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Upstream control of Agulhas Ring Shedding

Short title: UPSTREAM CONTROL OF AGULHAS RING SHEDDING

Abstract. Rings shed in the Agulhas retroflection region play an important role in the global thermohaline circulation. The shedding of these rings has been considered very irregular. In this paper, we present evidence for remote control of the timing and frequency of these events. This turns out to be a far more regular process, at a frequency of 4-5 cycles per year. The movement of the Agulhas retroflection, and thereby the shedding of rings, is timed by incoming eddies from the upstream regions. Eddies from the Mozambique Channel, and from the East Madagascar current reach the Retroflection region at the frequency of 4-5 times per year. The existence of these eddies can be related to incoming Rossby waves that cross the Indian ocean and reach the Agulhas current system. These may in turn be part of a basin wide oscillation. The irregularity found in ring shedding statistics can be ascribed to processes occurring between the actual shedding and the first unambiguous observation of a separated ring.

1. Introduction

The large Agulhas rings that are spawned at the Agulhas retroflection form a key link in the global thermohaline circulation (Gordon *et al.*, 1992; De Ruijter *et al.*, 1999; Weijer *et al.*, 1999). The interoceanic exchange brought about by the warm and saline Indian ocean water entering the South Atlantic is a crucial part of the warm water route for the renewal of North Atlantic Deep Water (NADW) (Gordon, 1985). Moreover, it stabilizes the northern overturning circulation of the Atlantic Ocean (Weijer *et al.*, 2000). Hydrographic measurements have established the Agulhas rings as the most energetic ones in the World Ocean (Olson and Evans, 1986; van Ballegooyen *et al.*, 1994). Intermittency in the shedding of these energetic and climatically important rings has been reported by many investigators (Feron *et al.*, 1992; Byrne *et al.*, 1995; Schouten *et al.*, 2000), but has not yet been explained satisfactorily. The average number of rings seems to be a rather steady 4-6 per year, but periods of up to five months without any rings have been reported (Goñi *et al.*, 1997; Schouten *et al.*, 2000). No clear seasonal, interannual or other dominant frequency in the shedding of Agulhas rings has as yet been found. The process of the ring shedding itself has been described to some extent, based on various observational and modeling studies (see (De Ruijter *et al.*, 1999) for a review). Theoretical and modeling studies have concentrated mainly on the local dynamics of the retroflection and ring shedding (Boudra and de Ruijter, 1986; Boudra and Chassignet, 1988). Given the geometrical configuration of the tip of Southern Africa, and at given inflow and outflow conditions representing the Agulhas, the local dynamics are intrinsically unsteady and involve retroflection and ring shedding (Ou and de Ruijter, 1986; Pichevin *et al.*, 1999).

The observational record includes local sea surface temperature measurements (Lutjeharms and Van Ballegooyen, 1988), hydrographic investigations (Gordon *et al.*, 1987), and satellite altimetry measurements of sea surface height (SSH) elevations (Feron *et al.*, 1992). The general behavior of the retroflection in relation to the shedding

of Agulhas rings has been described fairly intuitively by *Lutjeharms et al.* [1988]. The retroflection loop of the Agulhas Current slowly progrades westward between 20-15° east, shedding a ring at the westernmost extension. By then the retroflection is constituted by a shortcut more eastward, which will in turn slowly move to the west. A more statistical approach, using altimetric sea surface height (SSH) data has confirmed the overall correctness of this description (Feron et al., 1992).

The general characteristics of the Agulhas Current system are that of an intense western boundary current to the large scale wind-driven Sverdrup circulation of the southern subtropical Indian Ocean. The total Sverdrup transport in this gyre is of the order of 60 Sv ($1 \text{ Sv} = 10^6 \text{ m}^3 \text{ s}^{-1}$). This anticyclonic gyre shows some remarkable features. First, the transport is largely concentrated in the Southwest corner of the basin, where a strong recirculation of water from the Agulhas Return Current is present. Of 60 Sv, half is recirculated west of 60° E (Stramma and Lutjeharms, 1997). An even tighter recirculation, close to the African continent, has been identified by calculating a mean dynamic sea surface height from the mean divergence of eddy vorticity fluxes measured by the Geosat altimeter (Feron et al., 1998). The mean flow field as depicted by *Stramma and Lutjeharms* [1997] gives an inflow of 25 Sv into the northern Agulhas Current from east of Madagascar which originates from the South Indian Ocean Subtropical gyre, and an additional 5 Sv from the Mozambique Channel, which draws its waters from further north and probably connects to the Indonesian Throughflow (Gordon, 1986) via the South Equatorial Current. This additional 5 Sv added to the southern gyre is balanced by a 5 Sv exchange to the South Atlantic in the form of filaments and Agulhas rings.

A recent cruise dedicated to the determination of the nature of the flow through the Mozambique Channel (the first cruise of the Agulhas Current Sources Experiment, ACSEX I (De Ruijter et al., 2000a)) has shown that this flow is not constituted by a Mozambique current comparable to other western boundary currents, but merely

by a train of eddies (De Ruijter et al., 2000b). These eddies, as suggested by SSH measurements from space were shown unambiguously to be present, and even to extend over the full depth of the channel ($> 2500\text{m}$) with diameters of 300-400 km. They were shown to carry water from the north, including a core of Red Sea water that is actively mixing with Antarctic Intermediate water. The latter penetrates northward into the channel as a continuation of the Agulhas undercurrent (Beal and Bryden, 1997; De Ruijter et al., 2000b).

Eddies in the Mozambique Channel were also found by Biastoch et al. (1999) in a $1/3^\circ$ primitive-equation model simulation. In their model, they could track the relatively shallow eddies (estimated to reach only 400m deep) until 34° south, where the Agulhas separates from the coast. There the eddies disintegrate in the model (Biastoch and Krauss, 1999), but still cause an extra interoceanic transport. Such a transport pulse might control the timing of the ring shedding at the Agulhas Retroflection (Pichevin et al., 1999). The origin of these model eddies was attributed to local barotropic instability of the modelled South Equatorial Current (Biastoch and Krauss, 1999).

So eddies from the Mozambique Channel propagate southward into the Agulhas Current. Another possible source region that of Agulhas variability can be identified by analysis of the variability of the sea surface height, lies southeast of Madagascar (fig. 3). There the East Madagascar Current retroflects and probably also sheds rings (Lutjeharms, 1988).

Even more remote forcing of the variability of the Agulhas current system may be due to incoming Rossby waves from further east (Morrow and Birol, 1998). Annual Rossby waves found over the full width of the Indian Ocean seem to be excited by changes in the winds (Périgaud and Delecluse, 1992; Birol and Morrow, 2000). Also, a semiannual Rossby wave is observed over the basin, associated with eastern boundary forcing (Birol and Morrow, 2000). These signals might be associated with coastally trapped Kelvin waves coming from the north (Subrahmanyam and Robinson, 2000),

thus linking the subtropical variability of the south Indian Ocean to the equatorial dynamics of the Northern Indian Ocean. However, recent analysis of observations (Matano et al., 1998) and model results (Matano et al., 2000) seem to indicate that especially the annual Rossby wave does not reach the Agulhas Region due to the blocking of these baroclinic waves by topography such as the Mascarene Ridge.

In this paper, we focus on upstream influences on the shedding of Agulhas rings. We show that the underlying physical process controlling the progradation of the retroflection loop is much more regular than previously thought (Goñi et al., 1997; Schouten et al., 2000). Evidence is provided for upstream control of the timing and frequency of ring shedding events, both via anticyclonic eddies from the Mozambique Channel, and via SSH-anomalies from southeast of Madagascar. In the next section, we start at the Agulhas Retroflection, and follow the Agulhas current upstream, to identify the variability in the Indian Ocean far field that may control the ring shedding process and its frequency. We finish with a short summary of our findings, and relate this to the central question of this paper: How and to what degree is the variability in the retroflection region, and thereby the local process of Agulhas ring shedding, connected to, or controlled by the large scale circulation of the (southern) Indian Ocean and its variability?

2. Ring Shedding and the Retroflection

The frequency of ring shedding has previously been estimated by counting the number of Agulhas rings that is eventually seen drifting into the Atlantic. This number is highly variable (Byrne et al., 1995; Goñi et al., 1997; Schouten et al., 2000). Large periods occur without any events counted at all. In this section, we show that this is not a feature inherent to the east-west movement of the retroflection, but rather a result of the behavior of the rings once they have been shed.

Figure 1 shows a hovmöller diagram of a zonal section along 39° S (see Fig. 2

for the location). Sea surface height anomalies are plotted for the years between 1993 and summer 1999. The TOPEX/Poseidon altimeter data (October 1992 - May 1995) were taken from the pathfinder dataset (Information on processing can be found on the world wide web: neptune.gsfc.nasa.gov/~krachlin/opf/algorithms.html). These data were binned into $1^\circ \times 1^\circ \times 10$ day bins. The combined TOPEX/Poseidon and ERS2 altimeter data (June 1995 - July 1999) were gridded and provided by the CLS Space-Oceanography Division in Toulouse. For details on processing, error estimation and gridding procedure see (Le Traon et al., 1998). The data are gridded to a $0.25^\circ \times 0.25^\circ \times 10$ day grid which is possible and meaningful as a result of the combined forces of ERS2 and TOPEX/Poseidon in spatial and temporal resolution respectively. All sea surface height (SSH) anomalies are high-pass filtered with a 200-day cosine window, leaving in signals with frequencies higher than roughly three times per year. So the annual and biannual cycle are strongly suppressed. Next, a 30-day running mean is taken. This combination is an efficient way of bandpass filtering and leaving in frequencies roughly between three and six times per year.

The retroflection loop appears to have a very regular westward movement, at a frequency of almost five times per year (Fig. 1). Probably not all westward intrusions result in the full shedding of an Agulhas Ring. Rings may reconnect to the main current, split up into several pieces in the early stages of their existence, or stay trapped behind the topographic features of the retroflection area (Arhan et al., 1999; Schouten et al., 2000). All these factors may influence the number of rings counted to leave the region, and make a 'shedding event' very difficult to define. The large range of existing estimates is thus not necessarily a result of the Agulhas current system itself being highly variable, but rather a result of the irregular behavior of the Agulhas rings close to their spawning region in the Southeast Atlantic (Schouten et al., 2000).

Not only in the filtered, but also in a plot of the unfiltered data the message is essentially the same: the retroflection of the Agulhas, identified by the positive anomaly

at 39°S, moves slowly westward with a constant speed of 13 km/day. The signal is highly regular with a frequency of 4.5 per year. The speed of 13 km/day agrees exactly with the mean speed of westward progradation found earlier in SST measurements (Lutjeharms and Van Ballegooyen, 1988).

Qualitatively similar to the analysis of *Goni et al.* [1997], in (Schouten et al., 2000) three periods were identified in which no Agulhas rings were observed to penetrate the southeast Atlantic Ocean: the second half of 1993, between August 1995 and January 1996 and again between February and June 1996. These periods can not convincingly be connected to periods of less activity in the movement of the retroflection (Fig. 1). The first period, in 1993, coincides with two occasions of an early return to an easterly position (east of 16°E) of the retroflection. The beginning of 1996 shows two clear examples of a far westerly protrusion of the retroflection (Fig. 1). However, the rings counted in (Schouten et al., 2000) are usually first identified around 10°E, where they can for the first time be reliably recognized as individual rings. For the reasons described above, these rings may not exactly be the ones that are shed around 14°E, as a lot can happen in between.

A major discrepancy exists between the frequencies estimated by *Lutjeharms and van Ballegooyen* [1988], and the present results from SSH measurements. The present data show that the large positive sea surface height anomalies move with a frequency of between four and five cycles per year, whereas the SST data suggested a westward progradation and sudden jump eastward of the thermal edge of the Agulhas to occur with almost double that frequency.

An explanation for this large difference may be the following. The westward moving water masses with positive vorticity, identified by altimetry as positive SSH anomalies (Fig. 1), are first considered to be the retroflection, and later on to be a shed-off Agulhas Ring. The difference between these two statuses is very small: in both cases they contain the same water masses, the same anticyclonic flow characteristics, and consequently the

same SSH characteristics. The only difference is in their connection to the incoming Agulhas Current, and outflowing Agulhas Return Current. It is clear from Fig. 1 that there is often more than one location on the 39°S parallel with strongly positive SSH anomaly. When two centers of positive SSH anomaly are present on the parallel, the current may very well be divided between the two: part of the flow retroflects early around the eastern center, and part of the flow continues a bit further southwestward, retroflecting around the western cell. This scenario is consistent with modeling results of a simplified Agulhas (De Ruijter and Boudra, 1985), where the inshore part of the current shows a lesser tendency to retroflect than the offshore part, due to the difference in vorticity contained in the shear of the flow.

In the period before a ring-shedding takes place, the upper layer of the Agulhas may temporarily shift between the two preferred locations of retroflection, which may account for the larger number of shedding counted from SST-measurements only. Although most of the current already retroflects at the eastern location, the ring to the west may still entrain warm surface waters from the Agulhas, obfuscating the SST-picture. This is illustrated by Fig. 2. It may look as if the whole Agulhas current is still or again retroflecting far west (around 15°E), but in fact most of the water may already retroflect at 20°E .

The retroflection shows surprisingly regular behavior in the SSH field. The question arises whether this is mainly due to the regular local process of loop occlusion (Ou and de Ruijter, 1986; Pichevin et al., 1999), to anomalies from upstream or downstream in the recirculation gyre (eg (Van Leeuwen et al., 2000)), or to variability at the basin scale. To answer these questions, we follow the SSH signal upstream, and show that it is connected to anomalies that appear in the northern Agulhas region. Next, we trace these back to the source regions of the Agulhas, the Mozambique Channel and the East Madagascar Current. Finally, the phenomena found in those areas are shown to be connected to each other and, most probably, to form part of a basinwide system of

variability.

3. The Retroflection: Connection to Upstream Regions

In their model, *Biaosch and Krauss* [1999] found propagating anomalies from the Mozambique Channel to propagate southward and reach as far as 30°S. The recent ACSEX I cruise has shown that these anomalies are in fact large and energetic eddies (De Ruijter et al., 2000b). In this section, we show a connection between these Mozambique eddies and the movement of the Agulhas Retroflection. Also, evidence is presented for the so-called Natal Pulse (Lutjeharms and Roberts, 1988; Van Leeuwen et al., 2000) being a manifestation of this larger scale process. The meander in the current seems to be triggered by a Mozambique eddy on the offshore edge of the Agulhas. Thus, the Mozambique eddies influence the behavior of the downstream retroflection in several ways.

3.1 SSH Observations

To accommodate a clear view of the dominant processes involved in the movement of the retroflection, and its connection with upstream sources of water and dynamical properties, we have performed a multichannel singular spectrum analysis (MSSA) (Plaut and Vautard, 1994) on high-pass filtered, altimeter derived sea surface height anomalies. The MSSA technique enables one to extract moving patterns from multidimensional data. We focus on a few prominent MSSA-modes (the ones with highest explained variances) rather than on modes that are selected by some significance-test such as the one proposed for SST-data (Allen and Robertson, 1996). This Monte Carlo-based test has a clearly stated null-hypothesis for sea surface temperatures (the red noise hypothesis for white noise atmospheric forcing), but there is no physically based null-hypothesis yet for testing the statistical significance of modes found by the MSSA analysis of SSH anomalies.

The region of the Agulhas Current system has been chosen sufficiently large to enable signals from outside the direct source regions to play a role in the analysis. In figure 3 we have plotted the total root mean square of the SSH anomalies. This figure strongly suggests that upstream impact on the Agulhas retroflection behavior, if any, could come from two directions: from the Mozambique channel, and from (south)east of Madagascar. The variability in the Agulhas return current is not likely to affect the ring shedding, as no evidence is found of westward propagating anomalies in the Return Current (Fig.4).

On the more than four years of available data (June 1995 to January 2000) the MSSA technique is applied. The first six resulting principal components have dominant frequencies between four and five times per year, as could be expected because of the bandpass filtering. The first two oscillatory pairs that are identified are formed by the components 1/2 and 3/4 respectively. Locally the two components can describe up to 35 percent of the variance. Especially in the retroflection area the explained variance is high.

The first couple of MSSA-components has its variability very locally centered in the retroflection region between 15° and 25°E. A hovmöller plot through the near zonal line of highest variability around 39°S, comparable to the one of the actual measurements in figure 1, shows the regular behavior of the Agulhas Retroflection (Figure 4). With a frequency of 4.5 times per year the Agulhas Retroflection slowly moves to the west (as was also evident from figure 1), and returns to its original more easterly state. (It should be noted that the propagation speed in both figure 1 and 4 is the same, but that the period covered by figure 1 is over two years longer).

However, although these first modes give a good first order description of the behavior of the retroflection, they do not give information on the remote control for this behavior. For that, we have to include the next four components. These also have a frequency of 4.5 times per year, but have their variance not just in the retroflection

area, but more evenly distributed over the rest of the Agulhas region. The fraction of the variance contained in the first six modes together is over 25% over the whole region west of 40°E, reaching 75% in the central Mozambique Channel and in the Retroflection region.

Together these modes form a new picture of upstream control of variability in the Agulhas retroflection and ring shedding. From the reconstructed snapshots of the ocean, built up by the first six MSSA-modes, the dominant features of the variability can be studied. Along the offshore edge of the Agulhas Current, anticyclonic anomalies are advected southward. These can clearly be observed in a Hovmöller diagram (Fig. 6) along a line chosen through the maximum of the observed variability (Fig. 5). They move (Fig. 6) as anticyclonic anomalies in southwestward direction (locations 1-15) in the left half of figure 6, and seem to trigger the westward shifting of the retroflection (clearly visible at the locations 15-20). The amplitudes are slightly less than expected from the original data, but irregularities in the precise timing of the phenomenon, and also the filtering applied, can strongly reduce the strength of the complete reconstructed signal. So the amplitudes found from the MSSA analysis need to be considered with great care, and can not directly be interpreted in terms of the original amplitudes. These are considerably higher in the retroflection region where they can reach up to one meter, and also in the region further north, where the anomalies on the offshore edge of the Agulhas have amplitudes of $\sim 20 - 40$ cm.

3.2 Natal Pulse Generation

The otherwise remarkably stable Agulhas Current path along the African coast is intermittently disturbed by a growing solitary meander, the so-called Natal Pulse (Lutjeharms and Roberts, 1988), which in general precedes the shedding of an Agulhas ring by almost half a year (Van Leeuwen et al., 2000). The anomalous flow is likely caused by a barotropic instability that can grow in the Natal Bight, where

the continental shelf is less steep than elsewhere along the coast (De Ruijter et al., 1999). At the Natal Bight the flow is only marginally stable, so a slight strengthening or sharpening of the current can make the flow susceptible to barotropic instability. Based on altimetric data, *De Ruijter et al.* [1999] suggest that relatively large offshore anticyclonic anomalies may be responsible for that strengthening of the flow, and speculate that this may be due to internal variability of the recirculation gyre in the Southwest Indian Ocean. The analysis above suggests that the anomaly causing that instability is not such a regional scale phenomenon, but that it has its origin much further upstream.

Figure 8 shows a series of consecutive snapshots of SST in the vicinity of the Natal Bight. The first snapshot, made on May 30, 2000, clearly shows an anticyclonic eddy in interaction with the Agulhas current. The eddy can easily be traced back further north in altimeter data like the ones we treated above. It pulls warm surface waters from the Agulhas, enabling the clear view on its anticyclonicity. It is located slightly upstream of the Natal Bight, enhancing and narrowing the flow. Five days later, exactly at the place where the coastline recedes, and where the continental slope is less steep, a cyclonic meander starts to grow in the current (Fig. 8b). The next day, June 5, the interaction between the current and the eddy has become less intense (they are clearly separated again in the SST signal shown in fig. 8c). On June 7 it becomes obvious that the Natal pulse is traveling south with the Agulhas (Fig. 8d). This eddy was also measured hydrographically at 24 °S in the Mozambique Channel during the first cruise of the Agulhas Current Sources Experiment (ACSEX I) in April 2000 (De Ruijter et al., 2000b), and clearly shown to have a velocity, temperature and salinity profile reaching all the way to the bottom of the channel at 3000 meter. In addition, a drifter was released in the eddy. The path of this drifter shows a swirling route southward (Fig. 7), as expected for water trapped in an eddy that constitutes an anomaly like those followed in figure 6. The drifter is ejected from the eddy during the period of interaction

with the Agulhas current (second half of May), and is further advected southward.

4. Connection to the Agulhas sources

Figure 3 suggests two possible source regions for the above identified eddies: the Mozambique Channel, and the southeast Madagascar Current. In this section, we show altimetric evidence for both.

4.1 The Mozambique Channel

Hydrographic measurements in the Mozambique Channel fail to agree on a steady circulation. Different campaigns have led to different snapshots of the circulation in the channel (Harris, 1972; Sætre and Da Silva, 1984; Donguy and Piton, 1991), but they do agree as far as the absence of a continuous western boundary current close to the Mozambique coast is concerned. They all picture the channel as a region dominated by mesoscale current features (between 100 and 400 km wide). Eddies in the Mozambique Channel are also observed in the model simulations by *Bia stochastic and Krauss*, [1999].

Recently, the ACSEX I cruise was carried out in the Mozambique channel (De Ruijter et al., 2000b). Hydrographic measurements were made with the focus of this new view on the channels flow structure. Eddies as suggested by the SSH measurements from space were shown unambiguously to be present and even to extend over the full depth of the channel (De Ruijter et al., 2000b) with diameters of 300-400 km. They were shown to carry water from the north, including a core of Red Sea water that is actively mixing with Antarctic Intermediate Water. The latter flows northward a a continuation into the Mozambique Channel of the Agulhas Undercurrent (Beal and Bryden, 1997).

4.2 The South-east Madagascar Current

The South-east Madagascar Current carries about 20 Sv southward along the coast of Madagascar (Swallow et al., 1988). At the southernmost point of Madagascar, it becomes unclear what happens to the current. A purely Sverdrup-dominated balance would result in a free westward jet crossing the southern end of the Mozambique Channel, to form a direct source for the Agulhas current south of 25°S. Observations of ship's drift in the region fail to show a univocal picture of the situation (Lutjeharms et al., 2000). Together with the high variability observed in the satellite derived SSH field, the variable ship's drift measurements indicate a region that is dominated by eddies. There is some evidence pointing at a situation more like that south of Africa: with a retroflection of the South-east Madagascar current and the flow turning east back into the central Indian Ocean. Based on a single SST snapshot *Lutjeharms* [1988] already speculated on the retroflective nature of the South-east Madagascar Current. That idea is confirmed by some of the drifters that were placed in the South Equatorial Current, and showed signs of a retroflection (Lutjeharms et al., 1981). But just like in the Mozambique Channel, no uniform picture can be drawn either from hydrographic or ships drift measurements (Lutjeharms et al., 2000). Due to the large variability of the flow in this region, rings may be shed from this retroflection like they are from the Agulhas, as the local dynamical properties of the system are rather similar to those around the southern tip of Africa: a narrow western boundary current overshooting the end of the landmass (Africa or Madagascar). From the altimeter data, it becomes clear (see below) that also in this source area of the Agulhas, eddies play a role in the structure of the overall flow.

4.3 MSSA Results

Again we focus on the first four modes found by the MSSA analysis of the region of the larger Agulhas system, extending between 5°E and 55°E and between 45°S and

5°S (eg. see Fig 3). The eddies found to propagate on the offshore edge of the Agulhas current (Fig. 8), and into the Retroflexion region, can be traced back to the source regions of the Agulhas. This is done In figure 10, again by constructing a Hovmöller diagram along the lines of highest variability. At intervals of ~ 100 km the reconstructed values of the first four MSSA-modes are plotted through the Mozambique Channel and from the African coast to the southern tip of Madagascar. There is a small overlap between the southern part of this trajectory, and the northern end of that in figure 5, so the anomalies can be clearly followed to propagate into the retroflexion. Anomalies are coming from both the Mozambique Channel and southeast of Madagascar, and connect to the eddy path plotted in figure 5. The anomalous sea surface heights are $\sim 20 - 30$ cm. These relatively high values indicate that they are eddies indeed. During the recent ACSEX I cruise this eddy nature was confirmed by CTD and Lowered ADCP observations in the Mozambique Channel (De Ruijter et al., 2000b). Analysis of the altimetric data gives a frequency of between 4 and 5 of these eddies per annum. Southwestward propagation is in the order of 10 km day^{-1} .

5. Connection to the Central and East Indian Ocean

So far, we have shown eddies from the Mozambique Channel and from the East Madagascar Current to penetrate the Agulhas Current System, and most probably control the timing of ring shedding at the westernmost extension of that system. But also the central and Eastern parts of the South Indian Ocean seem to play a role in the upstream control of the Agulhas Retroflexion. East of Madagascar (roughly between $10 - 30^\circ\text{S}$) the SSH-variability is dominated by westward propagating baroclinic Rossby waves (Morrow and Birol, 1998). Band pass filtered altimetric data (again focusing on frequencies between 4-5 times per year) along two zonal bands throughout the width of the Indian Ocean are plotted in figure 11. The left panel shows the 12°S parallel, that corresponds to the northern tip of Madagascar. The right panel shows the 27°S

parallel, corresponding to the southern tip of Madagascar. Both panels show clearly the propagation of Rossby waves. As was shown by *Morrow and Birol* [1998], the speeds agree well with the revised Rossby wave propagation theory (Killworth et al., 1997) i.e. 17 km d^{-1} at 12°S and 5 km d^{-1} at 12°S . At 12°S , the Rossby waves clearly feel the steep topography of the Mascarene ridge at $\sim 60^\circ\text{E}$. West of this ridge the signal is confused, but can be followed nonetheless to the African coast at 41°E . This confusion is partially caused by the strong 50-60 day periodicity of the western extension of the South Equatorial Current. An MSSA analysis of this region ($40\text{-}60^\circ\text{E}, 5\text{-}13^\circ\text{S}$) yields as the first oscillatory mode (formed in this case by the first two eigenvectors) a single meander in the South Equatorial Current starting at the northern tip of Madagascar, propagating westward. The dominant frequency of this mode is 55 days^{-1} , and the local contribution to the variability west of 50°E is over 40%. This MSSA mode is strongly present in 1996, 1997 and 1999, but less in 1998 and the end of 1995. The existence of this intramonthly variability is confirmed by local current measurements at Cape Amber reporting 41% of the flow variance in the 40-55 day period band (Quadfasl and Swallow, 1986; Schott et al., 1988). Based on results of a single-layer model, this has been ascribed to barotropic instability of the current system north and east east of Madagascar (Kindle and Thompson, 1989). However, their model does not reproduce the 400km waves between the tip of Madagascar and the African continent observed in the MSSA modes described above, and previously in modelling results (Périgaud and Delecluse, 1992). Applying MSSA to sea surface height deviations of a larger region extending to 20°S , the oscillating behavior of the South Equatorial Current is evident in the first 6 components, all with periods around 60 days. Now the anomalous sea surface height elevations are propagating into the Mozambique Channel. The slight modification of the preferred period may be due to this connection southward: the period of the MSSA mode is set by the region with highest variance, in the Mozambique Channel. But the propagation of anomalies from the extension of the South Equatorial

Current into the channel still suggests that part of the meanders may shed into eddies entering the Mozambique Channel. The incoming Rossby waves from the east, with even slightly longer periods of around 90 days and at semiannual frequency, may act as a triggering mechanism for this process.

At 27°S, the Rossby waves show a significant intensification at $\sim 45^\circ\text{E}$ (Fig. 11). This can be due to the rising bottom (depths decrease from $\sim 4000\text{m}$ to $\sim 1500\text{m}$ within 500 km). But it may also be due to the interaction with the East Madagascar Current, that may lead to eddy shedding at the southern tip of Madagascar. As the intrinsic drift of a freely moving eddy is very similar to the propagation speed of Rossby waves, it is very difficult to distinguish between propagating waves and eddies. However, the sea surface elevations of over 20 cm found south and west of Madagascar are too high to be solely the expression of a (linear) Rossby wave. Also, the anomalies found south and west of Madagascar are more or less circular, and those found further east have more meridionally elongated shapes. The picture thus emerges of a regular train of Rossby waves that cross the Southeast Indian Ocean at a frequency of 4 per year, are focussed, and lead to the formation of eddies in the western part of the basin.

6. Summary and Discussion

In this paper, we have shown evidence for the existence of a direct link between the shedding of Agulhas Rings and incoming eddies from upstream areas, in particular the Mozambique Channel and the region south of Madagascar. The timing of Agulhas ring shedding is controlled by the eddies traveling downstream along the offshore edge of the Agulhas current. These eddies form part of a larger system probably incorporating the whole South Indian Ocean. The zonal movement of the Agulhas Retroflection loop can be followed in altimetric measurements. It moves slowly to the west, and returns to an eastern position with a frequency of 4-5 times per year. The location of the retroflection can be traced back to the arrival of an eddy from the north. In former analyses this

movement of the retroflexion has been associated with the shedding of Agulhas Rings. However, Ring shedding records are far more irregular than the behavior of the Agulhas Retroflexion described here. This can be attributed to the many complicating factors that dominate the signal once the rings have been shed into the Atlantic. In the first months of their life time, they interact strongly with the bottom topography, with each other, and with background currents. Also, rings may split or be recycled back into the Agulhas Current (Arhan et al., 1999; Schouten et al., 2000). All these influences prevent the regularity inherent to the current itself from being observed in the Ring shedding record. Unique determination from satellite altimetry is furthermore hampered by the unknown mean background circulation, the spatial and temporal resolution of the altimetric measurements, and the limitation to the upper layer of all available remote sensing observations.

Besides the impact on the movement of the retroflexion, the eddies from upstream may also control the timing of Agulhas ring shedding by generation of the so-called 'Natal Pulse' which has been observed to be related to ring shedding almost half a year later (Van Leeuwen et al., 2000). The anticyclonic eddy on the seaward edge of the current can provide the positive transport anomaly needed to destabilize the current near Durban (De Ruijter et al., 1999).

In the Mozambique Channel, eddies are observed to propagate in southwestward direction from the northern end of the channel. These eddies have been measured hydrographically. We have shown that they can be followed in MSSA-filtered altimetric data to be the same eddies as those observed on the offshore edge of the Agulhas. This is confirmed by a drifter released in one of the measured Mozambique eddies. This drifter clearly shows the rotating path of water inside an eddy, and the southward translation that is observed for the Mozambique eddies in the five year record of altimetric data. This single eddy has also been observed to interact with the Agulhas near Durban (in SST snapshots), triggering a large solitary southward traveling meander: a Natal Pulse.

The Mozambique eddies themselves may be connected to processes further east in the Indian Ocean, as Rossby waves are observed to cross the Indian ocean over the full zonal extent with frequencies close to that of the observed eddies in the Mozambique Channel and on the offshore edge of the Agulhas Current. These Rossby waves, propagating at speeds comparing well with theoretical estimates (Killworth et al., 1997), are found in the latitude band between 10 and 30°S. Both to the north and south of Madagascar interaction of these Rossby waves with local currents (the South Equatorial and East Madagascar Current respectively) may result in the shedding of eddies, as suggested by the strengthening of the anomalies in these areas.

However, the origin of the frequency of 4-5 per year remains unclear. The forcing mechanism resulting in the Rossby waves at this frequency is not yet identified. No seasonal forcing is expected at this frequency, and atmospheric variability is mainly found at shorter timescales. A candidate explanation is that the Rossby waves are the manifestation of an internal eigenmode of the Indian ocean. Interaction of a seasonal Rossby wave with the much shorter period of the local instability of the South Equatorial Current north of Madagascar leading to the observed periods is another one. Further study is presently underway to identify the origin of this phenomenon.

The interaction of the eddies from the north with the southern Agulhas current once it has become a free jet south of the African continent can be intuitively understood, but dedicated numerical studies should provide an answer to the question how and to what extent this process determines the shedding of Agulhas rings. The eddies do not seem to be a necessary condition for the existence of Agulhas rings, as instabilities in the retroflection have been shown able to produce these rings without remote forcing. Nevertheless, the eddies may very well act as the finite amplitude disturbance needed to trigger the instability after the conditions have been set by internal processes, and thereby determine the exact timing of the process.

Besides a dynamical impact, the Mozambique eddies also have distinct water mass

properties that give them also a direct thermohaline dimension. In situ observations have shown that a Mozambique eddy in the southern part of the channel contained a large core of intermediate water of Red Sea origin, thus containing a large saline anomaly with respect to the relatively fresh surrounding water (De Ruijter et al., 2000b). Red sea water has also been identified in the Southeast Atlantic ocean (Gordon et al., 1987), indicating that the eddies may indeed not only be a dynamical source of vorticity for the retroflection, but also a direct source of water at intermediate depths and above.

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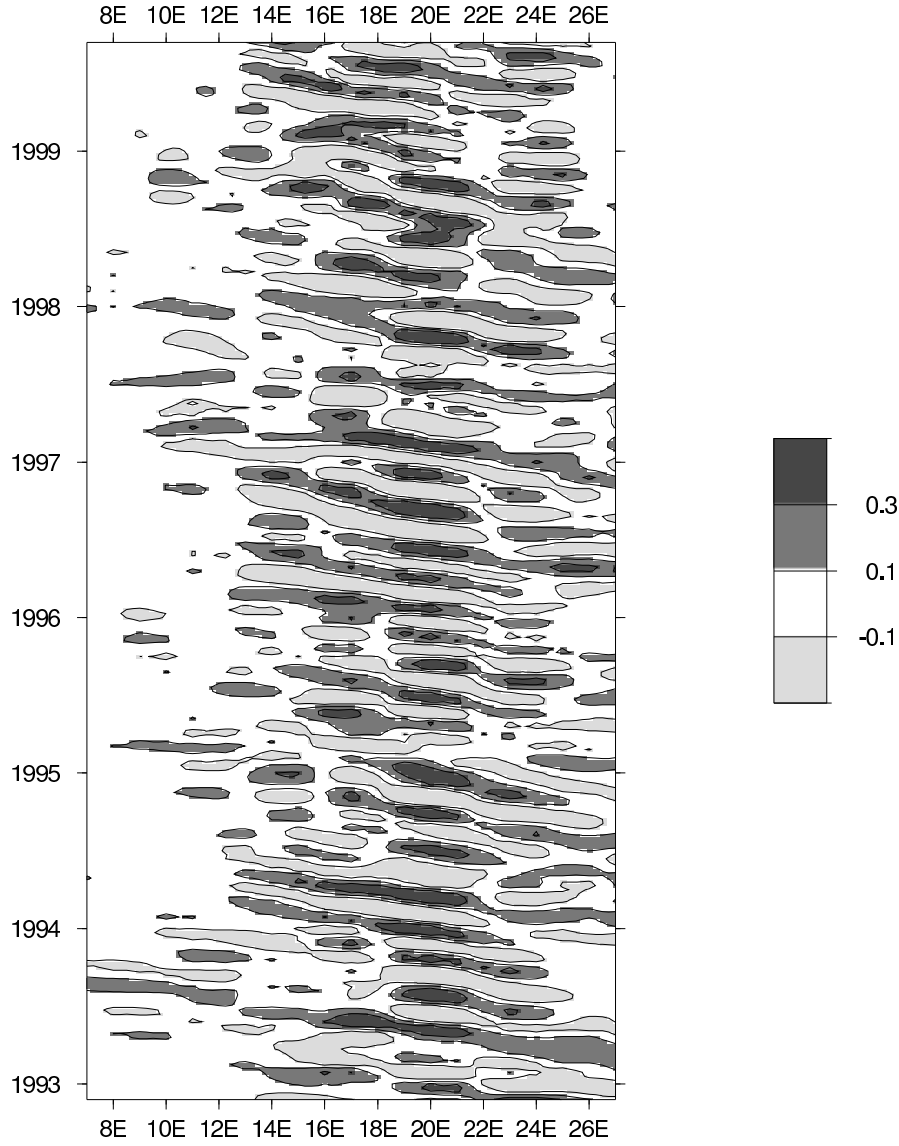


Figure 1. Hovmöller plot of filtered sea surface height anomalies (in meter) along a zonal section at 39°S. Bandpass filtered sea surface height anomalies are plotted for the period January 1993 - January 2000. The positive anomalies, associated with the retroflection of the Agulhas Current progrades to the westward between 22°E and 14°E. Jumps occur when the westward progradation of the centers of positive SSH anomalies end. These can be interpreted as ring shedding events, occurring ~ 4 -5 times per year. The maximum at 20°E should be noted, as that is the location to where the current returns after the shedding of a ring. Suddenly the anomaly that came from further east is enforced by the current.

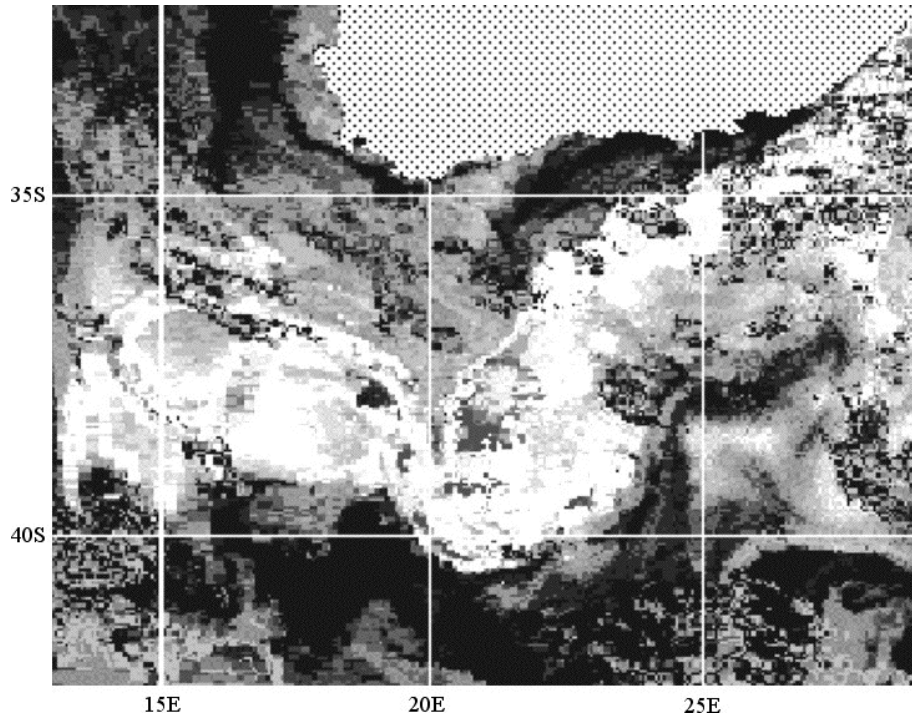


Figure 2. Snapshot of sea surface temperatures in the Agulhas Retroflexion region from March 18, 2000. Light colors denote higher sea surface temperatures. Temperatures range between 22 and 16 degrees Celsius. It is not clear from this picture where the main current flows. Is it still going all the way around the large ring in the west, or has the ring been shed already, and does the current retrofect south of the southernmost point of Africa? This is the ambiguous stage hampering univue determination of ring shedding from SST-only studies.

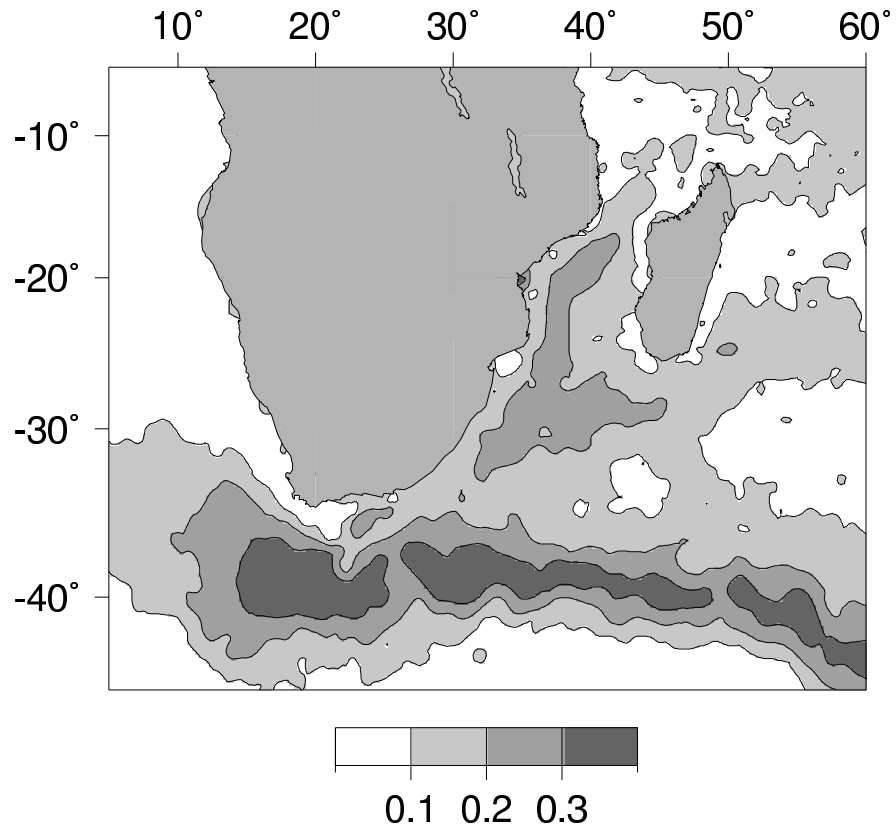


Figure 3. Variability of the sea surface height (meter) measured by TOPEX/Poseidon during 1993-1998. Two possible source areas of variability in the Agulhas region can be identified: the Mozambique Channel and south of Madagascar. Also, both regions are connected to a band of enhanced variability in the central and eastern Indian Ocean

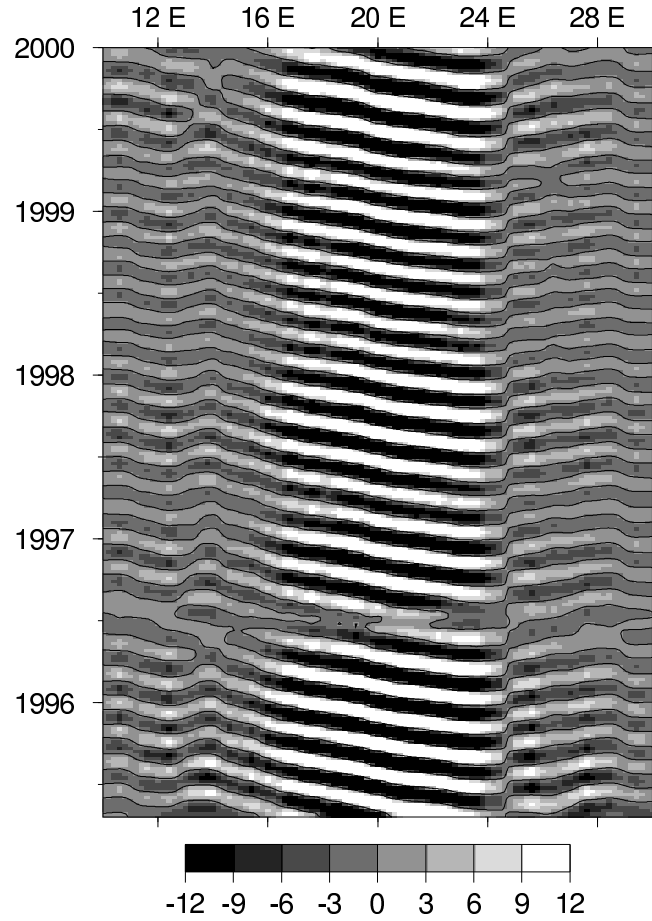


Figure 4. Hovmöller plot like in figure 1, but now taken through the line of maximum variability contained in the first MSSA mode. This coincides roughly with the 39°S parallel, and can be considered the mean path of the Agulhas Retroflexion and the Agulhas Return Current. The analysis has successfully captured the main features of the variability of the retroflexion area. Again we can see the retroflexion slowly moving west. Also clear from this plot is that there is no westward propagation of anomalies from the Return Current (from east of 25°E), although some variability is visible, set to the same frequency by the MSSA-technique.

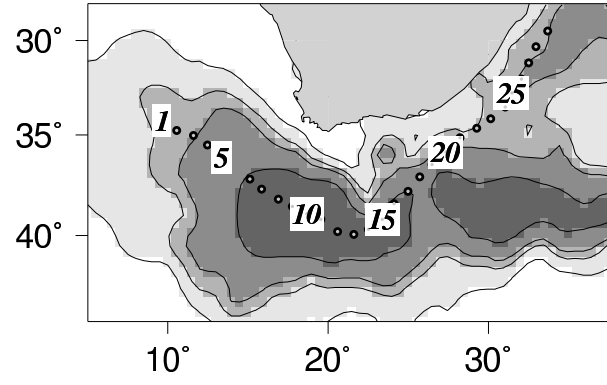


Figure 5. Variability in the Agulhas Retroflection region, and the track along which the Hovmöller plot of the upstream control is plotted. The numbers correspond to the horizontal axis of the Hovmöller plot. This track has been chosen along the line of maximum variability.

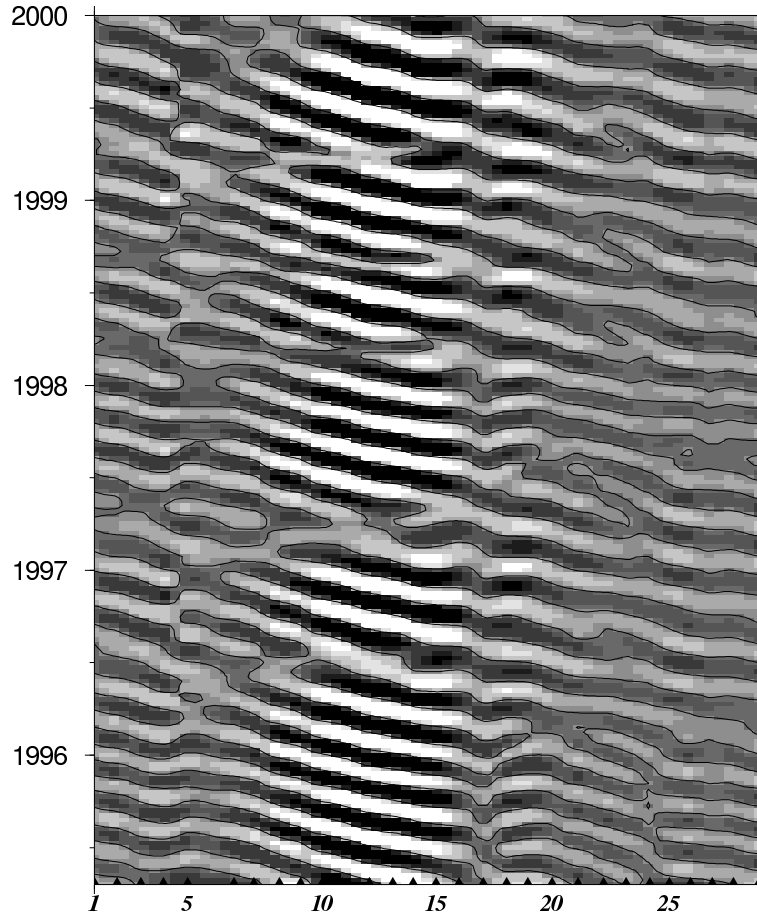


Figure 6. Hovmöller plot of the sum of the first six MSSA-modes along the track shown in figure 5. The numbers on the horizontal axis correspond to the locations shown there. Anomalies can be followed from the upstream Agulhas near 30°S (point 25) to the westernmost point of the retroflection (point 1). Amplitudes are given in cm.

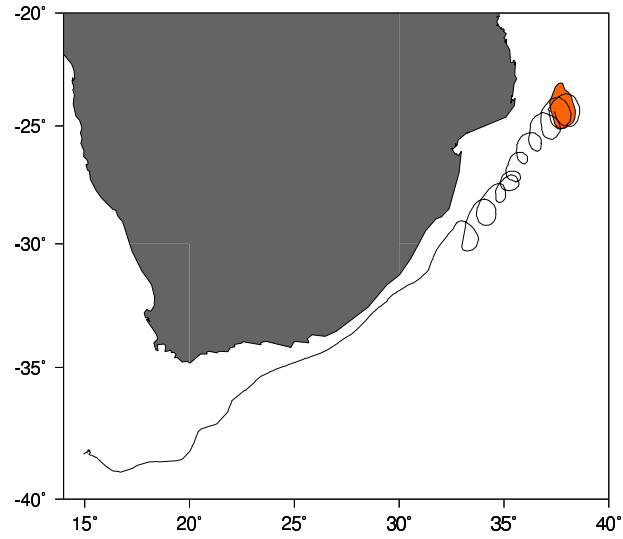


Figure 7. A drifter was released inside a Mozambique eddy during the ACSEX I cruise, on April 1 (it De Ruijter, 2000). The eddy (as identified by the 15cm SSH anomaly contour) is drawn here, with the track of the eddy in the subsequent weeks. After travelling south within the eddy for six weeks, it was released to the Agulhas current near the Natal Bight on May 15. This is during the interaction of the eddy with the current illustrated in the SST-snapshots of figure 8

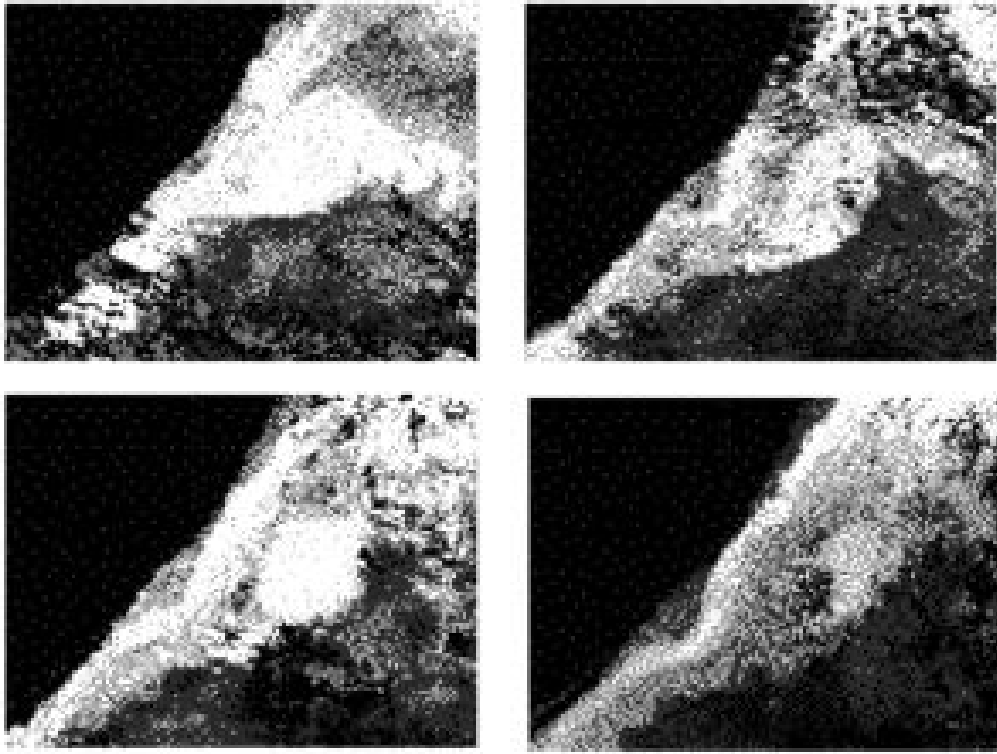


Figure 8. Four consecutive snapshots of the sea surface temperatures near the African coast around 30°S . Warm temperatures result in lighter colors. (a) May 31, 2000: A Mozambique eddy is in interaction with the main current. This is concluded from the warm sst of the eddy, that can only be achieved by connecting to the Agulhas. As air-sea interaction cools the sst of the eddy quickly, transport of warm water by the eddy is highly unlikely. (b) June 4, 2000: The current is pulled away from the coast, a meander is being formed. (c) June 5, 2000: The connection between the current and the eddy is weakened. The meander is moving southward. (d) June 7, 2000: The meander is clearly visible, and moving southward. Clouds partially obstruct a view of the eddy, but its sst have also decreased due to air-sea interaction, as can be concluded from the north-eastern part that is still visible.

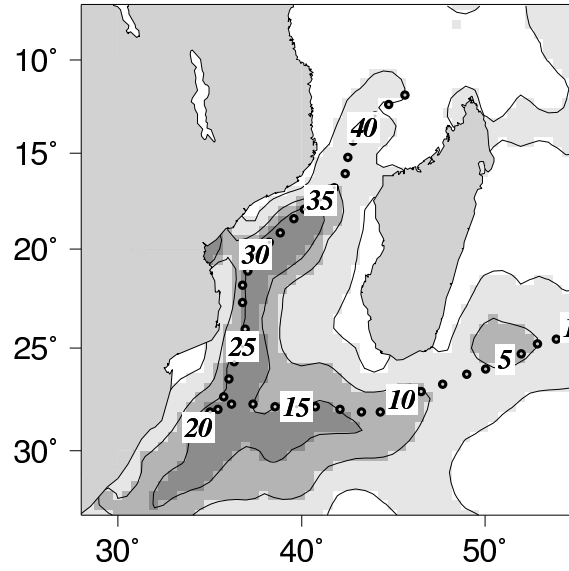


Figure 9. As figure 5. Now the track along which a hovmöller plot is constructed has been chosen in the Mozambique channel and south of Madagascar. These tracks cover the Mozambique eddies, and the possible eddies being spawned from the Madagascar current. There is a small overlap between figure 5 and this track, to accomodate a continuous tracking of the propagating anomalies. The hovmöller plot itself is shown in figure 10.

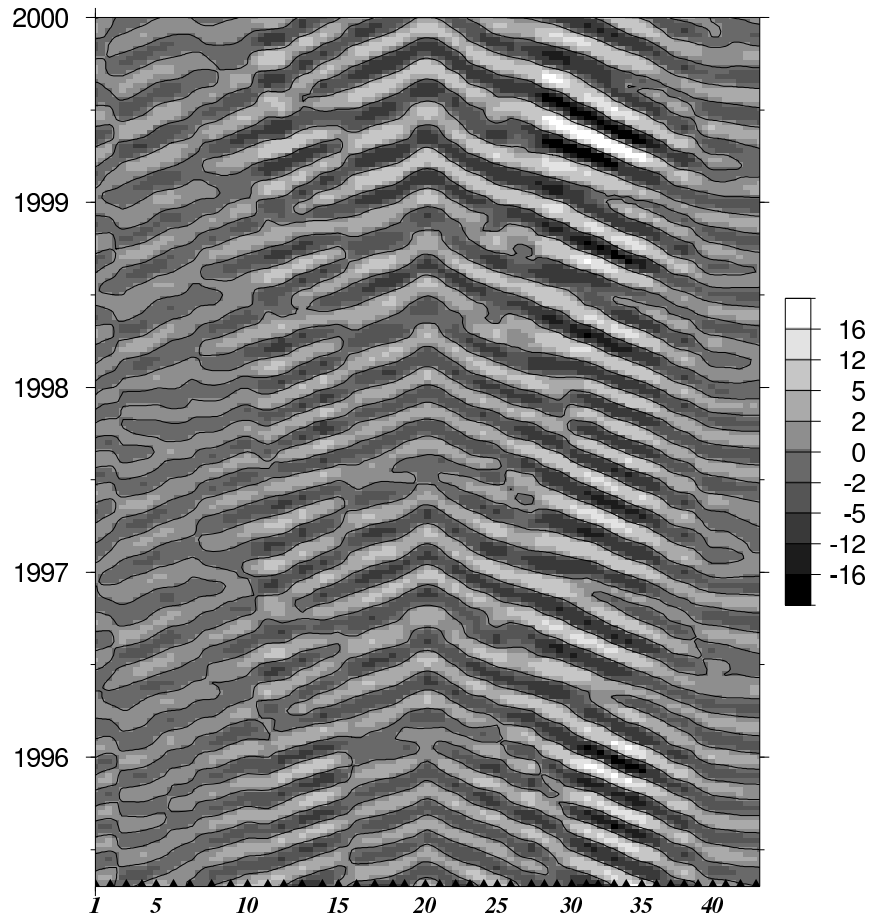


Figure 10. Hovmöller plot through the reconstructed components 3-4 of the MSSA analysis, along the tracks shown in figure 9. Amplitudes are given in cm. The discontinuity at point 20 denotes the most 'downstream' point of the plot. From both directions incoming anomalies can clearly be followed. From the Mozambique Channel to the Northern Agulhas at 30°S in the points (along the horizontal axis) 1-20 the translation is mainly in southwesterly direction, whereas the a movement along the line 40-20 means a westerly translation. A striking feature of this plot is the aparent synchronisation of both processes: anomalies from the norh and the east arrive simultaneously.

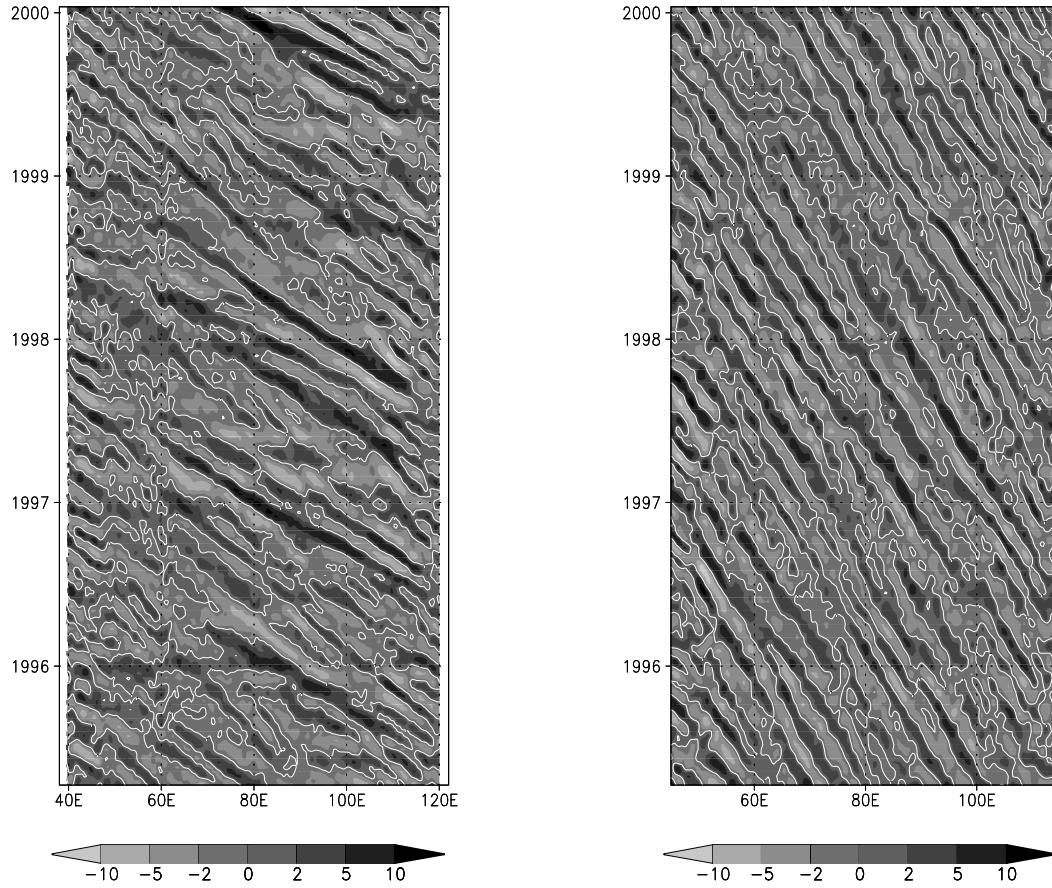


Figure 11. Hovmöller plot of bandpass filtered SSH anomalies along the 12°S (left panel) and 27°S (right panel) parallels. These cross the northern and southern tip of Madagascar respectively. Note the clear movement of Rossby waves, and the different speeds of propagation for the two latitudes. Also noteworthy is the influence of bottom topography near $60^{\circ}\text{E}, 12^{\circ}\text{S}$. Amplitudes are given in cm.

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