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Madagascar: A pacemaker for the Agulhas Current system?

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[1] Western boundary currents are driven by zonally integrated wind-stress curl over the width of subtropical basins. This cross-basin integration is interrupted in the South Indian Ocean where Madagascar presents a formidable barrier. Nevertheless, a western boundary current has been thought to exist in the Mozambique Channel, the Mozambique Current. Recent observations have however shown that no such current exists and that the flow in the channel instead consists of a train of eddies. Is this western boundary anomaly due to the presence of Madagascar? We have used a primitive equations model to investigate the flow in the South West Indian Ocean as if there were no Madagascar. We show that a normal, continuous western boundary current is then formed that constitutes a continuum with the Agulhas Current. The presence of Madagascar is shown to affect the frequency of inter-ocean exchange events south of Africa. **Citation:** Penven, P., J. R. E. Lutjeharms, and P. Florenchie (2006), Madagascar: A pacemaker for the Agulhas Current system?, *Geophys. Res. Lett.*, *33*, L17609, doi:10.1029/2006GL026854.

1. Introduction

[2] The Agulhas Current spawns rings at the Agulhas retroflection south of Africa [*Lutjeharms and van Ballegooyen*, 1988]. This process of inter-ocean exchange is a key link in the global thermohaline circulation and is largely controlled by impulses coming from far upstream [*Schouten et al.*, 2002]. The interactions of deep sea eddies with the Agulhas Current may cause the formation of Natal Pulses (i.e., single meanders on the trajectory of the current) [*Lutjeharms and Roberts*, 1988] which move downstream with the current. These eventually cause ring occlusion when they reach the Agulhas retroflection [*Van Leeuwen et al.*, 2000]. Triggering eddies for Natal Pulses may come from the termination of the southern branch of the East Madagascar Current [*De Ruijter et al.*, 2003] or from the Mozambique Channel [*De Ruijter et al.*, 2002; *Schouten et al.*, 2003]. The regular formation of Mozambique eddies at the narrows of the channel [*Ridderinkhof and de Ruijter*, 2003] is in sharp contrast to the western boundary current east of Madagascar [*Lutjeharms et al.*, 1981], the East Madagascar Current. Theory shows the influence of islands on Western boundary currents [*Pedlosky et al.*, 1997]. It is therefore important to establish what role the presence of Madagascar plays in the disparate nature of the currents to either side of it and thus to the impulses that control the inter-ocean leakage south of Africa.

2. Material and Method

2.1. ROMS Model and SAfE Configuration

[3] The model employed is the Regional Oceanic Modeling System (ROMS) [*Shchepetkin and McWilliams*, 2005], a split-explicit, free-surface oceanic model discretized in coastline- and terrain-following curvilinear coordinates. Higher order numerics allow the generation of steep gradients and a significant increase in the permissible time step. A non-local, K-profile planetary (KPP) boundary layer scheme [*Large et al.*, 1994] parameterizes the subgrid-scale vertical mixing processes. A parameterization of horizontal viscosity ($A_h = 0.025 \times \frac{\Delta x \Delta y}{2} \times |\text{deformation tensor}|$ [*Smagorinsky*, 1963]) provides a selective damping for the western boundary current [*Chassignet and Garraffo*, 2001; *Penven et al.*, 2006].

[4] The Southern Africa Experiment (SAfE) is a ROMS configuration designed for the resolution of the major oceanic phenomena around Southern Africa [*Penven et al.*, 2006]. SAfE is expected to resolve the greater Agulhas Current system, from its main sources of variability (the Mozambique Channel and the East Madagascar Current) to the propagation of the Agulhas Rings in the southern Atlantic Ocean. SAfE has been built using ROMSTOOLS [*Penven*, 2003]. The Mercator grid has a longitude increment of 0.25° ranging from 2.5°W to 54.75°E and from 46.75°S to 4.8°S. The horizontal resolution ranges from 19 km in the south to 27.6 km in the north. Typical eddy length scales in the Agulhas Current system are around 300 km. In this context, SAfE can be considered as an eddy resolving model (one can also note that ROMS higher order numerics enhances the effective resolution for a given grid size). The 32 s-coordinate vertical levels are stretched toward the surface ($\theta_s = 6$, $\theta_b = 0$, $h_c = 10$m [see *Haidvogel and Beckmann*, 1999]) to get a vertical resolution ranging from 37 cm to 5.7 m for the surface layer and from 11 m to 981 m for the bottom. SAfE bottom topography (h) is derived from GEBCO. To prevent the generation of pressure gradient errors, h is smoothed using a selective Shapiro filter to keep the topographic parameter $\frac{h_{+1/2} - h_{-1/2}}{h_{+1/2} + h_{-1/2}}$ below 0.2 [*Haidvogel and Beckmann*, 1999].

[5] Surface forcing is derived from the Comprehensive Ocean/Atmosphere Data Set (COADS) [*Da Silva et al.*, 1994] monthly climatology. At the lateral boundaries, for each prognostic variable, an active radiation condition connects the model solution to the surroundings [*Marchesiello et al.*, 2001]: in the case of inflow conditions, the solution is

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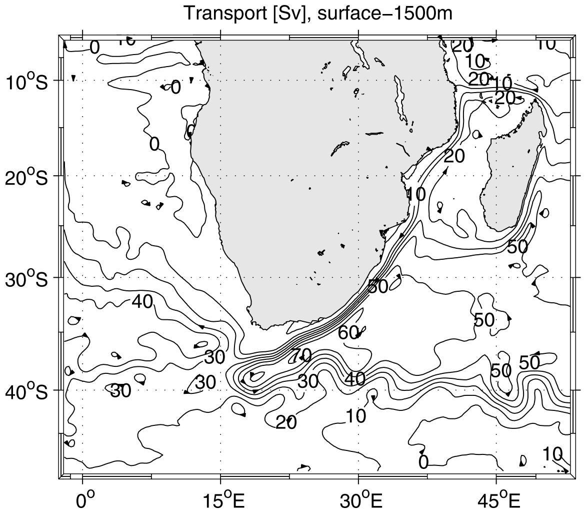


Figure 1. Transport function [Sv] for the modeled annual mean currents integrated from 1500 m to the sea surface.

nudged toward data. World Ocean Atlas 2001 (WOA) [*Conkright et al.*, 2002] mean-monthly climatology provides temperature and salinity. These data and COADS winds are combined to estimate geostrophic (reference level: 1000 m) and Ekman velocity components for the boundaries. Model initialization is done using WOA temperature and salinity for the month of January and no flow.

[6] SAfE was run for 10 years. Integrated properties show that after a spin-up of 2 years, SAfE has reached a statistical equilibrium (figure not shown). SAfE results are analyzed from year 3 to year 10.

2.2. AVISO Products

[7] Measured mean sea surface elevation (SSH) is the AVISO Rio05 product at 0.5° resolution, combining hydrographic data, surface drifter velocities, altimetry and a geoid model [*Rio and Hernandez*, 2004]. Measured surface eddy kinetic energy (EKE) is derived from SSH anomalies obtained from merged TOPEX/Poseidon, ERS-1/-2 and Jason gridded data (AVISO Ssalto/Duacs delayed time data) from 14 October 1992 to 5 January 2005 [*Ducet et al.*, 2000].

3. Model Results

3.1. Model Authentication

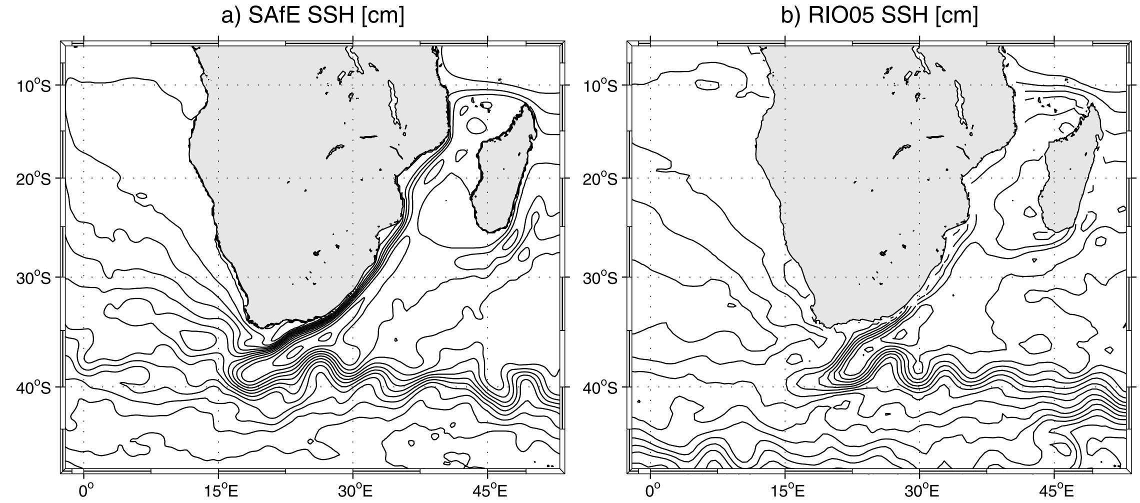
[8] The simulated volume transport in Sv (Sv = 10^6 m^3.s^{-1}) of the Agulhas Current system between surface and 1500 m is shown in Figure 1. The geographic locations of the main current elements in this mean portrayal are realistic. The South Equatorial Current bifurcates on the east coast of Madagascar at about 18°S [*Lutjeharms et al.*, 2000]. The southern limb of the East Madagascar Current increases in strength poleward, some of its waters ($\sim$6 Sv) moving into the southern Mozambique Channel, the rest ($\sim$20 Sv) joining the Agulhas Current at about 28°S. The flow through the Mozambique Channel ($\sim$18 Sv) is concentrated on its western side [*De Ruijter et al.*, 2002]. The Agulhas Current proper is highly concentrated and follows the shelf edge closely [*Gründlingh*, 1983], its volume transport of about 60 Sv to a depth of 1500 m being realistic [*Bryden et al.*, 2005]. There is a degree of recirculation ($\sim$20 Sv) in the South-West Indian Ocean shown in Figure 1 with the volume flux of the current increasing downstream. The Agulhas Return Current is at the correct latitude [*Lutjeharms and Ansorge*, 2001] and exhibits meanders at the observed longitudes [*Boebel et al.*, 2003].

[9] The simulated SSH of the Agulhas Current system (Figure 2a) bears a striking resemblance to that of measurements (Figure 2b). The similarity of the Agulhas Return Current in the two representations is particularly strong. The Agulhas Current proper is not well resolved by Rio05. This holds also for the East Madagascar Current and the flow through the Mozambique Channel. The modeled location of the Agulhas retroflection loop lies about 200 km too far westward. Figure 2 shows also the surface EKE, based on SAfE (Figure 2c) and from AVISO (Figure 2d), computed in both cases using SSH gradients with a similar temporal sampling. AVISO EKE shows five characteristic areas of high variability: the Mozambique Channel [*Cheney et al.*, 1983], the region south-east of Madagascar [*Lutjeharms et al.*, 2000], the Agulhas retroflection and the Agulhas Return Current. A band of high values lies just seaward of the Agulhas Current, representing the paths of Mozambique eddies [*Schouten et al.*, 2002, 2003]. The highest values are greater than 2000 cm^2.s^{-2}, found in the Agulhas retroflection and this holds for both AVISO as well as SAfE. In general, SAfE EKE is slightly on the low side, but the geographic patterns are very much alike. Particularly conspicuous is the distribution of high variability in the South Atlantic Ocean in both portrayals. This represents the paths of Agulhas rings and their dissolution [*Schouten et al.*, 2000]. All things considered, these comparisons give us substantial confidence that SAfE simulates the basic large-scale as well as mesoscale elements of the circulation appropriately.

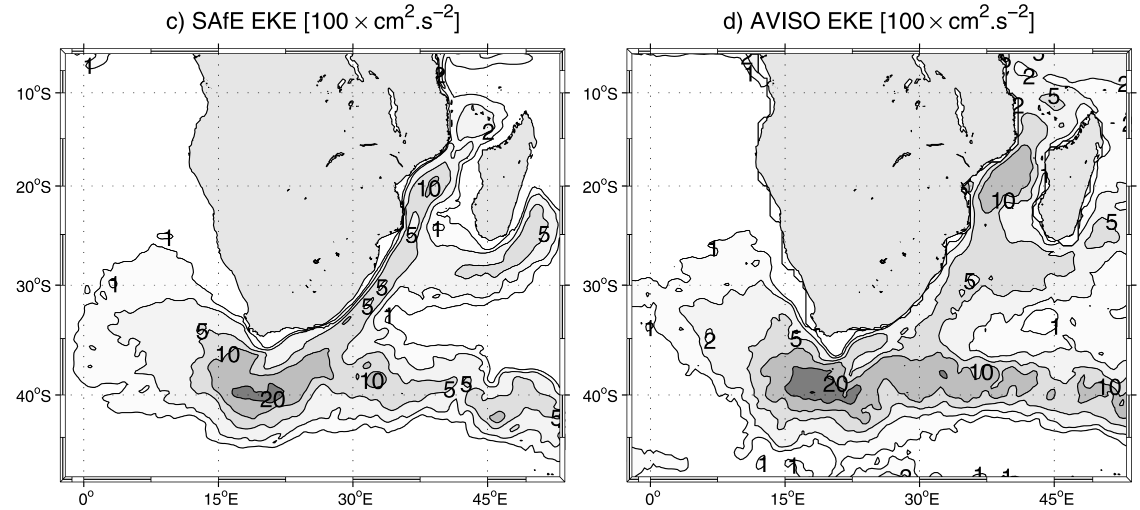
3.2. Madagascar Excision Experiment

[10] We designed a second experiment in which Madagascar has been removed. In the region where Madagascar is now missing, the bathymetry is re-interpolated using an objective analysis method in order to keep a regular bottom shape. Surface forcing and initial conditions are also re-interpolated with the same method: since the Agulhas Current is the Western Boundary Current of the Indian Ocean, it is the result of the wind integration over the entire basin; the direct effect of Madagascar on the local winds can therefore be neglected. The experiment is run for 10 years.

[11] Figure 3 presents the mean SSH and surface EKE for the simulation without Madagascar. Madagascar excision did not significantly perturb the mean SSH in the Benguela Current system, the mean position of the Agulhas retroflection nor the Agulhas Return Current. The averaged position and transport of the Agulhas Current appears to be also unaffected. EKE in the South Atlantic and in the Agulhas Return Current is almost unchanged, although it is slightly higher at the southern tip of the Agulhas Bank. Madagascar removal resulted in the absence of the East Madagascar Current and no generation of Mozambique Channel Eddies. Consequently, a continuous Mozambique Current follows the east coast of Southern Africa as it was previously described in older textbooks [*Glickman*, 2000; *Tomczak and Godfrey*,

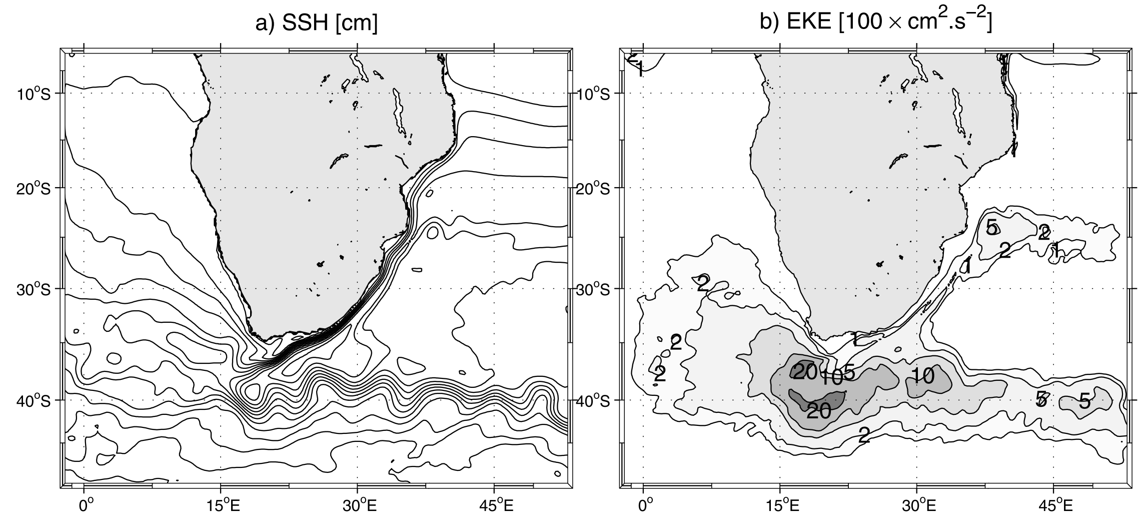

a) SAfE SSH [cm]

b) RIO05 SSH [cm]


c) SAfE EKE [$100 \times cm^2.s^{-2}$]

d) AVISO EKE [$100 \times cm^2.s^{-2}$]

Figure 2. Model/data comparisons: (a) SAfE annual mean SSH, (b) RIO05 SSH, (c) SAfE EKE [100× $cm^2.s^{-2}$] and (d) AVISO EKE [100× $cm^2.s^{-2}$]. The interval between the isocontours for SSH is 10 cm.


a) SSH [cm]

b) EKE [$100 \times cm^2.s^{-2}$]

Figure 3. Experiment without Madagascar: (a) annual mean SSH (interval between the isocontours: 10 cm), (b) surface EKE [100 × $cm^2.s^{-2}$].

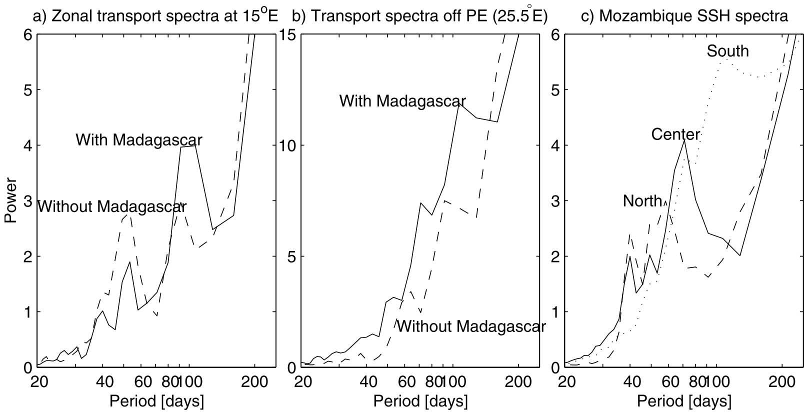


Figure 4. (a) Spectra of the zonal transport across a meridional section at 15°E. (b) Spectra of the transport across a 300 km section off Port Elisabeth (25.5°E). (c) Average SSH spectra over the 3 regions defined by *Schouten et al.* [2003] in the Mozambique Channel. The spectra in Figures 4a and 4b are normalized by the variance of the transport at 15°E for the simulation with Madagascar. The spectra in Figure 4c are normalized by the variances of the time series.

2003]. EKE is almost null in the ex-Mozambique Channel region.

[12] At about 25°S, a current flows eastward from Delagoa Bay. Associated to this current, a local EKE maximum (500 $cm^2.s^{-2}$) is present in this area. Since EKE reaches a minimum of about 100 $cm^2.s^{-2}$ at 30°S, downstream in the Agulhas Current, the eddies generated around 25°S do not seem to be able to propagate southward and therefore cannot interact with the Agulhas retroflection. Hence, the reasonable level of EKE in the Agulhas retroflection area (Figure 3b) is obtained without the help of variability coming from the upstream regions. This is in agreement with the CLIPPER 1/6° model results [see *Treguier et al.*, 2003, Figure 2]. In CLIPPER, the presence of an open boundary at 27°E prevented the injection of variability into the Agulhas retroflection.

[13] Immediately to the west of the Agulhas retroflection (at 15°E), the vertically integrated modeled transport across a meridional section between 45°S and 30°S (i.e., in the path of the Agulhas Rings, see Figure 2) is not significantly affected by the excision of Madagascar: 8.7 Sv with Madagascar and 9.3 Sv without Madagascar. The transport RMS is almost unchanged: approximately 16 Sv for each simulation. Although dominated by the annual cycle, the spectrum of the modeled transport for the simulation with Madagascar presents a maximum at about 100 days (Figure 4a). This maximum is significantly reduced for the simulation without Madagascar. In this case, the transport variability is redistributed toward the 50 days period, which seems to be the natural period for Agulhas Rings shedding. In the simulation with Madagascar, the 100 days maximum can be followed upstream of the Agulhas Current (Figure 4b). It is still present in the SSH spectrum for the south Mozambique Channel (Figure 4c). Figure 4c can be compared to the findings of Figure 9 of *Schouten et al.* [2003]. The maximum at 100 days can thus be related to the southward propagation of Mozambique Channel Eddies. Note that our model is able to reproduce the decrease in frequency observed in the Mozambique Channel by *Schouten et al.* [2003]: from about 50–60 days in the north, to about 70 days in the center, to about 100 days in the south. Hence, our simulations confirm that eddies generated around Madagascar (at a periodicity of 4 eddies per year for the Mozambique Channel Eddies [*Schouten et al.*, 2003]), by acting as a trigger in the Agulhas retroflection, are affecting the pace of the Agulhas Rings generation process.

4. Conclusions

[14] It has recently been demonstrated that intense eddies are being formed repetitively in the Mozambique Channel [*Ridderinkhof and de Ruijter*, 2003] and south of Madagascar [*De Ruijter et al.*, 2003]. It has also been shown that these eddies have a subsequent impact on the trajectory of the Agulhas Current [*Schouten et al.*, 2002] by triggering Natal Pulses and that these, in turn, eventually lead to the spawning of Agulhas rings [*Van Leeuwen et al.*, 2000]. Control of the inter-ocean exchanges south of Africa may thus lie largely with the eddies generated to the north. Our experiments indicate that it is principally the presence of the land mass of Madagascar that is responsible for the generation of these eddies and thus of the mesoscale, short-term behavior of the whole greater Agulhas system. In the Mozambique Channel the lack of a western boundary current is a result of it lying in the lee of Madagascar and thus having the integrated wind stress curl over the South Indian Ocean interrupted.

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