption right away.

4. Ring Splitting

In section 3, we described the decay of Agulhas rings that takes place rather continuously. However, a significant number of the rings appear to split up in the early stages of their lifetimes. In addition to the 20 rings that were shed from the Agulhas retroflection over our 4 year observational period, 13 rings were generated by splitting off from other rings. Three of the original 20 split once, one split twice, and two even split four times. Of these six rings that show splitting events, four were shed in the middle of the austral summer (during December/January). The sizes and spawning locations of these rings are not significantly different from those of the other rings.

One might well ask how reliable the interpretation of this degree of detail in unverified altimetric data is, particularly splitting events. Could the appearance of these events not be an artefact of the limited spatial resolution of the data? To date the products of only one splitting of an Agulhas ring have been explored at sea [*Arhan et al.*, 1999]. Distinct anticyclonic vortices of different dimensions and internal structure were found. Fortuitously, these particular eddies form part of our set of splitting products as well, giving us at least two hydrographic verifications. This gives us confidence that the other splitting events we have identified likewise represent real mesoscale features. The fact that the splitting products remain coherent anomalies in the altimetric data and that they may be tracked for a substantial period also argues against the idea of resolution artefacts. Such artefacts could be expected to be ephemeral.

4.1. Vema Seamount

Arhan et al. [1999] have reconstructed the splitting history of Agulhas rings they encountered at sea. Our analysis shows that such splitting was not an exceptional incident, but that it happens frequently. Not all splitting incidents can be attributed to a single mechanism, but bottom topography appears to play a striking role in this process (Figures 4 and 5).

The role of bottom topography in the decay of coherent vortices has also been documented for meddies in the North Atlantic. Three scenarios are observed in hydrographic measurements or float trajectory data. Encountering the line of Great Meteor Seamounts on their way west, meddies have been documented to split into two pieces [*Richardson and Tychensky*, 1998] as we observe with Agulhas rings, but passing between two seamounts with only a partial loss of 25% of the heat and salt content to the surrounding waters has also been observed and described [*Shapiro et al.*, 1995]. Finally, also complete destruction appears to be a possible result of the interaction between a meddy and strong topographic features. This scenario is observed by *Richardson and Tychensky* [1998] for a strong meddy encountering Hyeres Seamount, just north of Great Meteor Seamount. Agulhas rings may show similar behavior.

Remarkably, 6 out of 13 splitting incidents we have identified in this study occurred in the direct vicinity of the Vema Seamount. The Vema Seamount rises from the deep ocean floor to within 50 m below the sea surface at (9°E, 31°S). This makes it a major obstruction for Agulhas rings, which can penetrate several kilometers deep [*Olson and Evans*, 1986]. On encountering the seamount a ring may break up into two or three parts, which leave the region in different directions (Figures 4, 5). When an Agulhas ring (or part of it) has

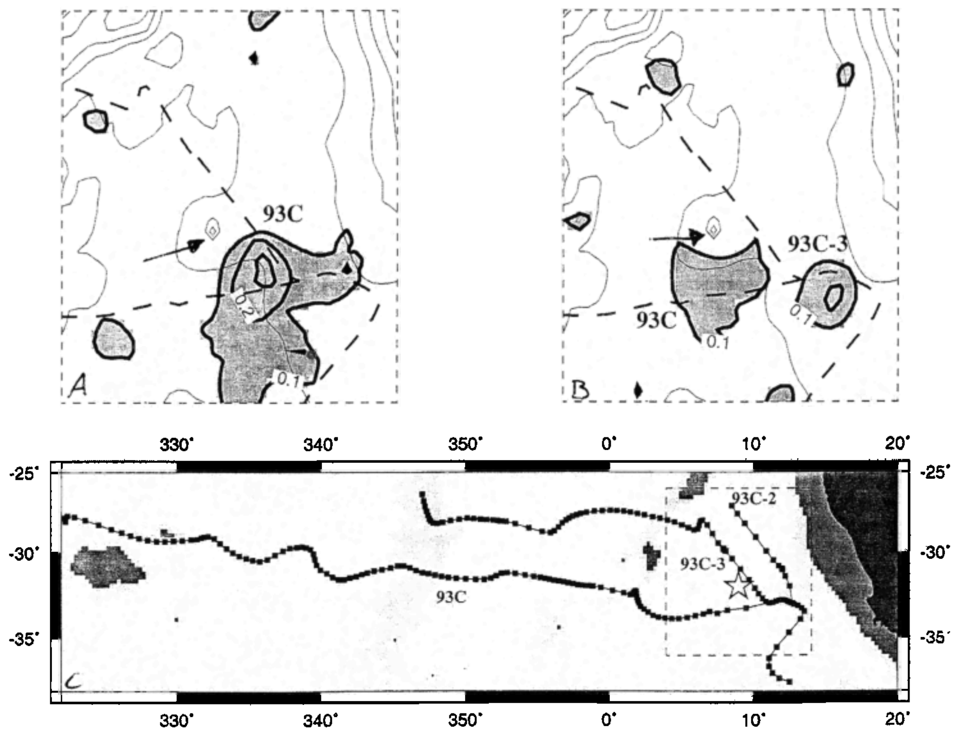

Figure 4. The first ring splitting event discussed in the text. (top) The actual splitting over Vema Seamount. The lighter contour lines are bottom topography, and the shaded areas have positive SSH anomalies of over 10 cm. Also superimposed are the paths of both split off parts (dashed lines). The arrows identify the Vema Seamount. (a) August 1993, with ring 93C approaching the Vema Seamount. (b) Three weeks later when ring 93C-3 had been torn off. (c) The paths of the splitting ring 93C and the split off parts 93C-2 and 93C-3. The Vema Seamount has been denoted by a star.

passed the seamount on its eastern flank, it is advected northward by the Benguela Current (Figure 6). The rings that stay west of Vema Seamount are seemingly not affected by a northward current. This supports the schematic picture of transports in the Cape Basin as given by *Garzoli and Gordon* [1996], with most of the Benguela transport flowing east of the seamount.

Although the limitations of the altimetric data prevent a detailed description of the processes involved in the splitting of Agulhas rings, two events are highlighted as examples of the effect of the Vema Seamount. The first one is the splitting of ring 93C (denoted in Figure 6 by upward pointing triangles). Shed in June 1993, it initially moved in a northward direction, until it reached the vicinity of the seamount, which it was seemingly unable to pass. A smaller part did move northward, and did split off immediately when ring 93C reached the seamount (Figure 4). This part, 93C-2, had an initial diameter of ~100 km (defined as the area of positive height anomaly) and a maximum sea surface height anomaly of 20 cm; it left the region quickly, probably advected by the Benguela Current, as the observed translation speed of 9 $cm\,s^{-1}$ is confirmed by the computed surface velocity for the CMM3-IES58 section of the Benguela Sources and Transport experiment (BEST) for August 1993 [*Garzoli et al.*, 1996]. This splitoff ring disappeared from the altimeter signal within 3 months, less than 600 km north of where it was formed. The remaining (larger) ring split into two roughly equal pieces (Figure 4), one of which passed the seamount to the east (93C-3), and the other of which passes the seamount to the west (93C itself). Both parts remained visible as anomalies in the altimetric data long after this: 93C-3 for another 2 years, 93C for over 3 years. By then, 93C had almost crossed the South Atlantic Ocean (Figure 4).

The second splitting event, described here as a further case study, took place in March 1996 (Figure 5). A large Agulhas ring (96A), shed only 2 months earlier, migrated over the Vema Seamount. Its path seemed undisturbed by the seamount, except that a major part of the ring was cut off. That cutoff part itself split into two pieces almost immediately thereafter. These two pieces continued to move north, where one of them disappeared from the altimetric signal within 6 months, and the other one crossed the Walvis Ridge to move west into the core of the South Atlantic subtropical gyre (Figure 5).

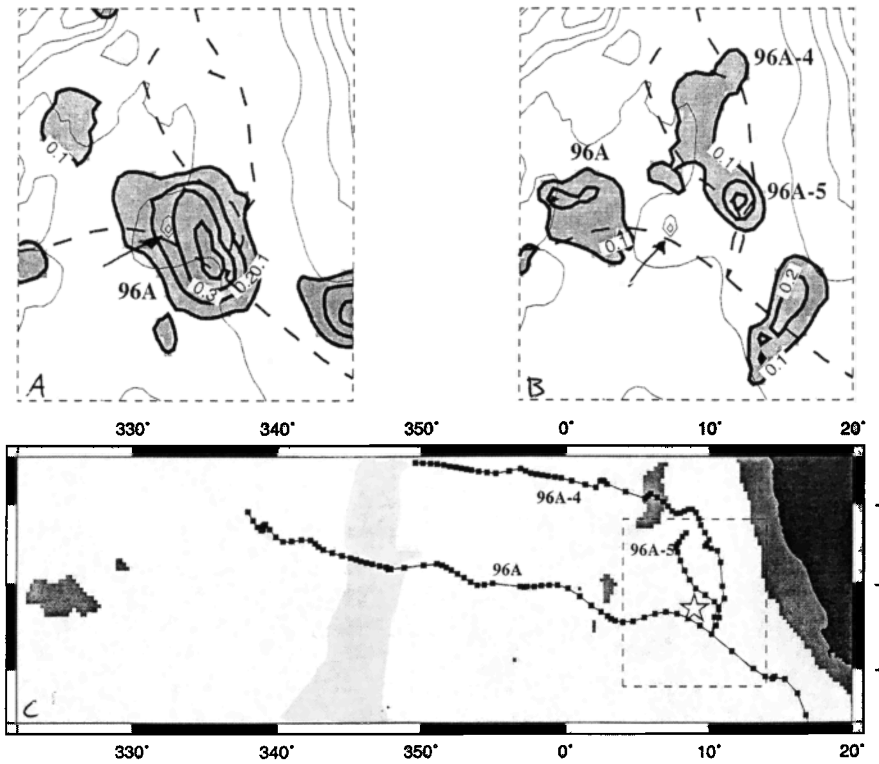

Figure 5. The second splitting event discussed in the text. (top) The actual splitting over the Vema Seamount, identified by arrows. (a) The third week of October 1996, when ring 96A was still one structure. (b) Six weeks later 96A-4, which had a very irregular shape, had split off. This irregular shape caused it to split again. To the southeast, a newly formed ring approached the seamount. Dashed lines show the paths taken by the original ring and its offspring. (c) The complete paths of the splitting ring 96A and the two split-off parts. The Vema Seamount has been denoted by a star.

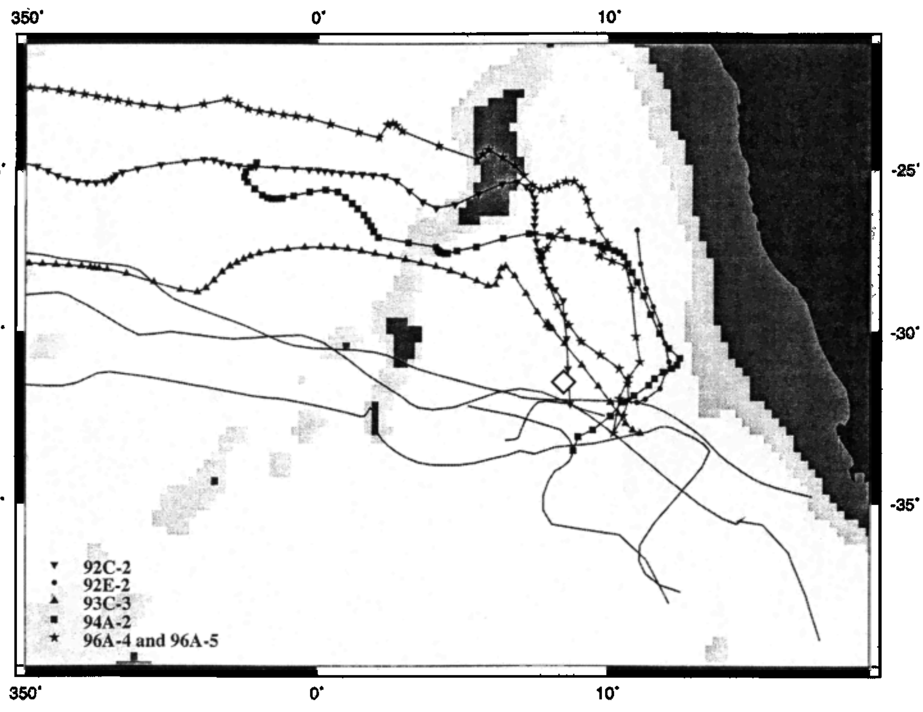

Figure 6. The paths of all rings that split over the Vema Seamount. The original rings are displayed just by lines; the split off parts are displayed by line with symbols. The northward tendency of the split-off parts, during the first period after splitting should be noted. The tendency of the parts that pass Vema Seamount on its west to be dominated by a westward drift component should also be noted.

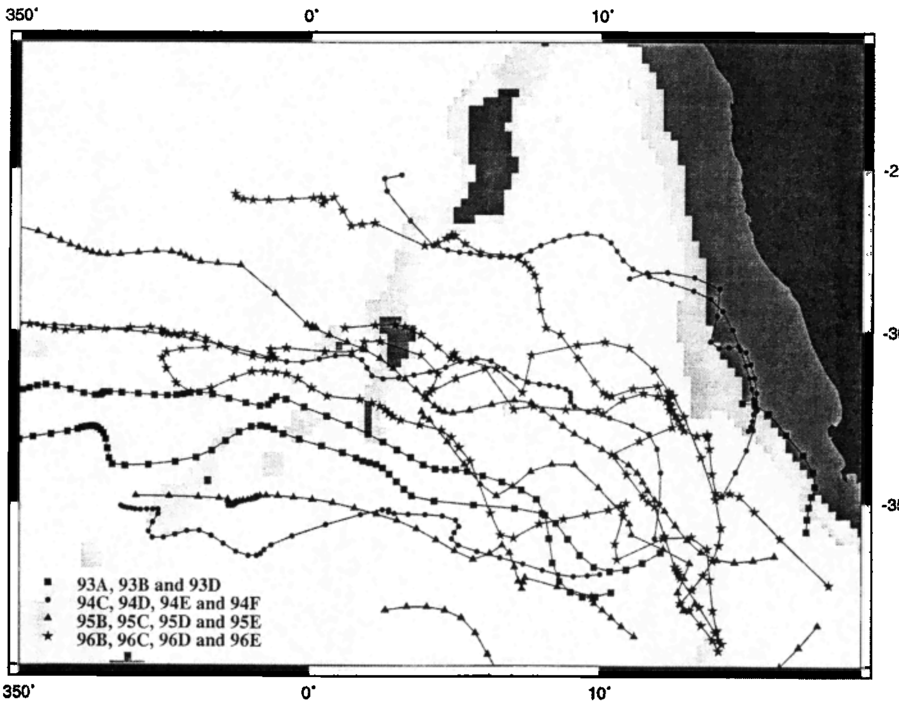

Figure 7. The other splitting incidents (not over Vema Seamount). Again, the paths of the split off parts are indicated also by symbols.

4.2. Other Eplitting Events

Not all splitting incidents identified in this data set can be attributed to the Vema Seamount. All other splitoff rings (seven in total) have been plotted in Figure 7. One ring (93C-5) split off from ring 93C-3 on crossing the Walvis Ridge and moved back into the Cape Basin before turning westward again and crossing the Walvis Ridge. On four occasions a ring split shortly after having been spawned at the Agulhas retroflection. Some of these may have been two separate rings from the beginning, that exhibited one combined SSH anomaly in the altimetric signal because of a lack of spatial resolution. The two remaining splitting incidents both resulted in two very stable rings. They took place in the Cape Basin, probably because the original rings became unstable because of a previous splitting event (the case of 93C-4 after splitting off 93C-3 over the Vema Seamount) or due to interaction with another ring (as 94B interacts with 94A before splitting off 94B-2). As mentioned earlier, the low spatial resolution makes deriving a relation between initial ring size and eventual splitting impossible. Nevertheless, splitting rings do not seem to be necessarily much larger than the rings that do not split.

5. Dissipating Rings

Agulhas rings that cross the Walvis Ridge and move westward into the South Atlantic subtropical gyre conceivably do not contribute directly to the Atlantic overturning circulation. However, a more direct contribution could possibly be made at an earlier stage, in the Cape Basin, by mixing of heat and salt into the environment of the dissipating rings.

A number of rings disappear as SSH anomalies from the altimetric data before crossing the Walvis Ridge (Figure 8). They constitute about one third of the total number of rings identified. Another 10% disappear just after crossing the Walvis Ridge. The equatorward movement of rings may lead to a 25% reduction of the SSH signal, because of conservation of potential vorticity. However, this would not constitute a sufficient reduction in SSH anomaly for them to disappear from the altimeter signal. It is therefore highly unlikely that all the anomaly disappearances can be attributed to the nature of the altimeter measurements. Although the rings do seem to show a tendency to become smaller and, usually, have less pronounced anomalies as they age, they should still remain clearly identifiable since anomalies as small as 10 cm can readily be measured. One is therefore forced to conclude that this class of "disappearing" rings consists of those that lose their coherence as features and disintegrate, with their anomalous heat, salt and vorticity contents would being dissipated at the location where one loses track of them in the altimetric observations. Even in the unlikely case of a small ring that comes to rest in the middle of a diamond-shaped hole in the altimetric net, the dissipation would still have to take place at that location, and the contribution would still be the same.

The rings that are shed from the Agulhas retroflection and that are seemingly dissipated in the Cape Basin have slightly smaller dimensions in the altimetric data than those that make it over the Walvis Ridge. The SSH anomalies were, however, not significantly lower: three of the five were ~ 40 cm. The other two were quite low, only 20 cm. This is more like the dissipated rings that had been split off by other rings: these, in general, had anomalies below 20 cm, except for ring 96A-5 which had an anomalous SSH of ~30 cm. All four rings with higher anomalies decayed rapidly to values around 15 cm, often within a month. The dissipating rings either were smaller from the beginning or were subject to stronger decay in the Cape Basin because, as suggested by the data, of stronger interaction with other rings, or of deformation by structural variations in the Benguela Current. Whatever the mechanism, they decayed far too rapidly to reach the more tranquil region west of the Walvis Ridge. Again, there is a bifurcation of the ring paths due to the Vema Seamount. Eight rings that later dissipated passed to the east, and three passed to the west (Figure 8). The latter were all lost more or less in the same region, where they should have crossed the Walvis Ridge but failed to do so. The five dissipating rings that were more strongly advected equatorward by the Benguela Current also ended up more or less in a similar region.

6. Discussion and Conclusions

On average, five Agulhas rings per annum were shed between the years 1993 and 1997. This number varies between years, and sometimes long periods of over half a year may occur in which there are no shedding events. The paths followed by the rings vary and are influenced by the intrinsic drift of the rings themselves, bottom topography, and background flow. During their lifetimes, the rings can cross the South Atlantic Ocean in ~2.5 – 3 years, but only two thirds of the rings make it farther than the Walvis Ridge, which is usually reached within a year of shedding.

About one third of the anomalies that are observed in the southeast Atlantic Ocean and that have the Agulhas retroflection as their origin, i.e., those assumed to be Agulhas rings, are lost from the altimeter signal before the Walvis Ridge. This accounts for 25% of the rings directly shed at the Agulhas retroflection and for 60% of split off rings. The latter originate from splitting events in which an Agulhas ring breaks up into two or more pieces. This splitting is often induced by bottom topography. The Vema Seamount in particular, appears to play a substantial role: 6 out of 13 splitting events during this period took place over this seamount. The split off rings often disappear from the altimetric signal in the Cape Basin, and this disappearance may indicate that the rings are completely dissipated here and that they lose their anomalous characteristics to the surrounding waters. Bottom topography may therefore have a strong influence on the mixing and dissipation of Agulhas rings.

In the first part of their trajectories, in the Cape Basin, the remaining rings decay to a rather stable

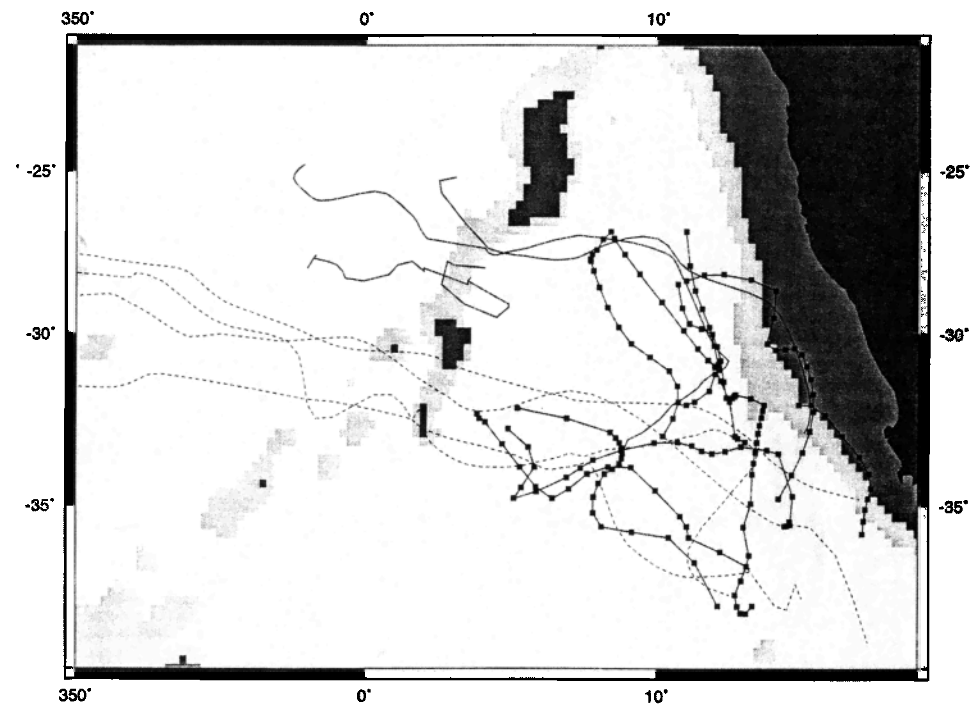

Figure 8. Trajectories of all rings that disappeared from the altimetric signal over the period 1993-1996. The rings that are lost east of the Walvis Ridge are indicated by symbols, the ones that are lost just after crossing it are indicated by solid lines. The original rings from which lost rings have split are indicated by dotted lines. Note that there are two regions where most rings disappear, around 4°E, 32°S and 10°E, 27°S.

anomalous height of ~ 25 cm within ~ 5 months from their initial anomalous SSH of ~ 50 cm . It is instructive to note that the model for Agulhas rings used by *Beismann et al.* [1999] shows a rapid decrease in ring energy during the first 5 months because of radiation of Rossby waves from the lower layers. This period is consistent with that found in the altimetric data (Figure 3). While crossing the southern Atlantic Ocean west of the Walvis Ridge, the rings hardly decay. This lack of decay may be due partially to the more quiescent environment west of the ridge, as there is less interaction with other rings and bottom topography. Shear diffusion, resulting from small-scale diffusion and large-scale deformation of the rings, may be an important decay mechanism in the Cape Basin, together with convective modification and double diffusive interleaving.

On the basis of the above numbers one can now try to make an estimate of the heat and salt fluxes into the Cape Basin and thus, possibly, the contribution of the rings to the Atlantic Ocean stability and overturning circulation. A direct contribution to the net northward transport is unlikely to be made by rings that penetrate the interior of the South Atlantic subtropical gyre. Their properties are probably absorbed in the Atlantic-Indian subtropical supergyre. However, we have shown that a major part of the properties of the rings may be contributed exclusively to the eastern part of the basin. The disappearing rings cause about one third of the total shed volume to mix into the Cape Basin. Added to that, the rings that migrate into the heart of the subtropical gyre decay to half their surface anomaly here. This decay implies a total volume decay of at least 50%. Together, this adds up to two thirds of the total inflow into the South Atlantic by Agulhas rings.

Estimates of the associated heat and salt inputs into the Atlantic overturning circulation are hard to give [*van Ballegooyen et al.*, 1994]. We base our estimates on the range of estimates found in literature and summarized in the section 1, and on the five rings per year that shed two thirds of their properties into the Benguela Region, which leads to an estimated contribution to the meridional salt transport of $\sim 3 \times 10^5$kgs^{-1}. The heat flux estimate ranges roughly between 3×10^{-3} PW and 0.15 PW. In the former case the Indian Ocean water of the rings is compensated by surrounding Atlantic waters [*van Ballegooyen et al.*, 1994]. The number of 0.15 PW is based on compensation of ring water by NADW as by *Gordon* [1985]. The impact of such sources of heat and salt on the Atlantic Ocean is not exactly clear yet, but a study by *Weijer et al.* [2000] suggests a strengthening of the overturning in direct response to enhanced Agulhas leakage.

Acknowledgments. JREL thanks his hosts at the Institue for Marine and Atmospheric Research of Utrecht University for a guest professorship and the kind invitation to contribute to this research. His travel was made possible by contributions from the South African Foundation for Research Development, the University of Cape Town, and the Netherlands Organisation for Scientific Research (NWO), via the Dutch National Research Program on Global Change (NRPII). Also, the work of MWS is supported by the NRPII program contract 013001237-10.

References

Arhan, M., H. Mercier, and J.R.E. Lutjeharms, The disparate evolution of three Agulhas rings in the south Atlantic ocean, *J. Geophys. Res.*, *104*, 20,987–21,005, 1999.

Broecker, W.S., The great ocean conveyor, *Oceanography*, *4*, 79–89, 1991.

Byrne, D.A., A.L. Gordon, and W.F. Haxby, Agulhas eddies: A synoptic view using Geosat ERM data, *J. Phys. Oceanogr.*, *25*, 902–917, 1995.

De Ruijter, W.P.M., Asymptotic analysis of the Agulhas and Brasil current systems, *J. Phys. Oceanogr.*, *12*, 361–373, 1982.

De Ruijter, W.P.M., A. Biastoch, S.S. Drijfhout, J.R.E. Lutjeharms, R.P. Matano, T. Pichevin, P.J. van Leeuwen, and W. Weijer, Indian-Atlantic interocean exchange: Dynamics, estimation and impact, *J. Geophys. Res.*, *104*, 20,885–20,910, 1999.

De Ruijter, W.P.M., and D.B. Boudra, The wind-driven circulation in the south-Atlantic-Indian ocean ,I, Numerical experiments in a one-layer model, *Deep Sea Res., Part A*, *32*, 557–574, 1985.

Dewar, WK., Ventilating warm rings: Theory and energetics, *J. Phys. Oceanogr.*, *17*, 2219–2231, 1987.

Duncombe Rae, C.M., S.L. Garzoli, and A.L. Gordon, The eddy field of the southeast Atlantic Ocean: A statistical census from the Benguela Sources and Transports project, *J. Geophys. Res.*, *101*, 11,949–11,964, 1996.

Feron, C.V., W.P.M. de Ruijter, and D. Oskam, Ring shedding in the Agulhas system, *J. Geophys. Res.*, *97*, 9467–9477, 1992.

Feron, R.C.V., W.P.M. de Ruijter, and P.J. van Leeuwen, A new method to determine the mean sea surface dynamic topography from satellite altimeter observations, *J. Geophys. Res.*, *103*, 1343–1362, 1998.

Fu, L.L., The general circulation and meridional heat transport of the subtropical South-Atlantic determined by inverse methods, *J. Phys. Oceanogr.*, *11*, 1171–1193, 1981.

Garzoli, S.L., G.J. Goñi, A.J. Mariano, and D.B. Olson, Monitoring the upper southeastern Atlantic transport using altimeter data, *J. Mar. Res.*, *55*, 453–481, 1997.

Garzoli, S.L., and A.L. Gordon, Origins and variability of the Benguela current, *J. Geophys. Res.*, *101*, 897–906, 1996.

Garzoli, S.L., A.L. Gordon, D.P. V.Kamenkovich, and C.M. Duncombe Rae, Variability and sources of the southeastern Atlantic circulation, *J. Mar. Res.*, *54*, 1039–1071, 1996.

Garzoli, S.L., P.L. Richardson, C.M. Duncombe Rae, D.M. Fratantoni, G.J. Goñi, and A.J. Roubicek, Thre Agulhas rings observed during the Benguela Current Experiment, *J. Geophys. Res.*, *104*, 20,971–20,985, 1999.

Goñi, G.J., S.L. Garzoli, A.J. Roubicek, D.B. Olson, and O.B. Brown, Agulhas ring dynamics from TOPEX/Poseidon satellite altimeter data, *J. Mar. Res.*, *55*, 861–883, 1997.

Gordon, A., Indian-Atlantic transfer of thermocline water at the Agulhas retroflection, *Science*, *228*, 1030–1034, 1985.

Gordon, A.L., Interocean exchange of thermocline water, *J. Geophys. Res.*, *91*, 5037–5046, 1986.

Gordon, A.L., and W.F. Haxby, Agulhas eddies invade the south Atlantic: Evidence from Geosat altimeter and shipboard CTD-survey, *J. Geophys. Res.*, *95*, 3117–3125, 1990.

Gordon, A.L., J.R.E. Lutjeharms, and M.L. Gründlingh, Stratification and circulation at the Agulhas retroflection, *Deep Sea Res., Part A*, *34*, 565–599, 1987.

Gründlingh, M.L., Tracking eddies in the southeast Atlantic and southwest Indian oceans with TOPEX/Poseidon, *J. Geophys. Res.*, *100*, 24,977 – 24,986, 1995.

Kamenkovich, V.M., Y.P. Leonov, D.A. Nechae, D.A. Byrne, and A.L. Gordon, On the influence of bottom topography on the Agulhas eddy, *J. Phys. Oceanogr.*, *26*, 892–912, 1996.

Lutjeharms, J.R.E., The exchange of water between the south Indian and south Atlantic oceans, in *The South Atlantic: Present and Past Circulation*, edited by G. Wefer, et al., pp. 125–162, Springer Verlag, New York, 1996.

Lutjeharms, J.R.E., and R.C. van Ballegooyen, The retroflection of the Agulhas current, *J. Phys. Oceanogr.*, *18*, 1570–1583, 1988.

Olson, D.B., and R.H. Evans, Rings of the Agulhas current, *Deep Sea Res., Part A*, *33*, 27–42, 1986.

Olson, D.B.R., R. Fine, and A.L. Gordon, Convective modification of water masses in the Agulhas, *Deep-sea Res.*, *39*, 163–181, 1992.

Ou, H.W., and W.P.M. de Ruijter, Separation of an inertial boundary current from a curved coastline, *J. Phys. Oceanogr.*, *16*, 280–289, 1986.

Piola, A.R.P., H.A. Figueroa, and A.A. Bianchi, Some aspects of the surface circulation south of 20S revealed by first garp global experiment drifters, *J. Geophys. Res.*, *92*, 5101–5114, 1987.

Richardson, P.L., and A. Tychensky, Meddy trajectories in the Canary Basin measured during the SEMAPHORE experiment, 1993-1995, *J. Geophys. Res.*, *103*, 25,029–25,045, 1998.

Schlitzer, R., Mass and heat transports in the south Atlantic derived from historical hydrographic data, in *The South Atlantic: Present and Past Circulation*, edited by G. Wefer, et al., pp. 125–162, Springer Verlag, New York, 1996.

Schmidtz, W.R., On the interbasin-thermohaline circulation, *Rev. Geophysics*, *33*, 151–173, 1995.

Shapiro, G.I., S.L. Meschanov, and M.V. Emelianov, Mediterrenean lens Irving after its collision with seamounts, *Oceanologica Acta*, *18*, 309–318, 1995.

Stramma, L., and J.R.E. Lutjeharms, The flow of the subtropical gyre of the south Indian ocean, *J. Geophys. Res.*, *102*, 5513–5530, 1997.

van Ballegooyen, R.C., M.L. Gründlingh, and J.R.E. Lutjeharms, Eddy fluxes of heat and salt from the southwest Indian ocean into the southeast Atlantic ocean: a case study, *J. Geophys. Res.*, *99*, 14,053–14,070, 1994.

van Leeuwen, P.J., W.P.M. de Ruijter, and J.R.E. Lutjeharms, Natal pulses and the formation of Agulhas rings, *J. Geophys. Res.*, *105*, 6425–6436, 2000.

Wakker, K.F., R.C.A. Zandbergen, M.C. Naeije, and B.A.C. Ambrosius, Geosat altimeter data analysis for the oceans around south africa, *J. Geophys. Res.*, *95*, 2991–3006, 1990.

Weijer, W., *Impact of interocean exchange on the Atlantic overturning circulation*, PhD thesis, Utrecht University, 2000.

W.P.M. de Ruijter, M.W. Schouten and P.J. van Leeuwen, Institute of Marine and Atmospheric Research, Utrecht University, P.O. Box 80005, 3508 TA Utrecht, The Netherlands (schouten@phys.uu.nl)

J.R.E. Lutjeharms, Department of Oceanography, University of Cape Town, 7700 Rondebosch, South Africa

(Receive August 23, 1999; revised March 3, 2000; accepted May 5, 2000.)