

## Mesoscale perturbations control inter-ocean exchange south of Africa

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[1] The quantification of inter-ocean leakage from the South Indian to the South Atlantic Ocean is an important measure for the role of the Agulhas system in the global thermohaline circulation. To explore the specific role of mesoscale variability (such as Agulhas rings and Mozambique eddies) in this process a high-resolution model (based on NEMO-ORCA) for the Agulhas region has been set up. It is nested into a global coarse-resolution model. The high-resolution nest captures all salient features of the greater Agulhas region, including the upstream perturbations of the Agulhas Current and Natal Pulses along the African coast. A comparison of the inter-ocean exchange in the high-resolution nest with its coarse resolution counterpart reveals that the latter significantly over-estimates the amount of water flowing into the Atlantic Ocean, demonstrating the need to explicitly simulate the mesoscale features. A sensitivity experiment that excludes the upstream perturbations revealed no difference in the amount of inter-ocean exchange. However, the realistic representation of Agulhas rings and their drift path into the South Atlantic depends on the simulation of those upstream perturbations. **Citation:** Biastoch, A., J. R. E. Lutjeharms, C. W. Böning, and M. Scheinert (2008), Mesoscale perturbations control inter-ocean exchange south of Africa, *Geophys. Res. Lett.*, 35, L20602, doi:10.1029/2008GL035132.

### 1. Introduction

[2] The global thermo-haline circulation of the ocean has to pass through a few chokepoints [Gordon, 1986] of which the region directly south of Africa is one. Here warm and salty subtropical water from the Indian Ocean flows into the South Atlantic, providing about two-thirds of the upper limb of the meridional overturning circulation in the Atlantic [Weijer *et al.*, 1999]. The mechanisms for this leakage consist largely of the shedding of Agulhas rings at the Agulhas Current's retroflexion [Lutjeharms, 2006], an intermittent process apparently affected by perturbations originating in the upstream portions of the Agulhas Current [van Leeuwen *et al.*, 2000]. The generation and role of these mesoscale processes in the production of Agulhas rings, and their effect on the net transport of water from the Indian to the Atlantic Ocean, is studied by utilizing a novel, high-resolution "two-way nesting" model of the Agulhas regime. It provides a realistic simulation of the mesoscale processes triggering the shedding and propagation of rings, including

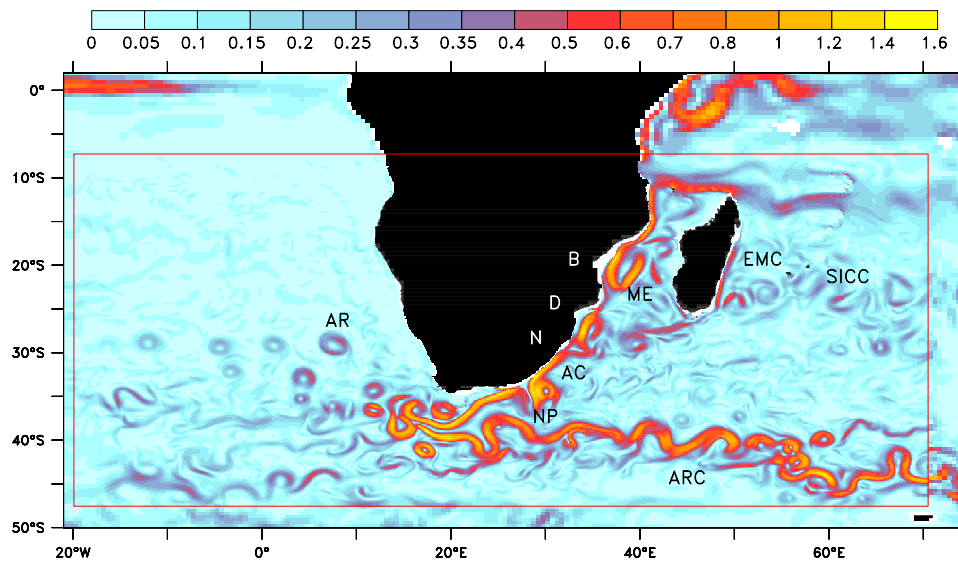
the emergence of eddies in the Mozambique Channel that are found critical for the generation of Natal Pulses [Schouten *et al.*, 2002], and thus, upstream retroflexion events of the Current. The sequence of model experiments demonstrates the effective control of the net inter-ocean exchange south of Africa by mesoscale dynamics.

[3] The Agulhas Current is the major western boundary current of the southern hemisphere with an average volume flux [Beal and Bryden, 1999] of about 70 Sv ( $1 \text{ Sv} = 1 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ ). Shortly after passing the southern tip of the African continent, the bulk of the current turns east in the Agulhas Retroflexion, with only about 20% of the volume flux leaking into the South Atlantic [de Ruijter *et al.*, 1999a]. Much of the leakage is associated with the shedding of Agulhas rings at the retroflexion that are the biggest anticyclonic vortices observed in the world ocean [Olson and Evans, 1986]. The importance of this exchange is emphasized by paleo-oceanographic studies [Peeters *et al.*, 2004] which suggest that the Indian to Atlantic Ocean connection has undergone large oscillations during glacial cycles, apparently linked to variations in upper-layer temperatures of the South Atlantic, and the deep water formation in the sub-polar North Atlantic. Accordingly, lack of a realistic Agulhas retroflexion has been identified as a critical deficiency of global climate models, with salinity anomalies due to false inflows of Indian Ocean water being advected throughout the Atlantic and impacting its meridional overturning circulation [Banks *et al.*, 2007, Weijer *et al.*, 1999]. A realistic simulation of the interocean exchange is a formidable challenge due to the highly nonlinear dynamics of the retroflexion regime, including its little known dependence on mesoscale flow perturbations further upstream. Present understanding of these perturbations and their effect on the retroflexion can be summarized as follows.

[4] The trajectory of the Agulhas Current's northern part is very stable [Gründlingh, 1983]. This path invariance is interrupted by the intermittent passage of a singular meander, the Natal Pulse [Lutjeharms and Roberts, 1988], proceeding from a region of reduced gradient in the shelf slope at the Natal Bight (Figure 1). It has been shown [de Ruijter *et al.*, 1999b] on theoretical grounds that this is the only location along the path of the northern Agulhas Current where the bathymetry will allow instabilities in the trajectory to develop. This can only come about if the current intensity exceeds a certain threshold and it has been suggested [de Ruijter *et al.*, 1999b] that this could be achieved by the adsorption of an anti-cyclonic eddy onto the current. To date only one case study [Schouten *et al.*, 2002] has actually shown this to occur. There is evidence [van Leeuwen *et al.*, 2000] that the downstream movement of Natal Pulses may cause the shedding of Agulhas rings at the retroflexion. Natal Pulses have also been implicated in the upstream retroflexion of the Agulhas Current [Lutjeharms and van Ballegooyen, 1988] through which

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**Figure 1.** Snapshot of the high-resolution model nested in the global, coarse resolution model. Shown are speeds (5-day average around 12 Feb 1969) at 100 m depth (in  $\text{m s}^{-1}$ ). The geographic locations of the bights of Beira (B), Delagoa (D) and Natal (N) are shown as are the circulation features Agulhas Current (AC), Agulhas Ring (AR), Agulhas Return Current (ARC), East Madagascar Current (EMC), eddies of the South Indian Countercurrent (SICC), Mozambique Eddy (ME) and Natal Pulse (NP).

all the water in the Agulhas Current is siphoned off to the Agulhas Return Current at an early stage with no normal inter-ocean exchange being feasible for a while.

## 2. Model

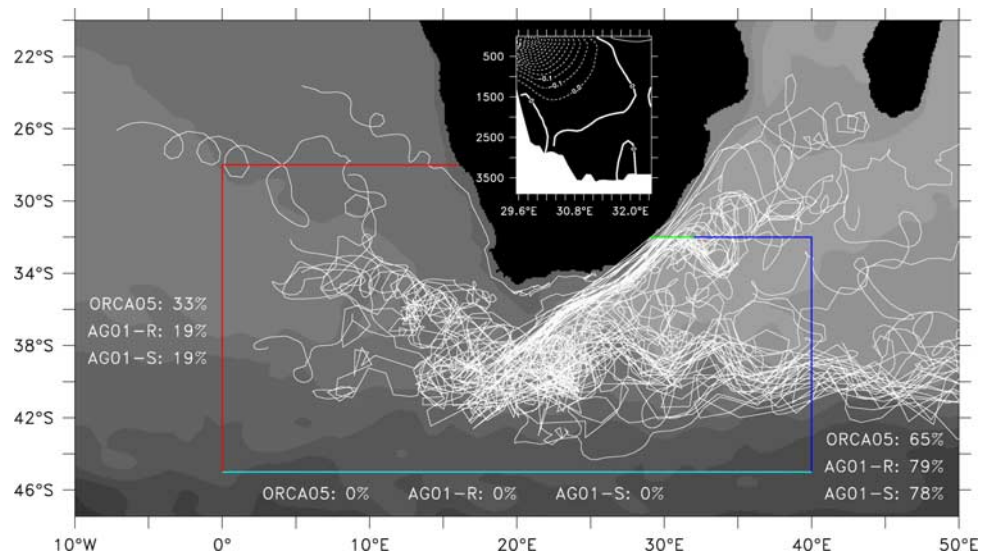
[5] Previous modelling studies have begun to capture these intricacies of the Agulhas system, however, at the expense of the modelled frequency and dimensions of rings being shed in the retroflection region due to compromises between resolution [Bjastoch and Krauss, 1999] and domain sizes [Speich *et al.*, 2006]. In this study, the question how important these mesoscale processes are for the net interocean exchange south of Africa is addressed by a sequence of experiments with a global ocean – sea-ice model at  $1/2^\circ$  resolution (ORCA05) based on the NEMO code [Madec, 2006]. It is forced by bulk formulae using daily, inter-annually varying wind and thermohaline surface forcing fields over the period 1958–2004 [Large and Yeager, 2004]. Its main, novel element is the “two-way nesting” [Debreu *et al.*, 2008] of a high-resolution,  $1/10^\circ$  model (AG01-R) of the Agulhas region ( $20^\circ\text{W}$ – $70^\circ\text{E}$ ,  $47^\circ\text{S}$ – $7^\circ\text{S}$ , red box in Figure 1) into this coarser, well established global model [Bjastoch *et al.*, 2008]. The nesting approach not only allows one to study the effect of outside perturbations on the Agulhas regime, but also the feedback of mesoscale Agulhas dynamics on the large-scale circulation, a characteristic that is not feasible with global high-resolution models [Maltrud and McClean, 2005]. The model features partially filled bottom cells (46 levels) and advanced advection schemes which have been shown to be crucial elements of a reasonable simulation of the Agulhas regime [Barnier *et al.*, 2006]. In a second set-up of the nested model (AG01-S), the specific role of Mozambique eddies is examined by placing the northern boundary of the

nest at  $27^\circ\text{S}$ , leaving the region around Madagascar at coarse resolution.

## 3. Representation of the Inter-ocean Exchange

[6] The main experiment (AG01-R) succeeds in representing the salient features of the Agulhas regime in a highly realistic way (Figure 1; see also auxiliary material<sup>1</sup>). These include the Agulhas Current with a realistic transport of  $71 \pm 16.4$  Sv at  $32^\circ\text{S}$  (concurring with estimates based on hydrographic sections [Beal and Bryden, 1999]) characteristically hugging the shelf edge and extending 200 km offshore; the highly variable Agulhas Undercurrent of  $4.8 \pm 3.8$  Sv [Bryden *et al.*, 2005]; Agulhas rings with a diameter of  $360 \pm 40$  km moving off into the South Atlantic with a translation speed of about 24 km/week and an Agulhas Return Current [de Ruijter *et al.*, 1999a] with a realistic representation of its average location, variability and shedding of eddies to either side. About  $5 \pm 1$  anti-cyclonic Mozambique eddies, matching observations in size and frequency [Schouten *et al.*, 2002], are formed per year with average diameters of  $270 \pm 45$  km and extending to the sea floor. Natal Pulses are evident on the onshore side of the Agulhas Current at least 2  $\pm$  1 times per year, moving downstream with an average rate of about 22 km/day. Upstream retroreflections [Lutjeharms and van Ballegooyen, 1988] are seen in the expected location south of Port Elizabeth at  $26 \pm 1^\circ\text{E}$ . What is the role of the host of mesoscale processes interacting with the Agulhas Current in the net volume transfer between the Indian and Atlantic Ocean? This question is addressed by comparing the reference simulation (AG01-R) with an experiment in which

<sup>1</sup>Auxiliary materials are available in the HTML. doi:10.1029/2008GL035132.



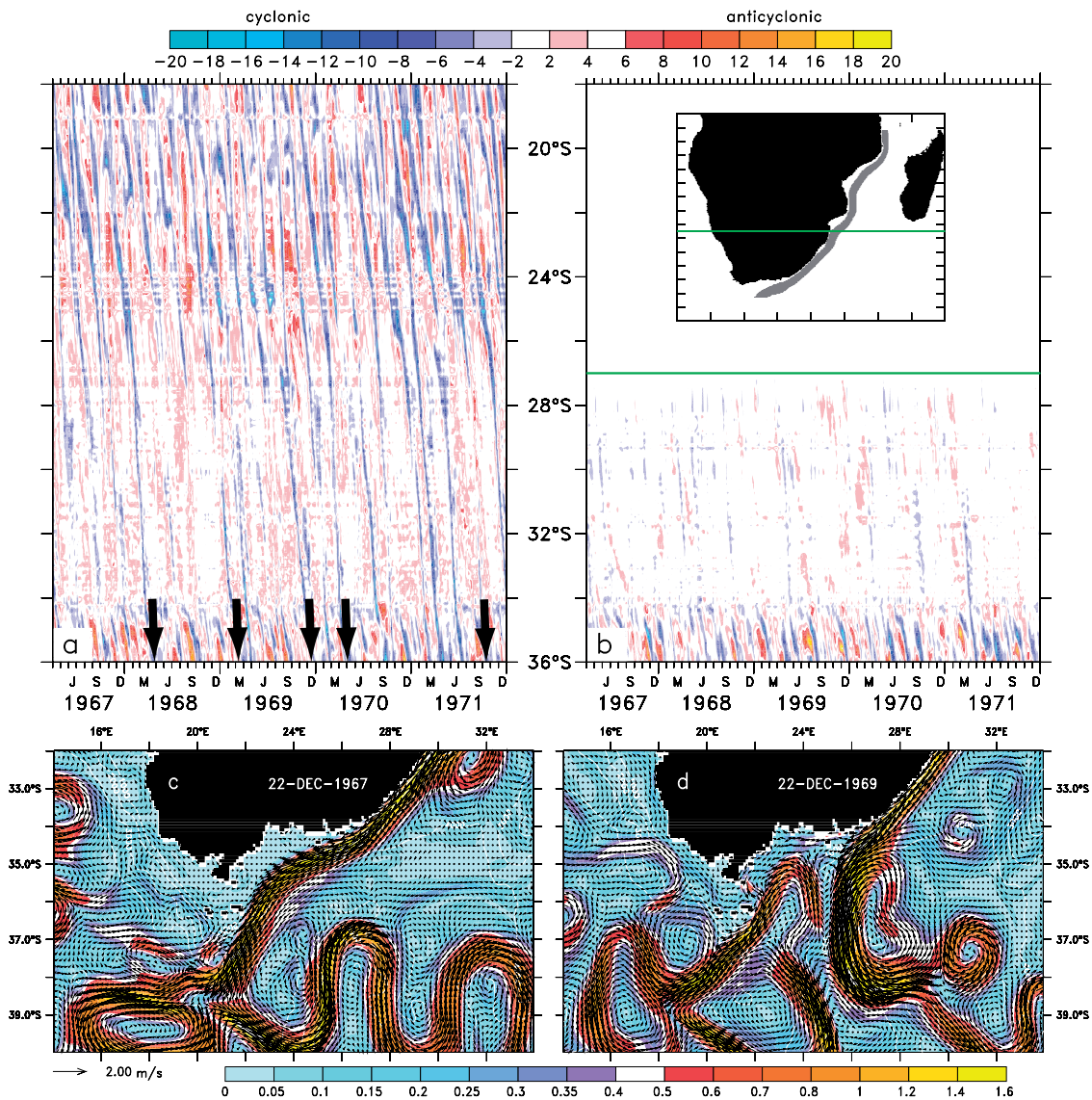
**Figure 2.** Example float trajectories for model year 1968. The floats have been seeded over the top 1500 m of the southward flowing Agulhas Current at 32°S (marked as green line and in the inserted figure), but may leave northward due to Mozambique eddies and countercurrent structures. Numbers on the control sections (red, light blue, blue) show the fractional amounts of particles crossing the lines during 11 years of integration. Values are given for the standard (AG01-R) and sensitivity (AG01-S) experiments as well for the base experiment (ORCA05), the latter without a high-resolution Agulhas nest.

the same global model was integrated without the high-resolution nest in the Agulhas regime. The solution of this non-eddy model (ORCA05) portrays the inter-oceanic exchange as a continuation of parts of the Agulhas Current as a smooth current, reminiscent of coarse resolution models typically used for climate studies. For assessing the portion of the Agulhas water flowing into the South Atlantic the Eulerian model field does not provide an optimal measure since mesoscale eddies lead to enormous fluctuations in the east- and westward velocities involving a complex suite of time-dependent recirculation features. We therefore adopted a Lagrangian diagnostic [Blanke *et al.*, 1999] based on tracking artificial “fluid” particles, where a large number of particles were seeded continuously over a time span of 4 years into the modelled Agulhas Current at 32°S. Each particle represents a certain amount (max. 0.01 Sv) of the total transport and is advected by the time-dependent flow field. At specified control sections in the Atlantic and Indian Ocean (Figure 2) particles are counted to give an average transport, similar to the analysis in the regional model by Speich *et al.* [2006]. In the reference simulation (AG01-R), with the eddy-resolving Agulhas nest, about 12 Sv (about one fifth of the Agulhas transport of 63 Sv at 32°S) reaches the northern/western sections in the Atlantic, representing the portion of upper water masses of the inter-oceanic exchange south of Africa, consistent with the range of observational estimations [de Ruijter *et al.*, 1999a]. This is in marked contrast to the non-eddy case (ORCA05), where a much higher fraction (one third) of the Agulhas water enters the Atlantic. (According to the theoretical study of Dijkstra and de Ruijter [2001], the leakage in this non-eddy case may be dependent by model parameters controlling the inertial-viscous character of the boundary layer regime.) The pronounced contrast between the two simulations with identical global conditions demonstrates

that the supply of Indian Ocean water to the South Atlantic, and thus, the warm water path of the global thermohaline circulation, is not determined by large-scale dynamics alone, but significantly influenced by the regional, meso-scale dynamics of the Agulhas regime.

#### 4. Role of Upstream Perturbations

[7] Upstream retroreflections (examples for regular and upstream retroreflection states are given in Figure 3) of the Agulhas Current are a prominent feature of the Agulhas dynamics, effectively causing one of the largest western boundary current in the world ocean to short-cut its southwestern path for about 2–3 months. It has been assumed that these upstream retroreflections are forced by passing Natal Pulses [Lutjeharms and van Ballegooyen, 1988] and that they may lead to substantial reductions in the inter-oceanic exchange [Lutjeharms and de Ruijter, 1996]. The time evolution of a coastal section along the African continent (Figure 3) indicates that the 5–6 Mozambique eddies generated per year are a necessary condition for the generation of Natal Pulses; however, this is not a sufficient condition since only 2–5 Natal Pulses per year appear in the same period. Furthermore, only large Natal Pulses, causing a displacement of the core of the Agulhas Current by more than 400 km offshore, in combination with a northward extension of the meander of the Agulhas Return Current are able to cause upstream retroreflections. Such instances are rare (about 1–2 per year in our example). Similar numbers can be gathered from observations (here not shown), although a one-by-one comparison is difficult to perform due to limitations in the observational data base and would require a dedicated along-track study [Schouten *et al.*, 2002]. Figure 3b shows the almost complete absence of Natal Pulses in a sensitivity experiment without Mozambi-

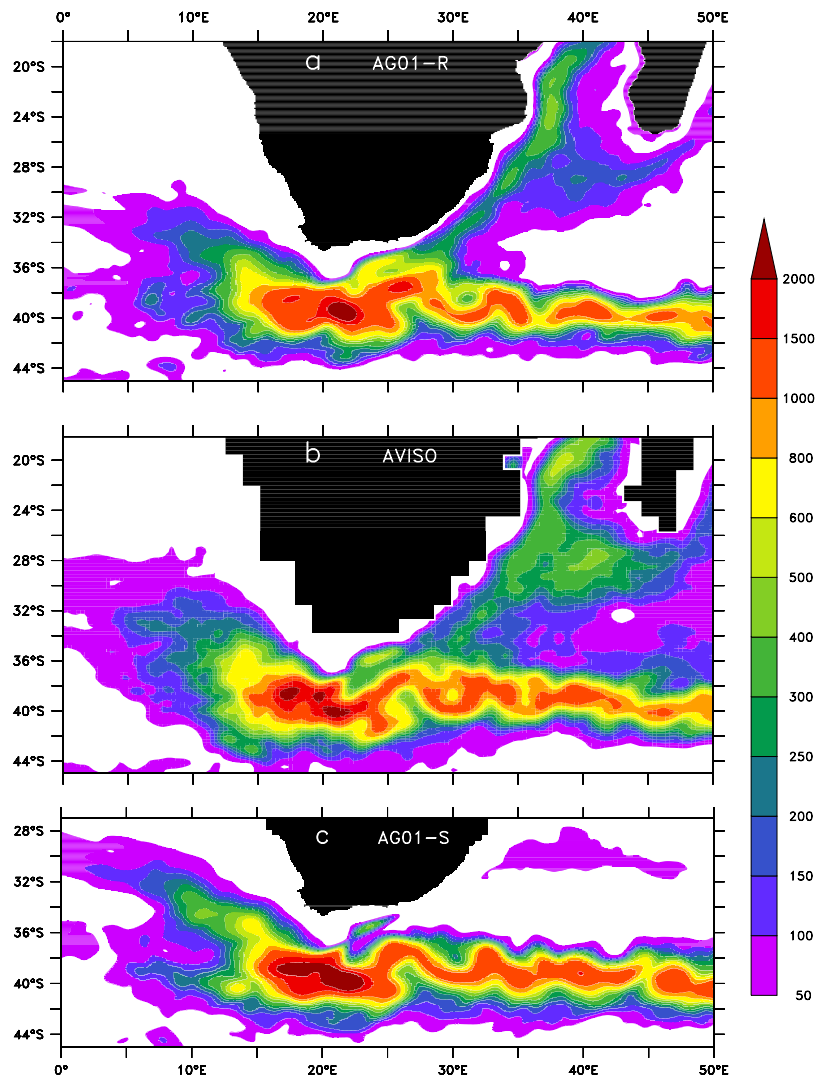


**Figure 3.** Hovmoeller plot of relative vorticity anomalies at 100 m depth for (a) reference (AG01-R) and (b) sensitivity experiment (AG01-S), the latter not including the Mozambique Channel in the high-resolution nest. The anomalies (in  $10^{-6} \text{ s}^{-1}$ ) were defined relative to the 1962–1971 mean and zonally averaged in a section along the African coast. Early retroreflections are marked by arrows. (This coastal-following section, shown in the inlet figure, was defined by speeds greater than  $0.3 \text{ m s}^{-1}$  in the 10-yr mean in the Mozambique Channel and in the Agulhas Current. The northern boundary of the high-resolution nest in AG01-S is marked by green lines.) Snapshots of typical situations for (c) regular and (d) upstream retroreflection states. Shown are speed (in  $\text{cm s}^{-1}$ ) and velocities (only every 2nd vector).

que eddies (AG01-S). Some single Pulses (e.g., in 1971) were generated by eddies from further offshore, but these are too weak and therefore do not cause any upstream retroreflections. However, the modelled upstream retroreflections are found to have a negligible effect on net inter-ocean exchange (Figure 2), thus not supporting previous hypotheses arguing for a large-scale relevance of these events [Lutjeharms and de Ruijter, 1996].

[8] The independency of the magnitude of inter-oceanic volume flux on upstream retroreflections does not imply that mesoscale upstream control mechanisms are unimportant for a proper description of the Agulhas leakage. Although simulating a similar number of Agulhas rings, those in the

sensitivity experiment without Mozambique eddies show uncharacteristic regularity in time and space. As a consequence the ring paths are much more constrained in the South Atlantic, like “pearls on a string” (Figure 4); a behaviour that is typical for coarser models [Barnier *et al.*, 2006] and also found in limited-area simulations [Speich *et al.*, 2006]. It is unclear whether a false regularity in the ring spreading may influence the temporal variability of Agulhas leakage or might bias water masses in the South Atlantic where Agulhas rings finally end up and release their anomalous loads of heat and salt. In a similar modelling study Penven *et al.* [2006] also found the interoceanic transport to be insensitive to upstream perturbations (although



**Figure 4.** Variance of sea surface height (in  $\text{cm}^2$ ) in (a) the reference model (AG01-R, 1970–1979), (b) Aviso satellite data (1991–1999), and (c) the sensitivity model (AG01-S).

they did not report differences in ring paths, probably because of the coarser resolution in the Agulhas retroflexion area or the weak but still existent upstream perturbations). However, the uniform eddy-permitting resolution of their model did not allow isolating the mesoscale in the Agulhas retroflexion area itself.

## 5. Summary

[9] Based on a realistic portrayal of the salient features of the Agulhas system, the model configuration advances our process understanding of the Agulhas system and demonstrates the significance of the local, mesoscale flow dynamics for the inter-ocean exchange south of Africa. Critical elements include the triggering of Natal Pulses by offshore eddies, the spawning of Agulhas rings with or without the advent of Natal Pulses, and the significant dependence of upstream retroflexion on Natal Pulses. A reliable representation of these processes appears of paramount importance for assessing the role of this regime in model simulations of past and future climate changes [Peeters *et al.*, 2004].

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