Upstream control of Agulhas Ring shedding

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[1] 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 the ring shedding 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. *INDEX TERMS:* 4520 Oceanography: Physical: Eddies and mesoscale processes; 4576 Oceanography: Physical: Western boundary currents; 4275 Oceanography: General: Remote sensing and electromagnetic processes (0689); 4556 Oceanography: Physical: Sea level variations; 4512 Oceanography: Physical: Currents; *KEYWORDS:* Agulhas Current, eddy/eddies, Mozambique Channel, Indian Ocean, interocean exchange, Agulhas Ring shedding

1. Introduction

[2] 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.*, 1999b; *Weijer et al.*, 1999]. The interocean 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, model studies show that it stabilizes the northern overturning circulation of the Atlantic Ocean [*Weijer et al.*, 2001]. 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 yr^{-1}, but periods of up to 5 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.* [1999a] 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 South 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]. Remote forcing by meanders in the upstream Agulhas Current has been proposed as a triggering mechanism for shedding of Agulhas Rings [*Van Leeuwen et al.*, 2000]. A recent theoretical study has shown that different steady retroflection regimes, a viscous and an inertial one, exist for the Agulhas Current [*Dijkstra and de Ruijter*, 2001a]. Barotropic instabilities of these steady flows occur in the viscous regime with patterns related to Rossby basin modes. Finite amplitude development of these instabilities display ring-like localized anomaly patterns which travel around the tip of South Africa. This indicates that the origin and frequency of the ring formation is set by the physics of the large-scale barotropic instabilities [*Dijkstra and de Ruijter*, 2001b].

[3] 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*, 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

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statistical approach, using altimetric sea surface height (SSH) data has confirmed the overall correctness of this description [*Feron et al.*, 1992].

[4] The general characteristics of the Agulhas Current system are that of an intense western boundary current to the large-scale wind-driven circulation of the southern subtropical Indian Ocean. The total Sverdrup transport in this gyre is of the order of 60 Sv (1 Sv = 10^6 m^3 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 farther 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.

[5] 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.*, 2000]) 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.*, 2002]. 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 m) with diameters of 300–400 km. They were shown to carry water from the north, including a core of Red Sea and/or Persian Gulf water that is actively mixing with Antarctic Intermediate water. The latter penetrates northward into the channel, probably as a continuation of the Agulhas Undercurrent [*Beal and Bryden*, 1997; *de Ruijter et al.*, 2002].

[6] Eddies in the Mozambique Channel were also FOUND by *Biastoch and Krauss* [1999] in a 1/3° primitive equation model simulation. In their model, they could track the relatively shallow eddies (estimated to reach only 400 m deep) until 34°S, 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 modeled South Equatorial Current [*Biastoch and Krauss*, 1999].

[7] Besides southward propagating eddies from the Mozambique Channel, another possible source region of Agulhas variability that can be identified by analysis of the variability of the sea surface height, lies southeast of Madagascar (Figure 1), where the East Madagascar Current seems to retroflects and probablyalso sheds rings [*Lutjeharms*, 1988].

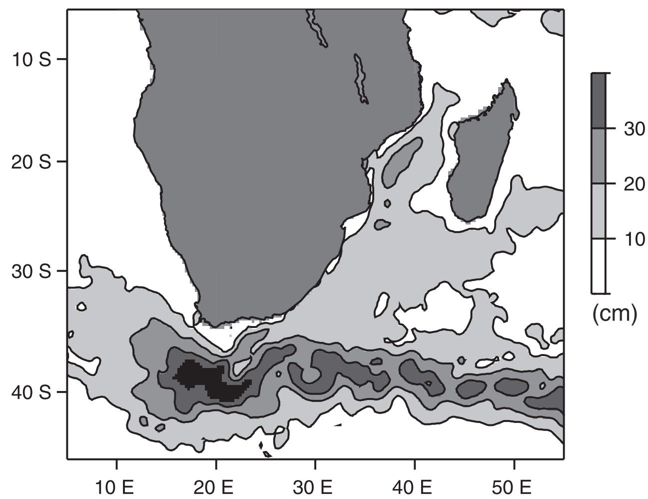

Figure 1. Variability of the sea surface height (meters) measured by TOPEX/Poseidon during 1993–1998. Two possible source areas of variablity in the Agulhas region can be identified: the Mozambique Channel and south of Madagascar. Also, both regions are connected to a band of enhanced variablity in the central and eastern Indian Ocean.

[8] These source regions seem to be connected to incoming Rossby waves from farther 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*, 2001]. Also, a semiannual Rossby wave is observed over the basin, associated with eastern boundary forcing [*Birol and Morrow*, 2001]. 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 altimetric observations [*Matano et al.*, 1998] and model results [*Matano et al.*, 2001] indicate that especially the annual Rossby wave does not reach the Agulhas region due to the blocking of these barotropic waves by topography such as the Mascarene Ridge.

[9] 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

[10] 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.

[11] Figure 2 shows a space–time diagram of a zonal section along 39°S (see Figure 1 for the location). Sea surface height anomalies are plotted for the years between 1993 and summer 1999 (anomalies are given with respect to the University of Texas, Center for Space Research (CSR), mean sea surface height, version of 1995). The TOPEX/Poseidon altimeter data (October 1992 to May 1995) were taken from the pathfinder dataset (farther 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° × 1° × 10 day bins. The combined TOPEX/Poseidon and ERS2 altimeter data (June 1995 to 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° × 0.25° × 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. The annual and semi-annual cycle are strongly suppressed. Next, a 30 day running mean is taken. This combination is an efficient way of bandpass filtering and leaving frequencies roughly between three and six times per year unaltered. In Figure 3 the average power spectrum for the gridded altimetry measurements in the region between 20°–45°E and 45°–30°S has been plotted (dotted line). The solid line shows the spectrum of the bandpass filtered data set. It is clear from this picture, that no clear spectral peaks exist and no significant signals have been removed by the filtering procedure.

[12] The retroflection loop appears to have a very regular westward movement, at a frequency of four to five times per year (Figure 2). 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 south-east Atlantic [*Schouten et al.*, 2000].

[13] 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, here identified by the positive

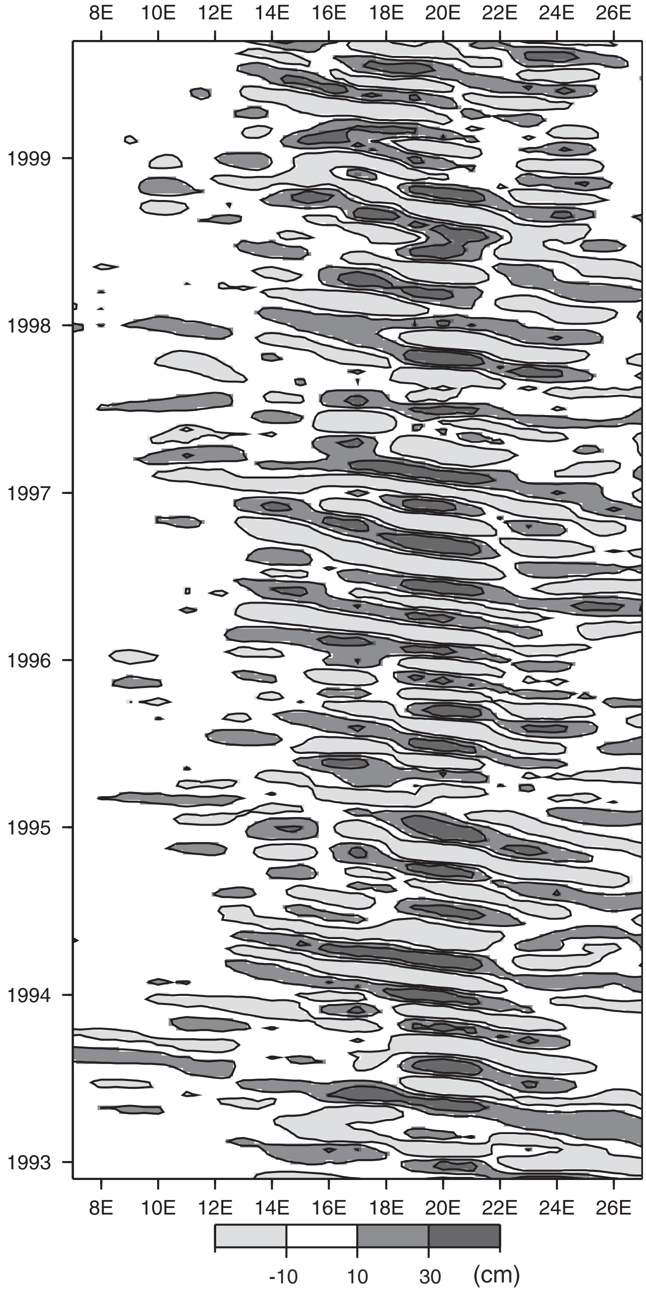

Figure 2. Longitude–time diagram of filtered sea surface height anomalies (meters) along a zonal secion at 39°S. Band-pass filtered sea surface height anomalies are plotted for the period January 1993 to August 1999. Before 1995 only T/P data are used; from 1995 onward, combined TP/ERS data are used. The positive anomalies, associated with the retroflection of the Agulhas Current, prograde to the westward between 22° and 14°E. Jumps occur when the westward progradation of the centers of positive SSH anomalies end. These can be interpretated 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 farther east is enforced by the current.

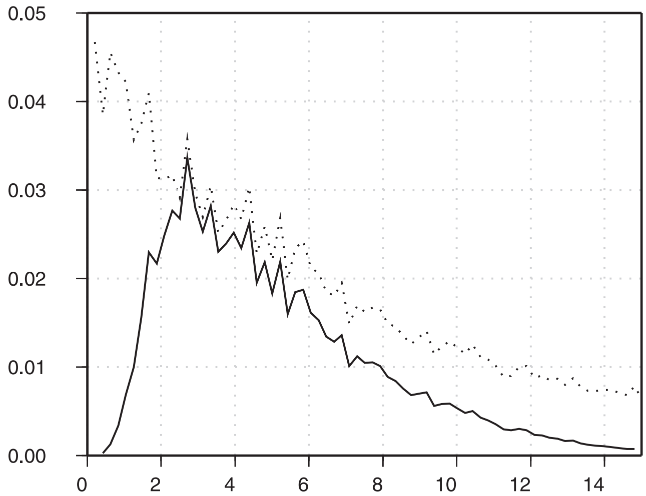

Figure 3. Spectrum of the variability in the combined TOPEX/Poseidon-ERS SSH data. Along the horizontal axis the frequencies are given (cycle per year). The dotted line shows the average spectrum for all grid points in the Agulhas Retroflection region (10°–35°E, 45°–30°S). The solid line denotes the spectrum after the bandpass filtering described in the text. This filtering has been applied to produce Figure 2. For the MSSA analyses, just the high-pass filtering is applied, as MSSA effectively filters out the high-frequency noise.

anomaly at 39°S, moves slowly westward with a constant speed of 13 km d^{-1}. The identification of the retroflection as a strong positive SSH anomaly has been confirmed by comparing numerous snapshots of the anomalous SSH field and snapshots of sea surface temperature, on which the retroflection loop of the Agulhas Current is often clearly identifiable. The signal is highly regular with a frequency of 4.5 yr^{-1}. The speed of 13 km d^{-1} agrees exactly with the mean speed of westward progradation found earlier in SST measurements [*Lutjeharms and Van Ballegooyen*, 1988].

[14] *Schouten et al.* [2000] identified three periods in which no Agulhas Rings were observed to penetrate the southeast Atlantic Ocean. These results are qualitatively similar to those obtained by [*Goñi et al.*, 1997], although they used a smooth mean sea surface to provide more realistic snapshots of the total circulation. The three periods without observed ring shedding are the second half of 1993, between August 1995 and January 1996 and again between February and June 1996. These periods cannot convincingly be connected to periods of less activity in the movement of the retroflection (Figure 2). 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 (Figure 2). However, the rings counted by *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 have been shed around 14°E, as a lot can happen in between.

[15] A discrepancy exists between the frequencies estimated by *Lutjeharms and Van Ballegooyen* [1988], and the present and previous 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.

[16] This may be due to the fact that in the period after shedding a ring resides close to the retroflection, where it can intermittently entrain warm filaments of the Agulhas around its periphery. That may account for the larger number of shedding counted from SST measurements only. The altimeter measurements cannot resolve such high frequencies, although much of the high-frequency noise in SSH data could be caused by these fluctuations.

[17] 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 [e.g., *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. Retroflection: Connection to Upstream Regions

[18] *Biastoch and Krauss* [1999], using a high-resolution numerical model of the region around South Africa, found shallow eddies from the Mozambique Channel to propagate southward and reach as far as 30°S. Observations during the recent ACSEX (Agulhas Current Sources Experiment) cruise have confirmed the existence of a train of large and energetic eddies that appear to reach all the way to the bottom [*de Ruijter et al.*, 2002]. 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 Natal pulse, a large solitary 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

[19] 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. These anomalies were not low-pass filtered, as the MSSA technique effectively filters out high-frequency noise. The 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

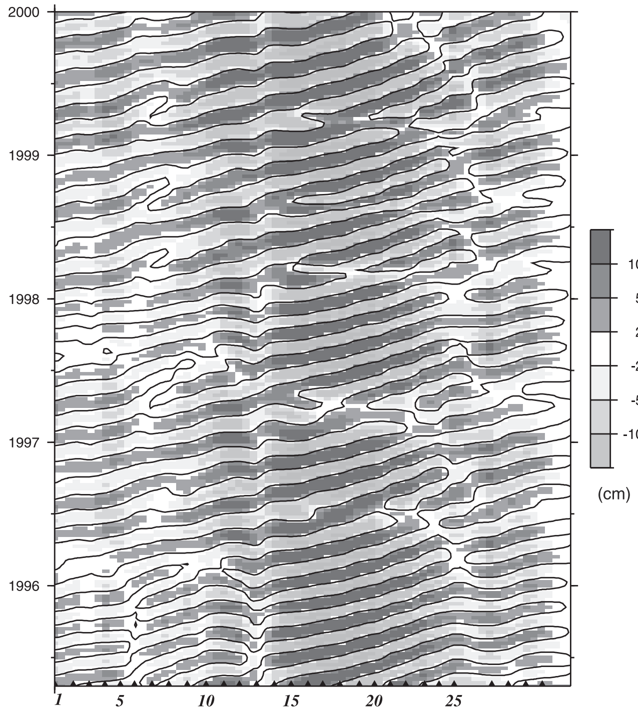

Figure 4. Space–time plot of the sum of the first six MSSA modes along the track shown in Figure 5. The numbers on the horizontal axis correspond to the locations shown there. Anomalies can be followed from the upstream Agulhas near 30°S (point 1) to the westernmost point of the retroflection (point 29). Amplitudes are given in centimeters.

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.

[20] 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 1 we have plotted the total root mean square of the SSH anomalies. Given the close correlation between variability in the sea surface height and the eddy kinetic energy (e.g., compare *Stammer* [1997] and Figure 1), the variability map in Figure 1 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, as these are the two upstream regions of oceanic variability. The variability in the Agulhas Return Current is not likely to affect the ring shedding, as no evidence is found of regularly westward propagating anomalies in the return current. Figure 2 shows regular westward propagation starting near 25°E, and only intermittently from farther downstream. This seems contradictory with results by *Matano et al.* [1998], but the westward wave propagation they show in the return current appears only intermittently.

[21] On the more than 4 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 high-pass filtering. The high-pass filtering has only removed 20–30% of the total variability over the greater Agulhas region, but it has enabled us to extract modes of intermonthly variability without temporal aliasing of the annual and interannual signal. 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% of the variance of the high-pass filtered signal. Especially in the retroflection area the explained variance is high.

[22] To give a good first-order description of the retroflection, and include the remote control variability, we reconstruct the data set based on the first six MSSA components. They all have frequencies of 4–5 times per year. Their variance is located not just in the retroflection area, but also in the rest of the Agulhas region. As all six modes have roughly the same dominat periods, the variability at that period is distributed between them. The most regular signal is the movement of the retroflection, which shows up as the first couple of MSSA components. The upstream connection is slightly less regular, as is to be expected as a larger region is involved, in which also other processes play a role. Although the dominant pattern is the same in these modes, the focus is on different parts of the region, as that allows the analysis to deal with regional disturbances of the main pattern. 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.

[23] 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 SSH anomalies are advected southward. These can clearly be observed in a space–time diagram (Figure 4) along a line chosen through the maximum of the observed variability (Figure 5). They move (Figure 4) as anticyclonic anomalies in southwest-

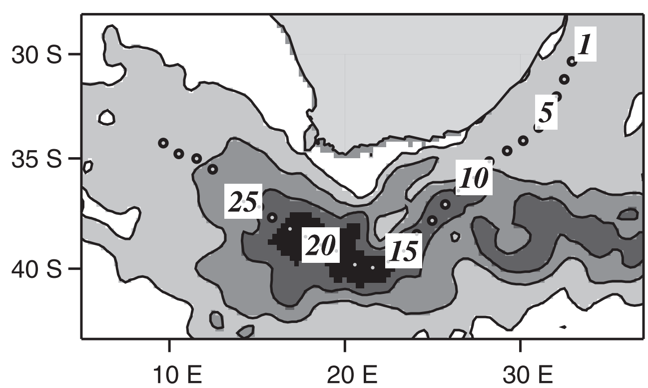

Figure 5. Variability in the Agulhas Retroflection region and the track along which the space–time plot of the upstream control is plotted. The numbers correspond to the horizontal axis of the space–time plot. This track has been chosen along the line of maximum variability.

ward direction (locations 1–12) in the left half of Figure 4, and seem to trigger the westward shifting of the retroflection (clearly visible at the locations 13–29). The amplitudes are slightly smaller than in the original data, but irregularities in the precise timing of the phenomenon, 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 cannot directly be interpreted in terms of the original amplitudes. These are considerably higher in the retroflection region where they can reach up to 1 m, and also in the region farther north, where the anomalies on the offshore edge of the Agulhas have amplitudes of ∼20–40 cm.

3.2. Natal Pulse Generation

[24] 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 may be 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.*, 1999a]. 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.* [1999b] 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 farther upstream.

[25] The eddy that was measured hydrographically a 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.*, 2002] was clearly shown to have a velocity, temperature and salinity profile reaching all the way to the bottom of the channel at 3000 m. In addition, a drifter was released in the eddy. The path of this drifter shows a swirling route southward (Figure 6), as expected for water trapped in an eddy that constitutes an anomaly like those followed in Figure 4. The drifter was ejected from the eddy during the period of interaction with the Agulhas Current (second half of May 2000), and is farther advected southward.

[26] Figure 7 shows a series of consecutive snapshots of SST in the vicinity of the Natal Bight. The first snapshot, made on 31 May 2000, clearly shows an anticyclonic eddy in interaction with the Agulhas Current. The eddy can easily be traced back farther north in altimeter data, and is the same one that was carrying the drifter shown 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 (Figure 7b). The next day, 5 June, the interaction between the current and the eddy has become less intense (they are clearly separated again in the SST signal shown in Figure 7c). On 7 June it becomes obvious that the Natal pulse is traveling south with the Agulhas (Figure 7d).

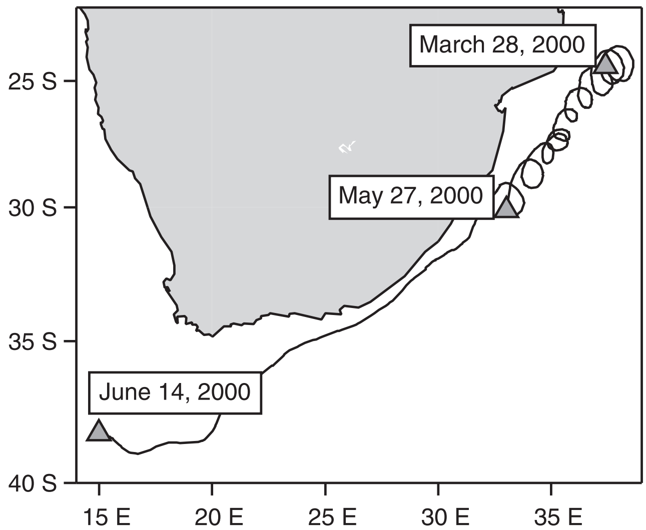

Figure 6. A drifter was released inside a Mozambique eddy during the ACSEX I cruise, on 28 March [*de Ruijter et al.*, 2002]. The eddy (as identified by the 15 cm SSH anomaly contour) is drawn here, with the track of the eddy in the subsequent weeks. After traveling south within the eddy for 6 weeks, it was released to the Agulhas Current near the Natal Bight on 27 May. This is during the interaction of the eddy with the current illustrated in the SST snapshots of Figure 7.

4. Connection to the Agulhas Sources

[27] Figure 1 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

[28] Hydrographic measurements in the Mozambique Channel fail to agree on a steady circulation. Different research cruises have led to different snapshots of the circulation in the channel [*Harris*, 1972; *Saetre 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 [*Biastoch and Krauss*, 1999].

[29] Recently, the ACSEX I cruise was carried out in the Mozambique Channel [*de Ruijter et al.*, 2002]. It should be noted that this cruise was carried out in April/May, which is in the season of lowest transport observed in the model of [*Biastoch and Krauss*, 1999] and in POCM [*Matano et al.*, 2001]. Hydrographic measurements were made with the focus of determining the flow structure of the channel, and resolving both the western boundary current and the eddies. No continuous southward current was found along the slope. Eddies as suggested by the SSH measurements from

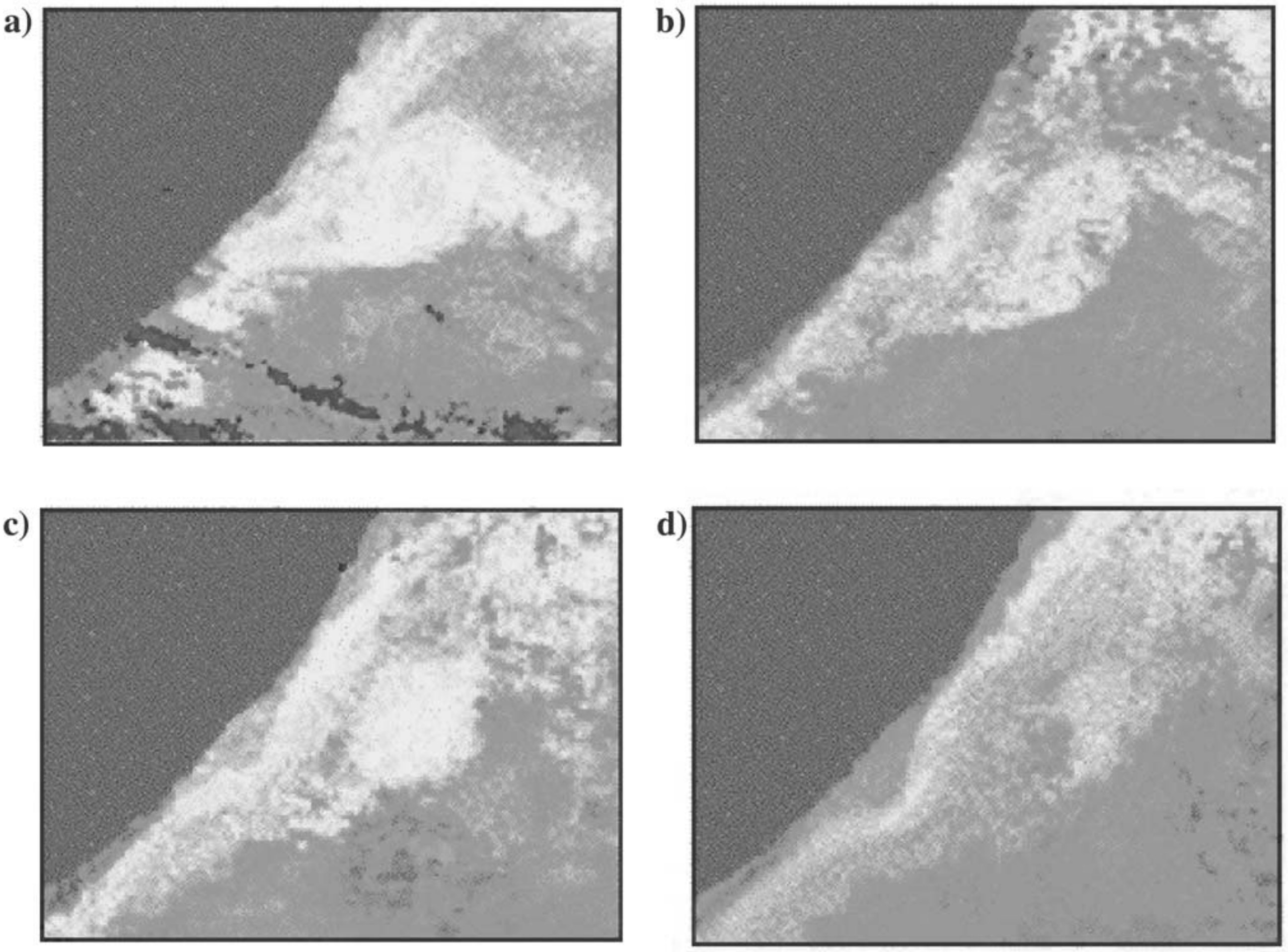

Figure 7. Sea surface temperature snapshots of the region near 30°S, off Durban. Interaction between a Mozambique eddy and the Agulhas Current leads to the formation of a large meander: the Natal Pulse. (a) 31 May 2000: the Mozambique eddy followed by a drifter (Figure 7) is in interaction with the main current; (b) 4 June 2000: the current is pulled away from the coast, a meander is being formed; (c) 5 June 2000: the connection between the current and the eddy is weakened; the meander is moving southward; and (d) 7 June 2000: the meander is clearly visible and moving southward. Clouds partially obstruct a view of the eddy, but its SST has also decreased due to air-sea interaction. See color version of this figure at back of this issue.

space were shown unambiguously to be present and even to extend over the full depth of the channel [*de Ruijter et al.*, 2002] with diameters of 300–400 km. They were shown to carry water from the north, including a core of intermediate water from the North Indian Ocean that is actively mixing with Antarctic Intermediate Water. The latter flows northward, most probably as a continuation into the Mozambique Channel of the Agulhas Undercurrent [*Beal and Bryden*, 1997].

4.2. East Madagascar Current

[30] The Southern limb of the 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 southeast Madagascar Current and the flow turning east back into the central Indian Ocean. Based on a single SST snapshot [*Lutjeharms and van Ballegooyen*, 1988] already speculated on the retroflective nature of the southeast 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

[31] Again we focus on the first six modes found by the MSSA analysis of the region of the larger Agulhas system, extending between 5° and 55°E and between 45° and 5°S (e.g., see Figure 1). The eddies found to propagate on the offshore edge of the Agulhas Current and into the retroflection region, can be traced back to the source regions of the Agulhas. This is done in Figures 8 and 9, again by constructing a space–time 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 4, so the anomalies can be clearly followed to propagate into the retroflection. Anomalies are coming from both the Mozambique Channel and southeast of Madagascar, and connect to the eddy path plotted in Figure 4. The anomalous sea surface heights are ~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.*, 2002]. 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 5 km d^{-1}.

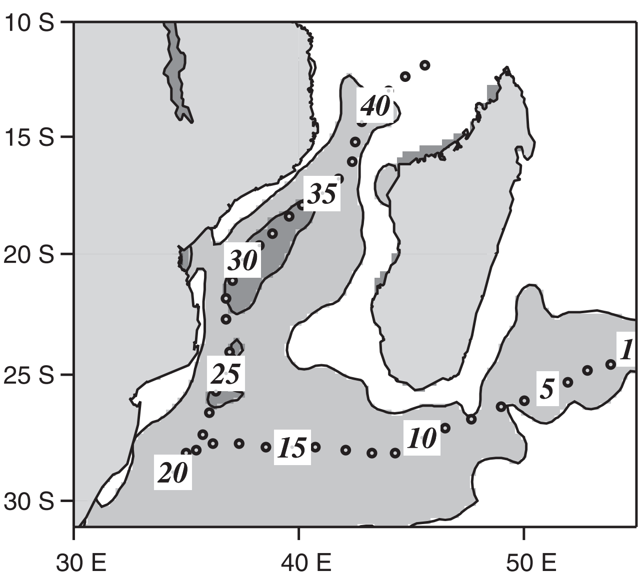

Figure 8. As Figure 4. Now the track along which a space-time plot is constructed has been chosen in the Mozambique Channel and south of Madagascar. These tracks cover the Mozambique eddies, and the possible eddies being spawned from the Madagascar Current. There is a small overlap between Figure 4 and this track, to accomodate a continuous tracking of the propagating anomalies. The space-time plot itself is shown in Figure 9.

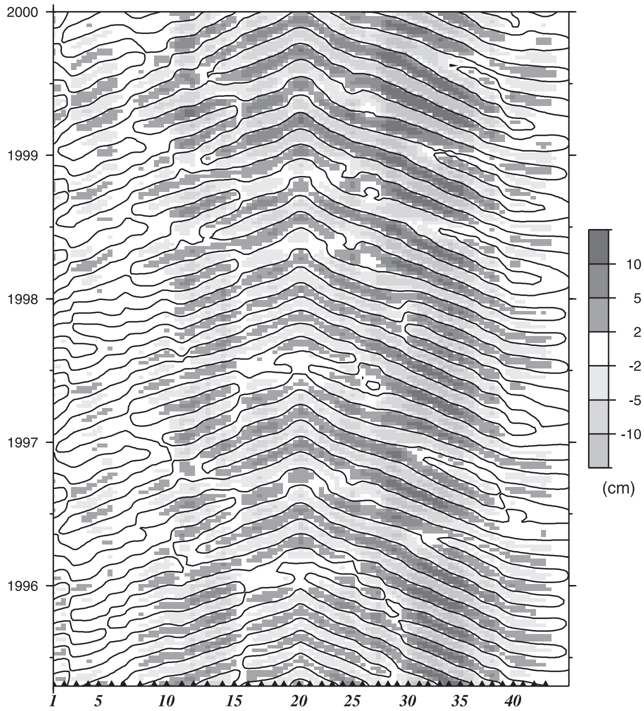

Figure 9. Space-time plot through the reconstructed components 3–4 of the MSSA analysis, along the tracks shown in Figure 8. Amplitudes are given in centimeters. The discontinuity at point 20 denotes the most "downstream" point of the plot. From both directions incoming anomalies can clearly be followed. 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 southwestward direction, whereas a movement along the line 40-20 means a southward translation. A striking feature of this plot is the apparent synchronization of both processes: anomalies from the north and the east arrive simultaneously.

5. Connection to the Central and East Indian Ocean

[32] 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 Retroflection. East of Madagascar (roughly between 10° and 30°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 10. 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

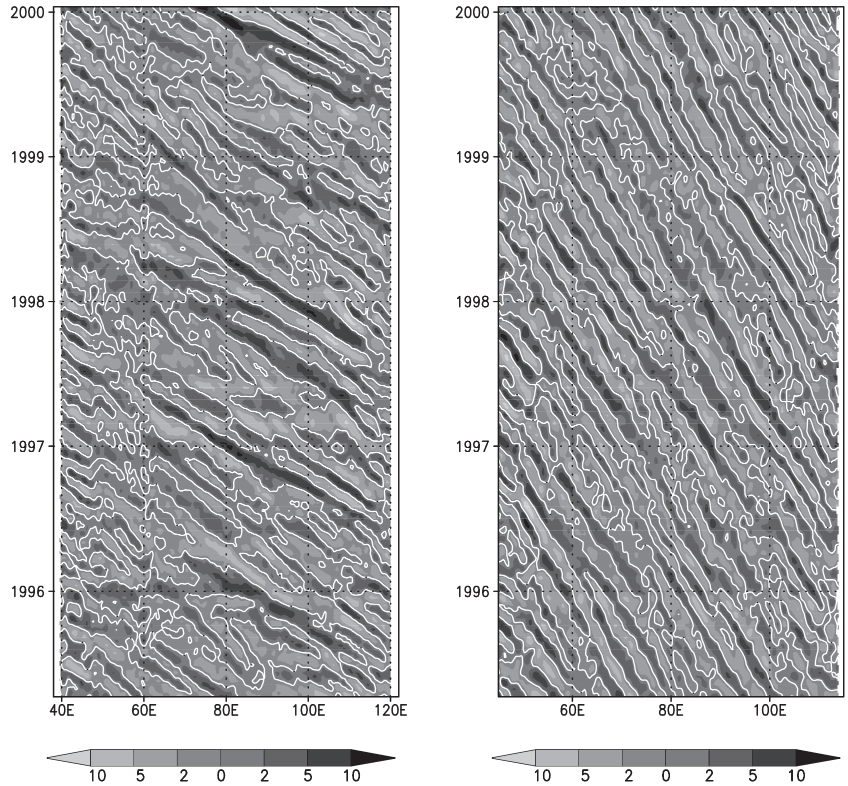

Figure 10. Hovvmöller plot of bandpass filtered SSH anomalies along the (left) 12°S and (right) 27°S parallels. These cross the northern and southern tip of Madagascar, respectively. Note the clear movement of Rossby waves, and the different speeds of propagation for the two latitudes. Also noteworthy is the influence of bottom topography near 60°E, 12°S. Amplitudes are given in centimeters.

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 27°S. At 12°S, the Rossby waves clearly feel the steep topography of the Mascarene ridge at ~60°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°–60°E, 5°–13°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 d^{-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 was identified by local current measurements Near 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 400 km waves between the tip of Madagascar and the African continent observed in the MSSA modes described above, and previously in modeling results [*Périgaud and Delecluse*, 1992]. MSSA analysis of the Mozambique Channel alone yields a dominant frequency of 4 per year, and clearly a formation of eddies in the channel, starting with an anomaly propagating from the northern part of the channel through the narrowest part at 16°S, into the channel itself. Interaction of the incoming Rossby waves from the east with the high shear regions of the South Equatorial Current north of Madagascar may act as a triggering mechanism for this process. The absence of local forcing (the local instability process seems to be disconnected from the channel region, and has too high a frequency) and the correspondence in frequency are a strong indication for such a connection with the far field.

[33] At 27°S, the Rossby waves show a significant intensification at ~45°E [see also *Morrow and Birol*, 1998, Plate 5]. This could be due to the rising bottom (depths decrease from ~4000 to ~1500 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 farther 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 focused, and lead to the formation of eddies in the western part of the basin.

6. Summary and Discussion

[34] 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 retroflection has been associated with the shedding of Agulhas Rings. However, Ring shedding records are far more irregular than the behavior of the Agulhas Retroflection 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.

[35] Besides the impact on the movement of the retroflection, 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 currentnear Durban [*de Ruijter*, 1999a].

[36] 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 was 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 5 year record of altimetric data. This same 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.

[37] The Mozambique eddies themselves may be connected to processes farther 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.

[38] 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.

[39] 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 may 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 to be 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.

[40] 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 and/or Persian Gulf origin, thus containing a large saline anomaly with respect to the relatively fresh surrounding water [*de Ruijter*, 2002]. Red seawater 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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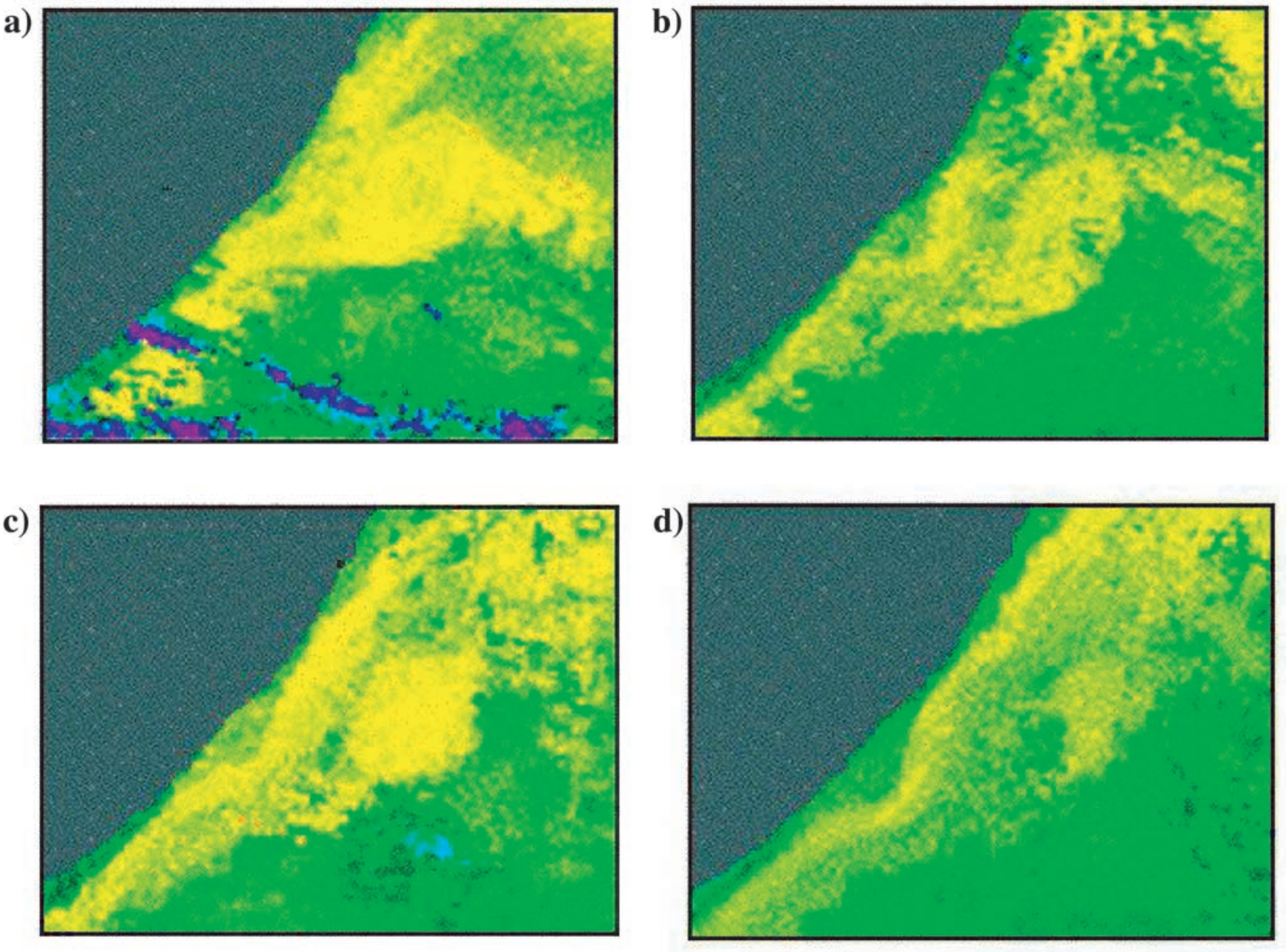

Figure 7. Sea surface temperature snapshots of the region near 30°S, off Durban. Interaction between a Mozambique eddy and the Agulhas Current leads to the formation of a large meander: the Natal Pulse. (a) 31 May 2000: the Mozambique eddy followed by a drifter (Figure 7) is in interaction with the main current; (b) 4 June 2000: the current is pulled away from the coast, a meander is being formed; (c) 5 June 2000: the connection between the current and the eddy is weakened; the meander is moving southward; and (d) 7 June 2000: the meander is clearly visible and moving southward. Clouds partially obstruct a view of the eddy, but its SST has also decreased due to air-sea interaction.