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Agulhas ring formation as a barotropic instability of the retroflection

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[1] Agulhas Leakage is an important link in the global ocean circulation, as it transfers a significant volume of relatively warm and salty water from the Indian Ocean to the Atlantic Ocean. The main route of this transfer is through the shedding of large Agulhas rings from the Agulhas retroflection. In this paper we study the dynamics of the ring formation process by analyzing the stability of the Indian/Atlantic supergyre in a reduced gravity model. We show that the ring-shedding process results from a barotropic instability of the steady circulation in the Agulhas retroflection region. The destabilizing mode appears to be linked to a Rossby basin mode of the combined South Indian/Atlantic basin, which is localized in the retroflection region by the background flow. **Citation:** Weijer, W., V. Zharkov, D. Nof, H. A. Dijkstra, W. P. M. de Ruijter, A. Terwisscha van Scheltinga, and F. Wubs (2013), Agulhas ring formation as a barotropic instability of the retroflection, *Geophys. Res. Lett.*, *40*, 5435–5438, doi:10.1002/2013GL057751.

1. Introduction

[2] One of the most fascinating phenomena in the ocean is the retroflection of the Agulhas Current (see *de Ruijter et al.* [1999] and *Beal et al.* [2011] for reviews). Flowing southwestward along the east coast of southern Africa, the Agulhas Current overshoots the continent and makes a tight turn back into the South Indian Ocean as the Agulhas Return Current. Occasional occlusions of this loop generate Agulhas rings that subsequently drift westward into the South Atlantic Ocean [e.g., *Lutjeharms and Gordon*, 1987; *Schouten et al.*, 2000]. This exchange couples the wind-driven gyres of the South Indian and Atlantic Oceans into a so-called "supergyre" [*de Ruijter*, 1982; *Speich et al.*, 2007] and provides a gateway for the upper limb of the global overturning circulation [*Gordon*, 1985]. In fact, the associated input of warm and salty water into the Atlantic may impact the strength [*Weijer et al.*, 1999], stability [*Weijer et al.*, 2001], and variability [*Biastoch et al.*, 2008] of the Atlantic Meridional Overturning circulation.

[3] The dynamical reason for the process of ring shedding is still a matter of debate. *Nof and Pichevin* [1996] analyzed the nonlinear inviscid dynamics of an Agulhas-like current and derived a contradiction ("retroflection paradox") that suggests that a steady retroflection of the Agulhas Current cannot exist. They argue that the regular shedding of these rings provides a net westward force that is essential for sustaining the Agulhas Return Current.

[4] An alternative point of view was put forward by *Dijkstra and de Ruijter* [2001a] and *Dijkstra and de Ruijter* [2001b] (hereafter jointly DdR01), who argued that Agulhas rings are instead a result of a barotropic instability of a steady retroflecting state. They found that partially retroflecting steady states *do* exist in their reduced gravity shallow water model, and that these states may become unstable to an oscillatory mode. They tentatively identified this mode as a Rossby basin mode in a rectangular basin [*Longuet-Higgins*, 1964; *Pedlosky*, 1965], modified by the basin geometry, and destabilized by the background flow. *LaCasce and Isachsen* [2007] showed that such barotropic instabilities even exist in background states with a non-retroflecting Agulhas Current.

[5] Both views on ring shedding are not mutually exclusive, however, since the retroflection paradox (i) only concerns retroflections in the inviscid state, a limit which is all but impossible to achieve in the numerical context of DdR01 and (ii) only makes a statement about the *necessity* of rings to sustain a retroflection and not on the dynamics that lead to ring generation. In this context the reader is also referred to *van Leeuwen and de Ruijter* [2009, 2012] and *Nof et al.* [2012].

[6] The computational domain of DdR01 only captured a very small environment of the Agulhas Retroflection region. The modes that were found appeared to be strongly constrained by the presence of boundaries. This makes it difficult to assess the robustness and generality of the results in the context of a more realistic basin size. In this paper we extend the work in DdR01 by studying the stability of the South Indian/Atlantic supergyre in a domain of realistic dimensions. We show that the supergyre is destabilized by a mode that has a dominant expression in the Agulhas retroflection region. The spatial and temporal evolution of this mode, the retroflection mode, shows close resemblance to the ring-shedding process, suggesting that this process is related to a barotropic instability of the shear zone in the Agulhas retroflection region.

2. Model and Methods

[7] We use a 1.5 layer reduced gravity shallow water model introduced by *Dijkstra and Molemaker* [1999] and

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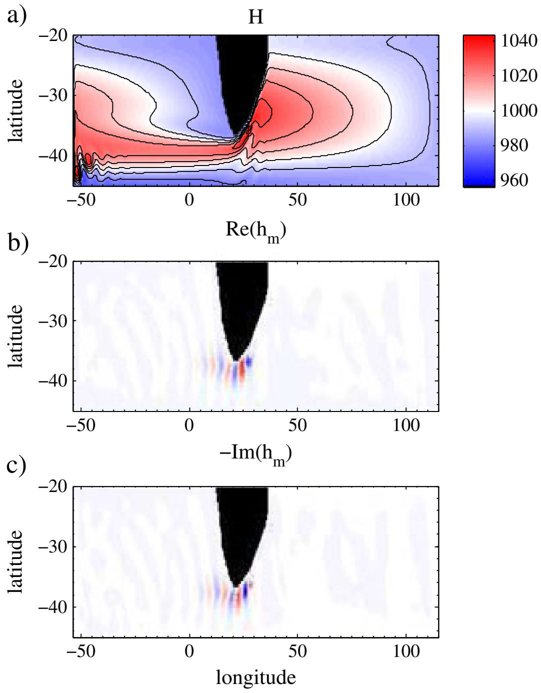

Figure 1. (a) Layer thickness H of our steady standard solution; contour interval is 5 m. (b) Real and (c) minus imaginary patterns of the dominant mode h_m that destabilizes this solution. The patterns define an entire oscillatory cycle through the sequence $\mathcal{R}(h_m) \rightarrow -\mathcal{I}(h_m) \rightarrow -\mathcal{R}(h_m) \rightarrow \mathcal{I}(h_m)$. The amplitude of the mode is assumed to be infinitesimally small.

represented by Equation (4) of *Schmeits and Dijkstra* [2000] (but note that the reduced gravity parameter g' replaces the gravitational constant g here). The model hence excludes baroclinic instability. Dynamic variables are zonal (u) and meridional (v) velocity, and layer thickness h. We use a Laplacian formulation for eddy viscosity (with coefficient A_h) and include a Rayleigh (interfacial) damping term (with coefficient r). The equilibrium layer thickness is indicated by H_0.

[8] We perform three types of analyses [see *Dijkstra et al.*, 2001; *Weijer et al.*, 2003, for more details]: (i) we follow steady states through parameter space using pseudo-arclength continuation; (ii) we perform linear stability analyses to determine the least stable normal modes; and (iii) we perform forward time integration using a Backward Euler time-stepping scheme. We use Matrix Renumbering Incomplete LU factorization [*Botta and Wubs*, 1999] to solve the sparse systems of algebraic equations and the Jacobi-Davidson QZ method to solve the generalized eigenvalue problems [*Sleijpen and van der Vorst*, 1996].

[9] Our domain ranges from –54° to 115° longitude and from –45° to –20° latitude. A continent mass representing southern Africa is based on the 700 m isobath from ETOPO2 and adjusted manually to smoothen the profile. No efforts are made to include a realistic representation of South America, Madagascar, or Australia. The horizontal resolution is 0.5° × 0.5°; although insufficient to properly resolve the Agulhas Current, it is dictated by the computational requirements and our desire to represent the Indian-Atlantic subtropical gyre in its full extent. Several transient integrations were repeated on a 0.25° × 0.25° grid to demonstrate robustness of the results with respect to spatial resolution.

[10] The model is forced by a zonal wind stress of the form $\tau_\phi(\theta) = \tau_0 \cos(2.7\pi(\theta - \theta_s))$. It is zonally constant but has a meridional structure that places the latitude of zero wind stress curl at θ_s = 44°S.

3. Results

[11] First, we determine a steady state (U, V, H) of the model for parameter values of $A_h = 592\,\mathrm{m^2 s^{-1}}$, $r = 7.3 \cdot 10^{-8}\,\mathrm{s^{-1}}$, $H_0 = 1000\,\mathrm{m}$, $g' = 0.1\,\mathrm{ms^{-2}}$, and $\tau_0 = 0.11\,\mathrm{Nm^{-2}}$. The associated Rossby deformation radius at 40°S is about 100 km. The resulting steady state (Figure 1a; referred to as our standard solution) features a realistic Agulhas Current transport of 60 Sv, but Agulhas Leakage (50 Sv) is significantly overestimated; this can be expected given the low resolution of our model and the absence of bathymetry [*Matano*, 1996; *Speich et al.*, 2006]. The location of the retroflection at 20°E compares well with observations, as does the meandering character of the Agulhas Return Current.

[12] A linear stability analysis of this standard solution shows that it is (linearly) unstable with respect to a single (complex-valued) eigenmode $X_m = (u_m, v_m, h_m)$ that we will refer to as the retroflection mode. The oscillation period (T_{osc}) and growth time scale (T_{gr}) are determined by its eigenvalue and are found to be 55 and 69 days, respectively. The spatial pattern of h_m is clearly localized in the

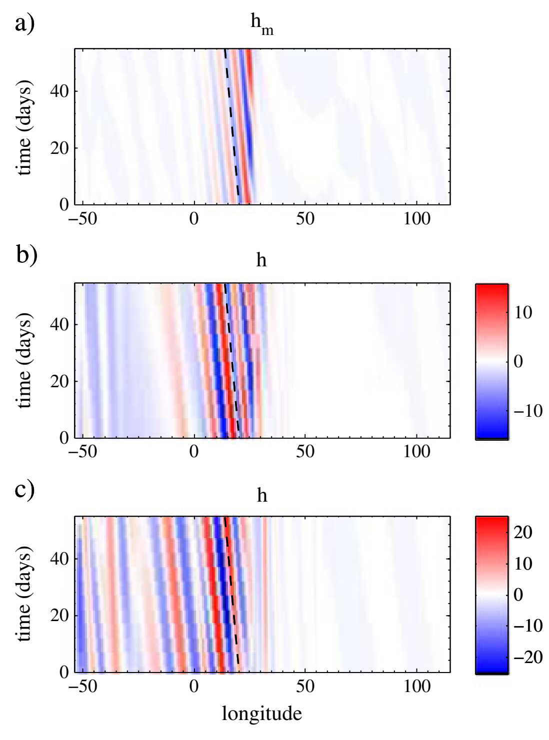

Figure 2. (a) Hovmüller plot of h_m at 38°S implied by one cycle of the retroflection mode. The amplitude of the mode is assumed to be infinitesimally small. (b) Hovmüller plot of h anomalies (in meters) at 38°S for a time integration with horizontal viscosity of $A_h = 355\,\mathrm{m^2\,s^{-1}}$. (c) as in Figure 2b but for $A_h = 118\,\mathrm{m^2\,s^{-1}}$ and double spatial resolution (0.25°). Dashed lines indicate a propagation speed of $-0.13\,\mathrm{m\,s^{-1}}$.

retroflection region (Figures 1b and 1c). It represents a wave train with zonal wavelength of about 7° (or $6.1 \cdot 10^5$ m) that propagates westward (Figure 2a) with a speed of -0.13 m s^{-1}.

[13] The temporal behavior of the flow is studied by performing time integrations with the same model at subsequently lower values of A_h. Simulations for $A_h = 355$ m^2 s^{-1} and for $A_h = 118$ m^2 s^{-1} (at doubled resolution, 0.25°) show the same propagation characteristics as implied by the eigenmode, albeit extending further west with decreasing friction (Figures 2b and 2c). A sequence of snapshots of the high-resolution run (Figure 3) clearly shows (i) the development of ring-like thickness anomalies and anticyclonic circulation in the Agulhas retroflection region; (ii) subsequent westward propagation into the South Atlantic Ocean; and (iii) a characteristic period of about 2 months [see also *LaCasce and Isachsen*, 2007, Figure 6]. Although computational constraints prevent us from reaching a parameter regime where these anomalies are truly detached and highly nonlinear, it is clear that the characteristics displayed here are fully consistent with the process of Agulhas Ring formation and shedding, as inferred from observations [e.g., *Schouten et al.*, 2000].

[14] As shown in supplementary information, the mean zonal velocity at 25°E of our standard solution displays a strong shear between the westward Agulhas Current and the eastward Agulhas Return Current to the south (Figure S1a). Consequently, the gradient of the potential vorticity $\beta_0 - U''$ (where β_0 is the gradient of planetary vorticity) undergoes a zero crossing, which is a necessary condition for barotropic instability [e.g., *Kuo*, 1949]. The maximum variance of thickness anomalies associated with the retroflection mode is indeed collocated with this zero crossing. Hence, we conclude that the mode results from a barotropic instability of the mean flow in the retroflection region. Indeed, the zonal length scale of the instability is consistent with the least stable mode of a narrow shear zone, following the analysis of *Talley* [1983] (as shown in Figure S1b).

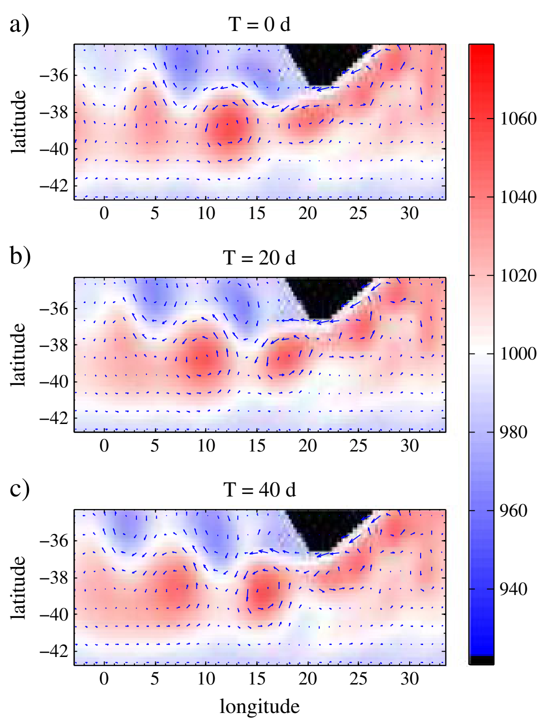

Figure 3. Three snapshots of h (shading) and velocity (vectors; plotted every 4th grid point), 20 days apart in the Agulhas region for the time integration with double spatial resolution (0.25°) and viscosity of $A_h = 118$ m^{2}s^{-1}.

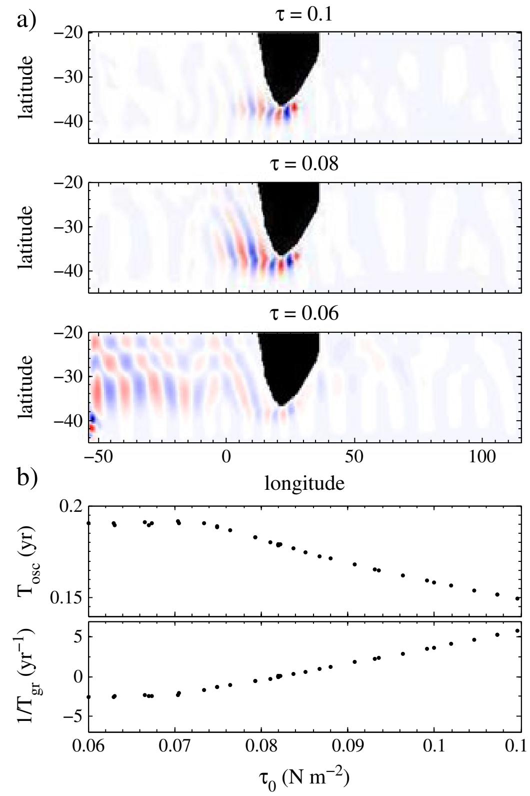

Figure 4. (a) Retroflection mode ($\mathcal{R}(h_m)$) for three values of the wind stress amplitude τ_0. (b) Oscillation period (T_{osc}; top) and growth rate ($1/T_{gr}$; bottom) of the retroflection mode as a function of the wind stress amplitude τ_0.

[15] To determine the spectral origin of the retroflection mode, we attempted to link it to a mode of the unforced basin. To that end, we performed a parameter continuation of the background state by reducing the wind stress τ_0. For each steady state, we tried to identify the retroflection mode by calculating the eigenvalue closest to its previously determined value. The retroflection mode could not be unambiguously followed below $\tau_0 = 0.06$ Nm^{-2}, as apparently the spectrum of the basin modes is too dense for our method to yield robust results. The growth rate $1/T_{gr}$ determined through this process (Figure 4b) crosses zero at $\tau_0 = 0.08$ Nm^{-2}, indicating the presence of a Hopf bifurcation. Both the growth rate and oscillation period display a kink at a value of $\tau_0 = 0.07$ Nm^{-2}, which seems to be associated with the transition from a localized (e.g., $\tau_0 = 0.08$ Nm^{-2} in Figure 4a) to a basin-wide ($\tau_0 = 0.06$ Nm^{-2}) pattern. We interpret this global pattern as a (damped) Rossby basin mode of the coupled South Indian/Atlantic Ocean.

4. Summary and Discussion

[16] The results presented here indicate that the Agulhas ring-shedding process is related to a barotropic instability of the South Indian/Atlantic supergyre, in particular, the shear zone between the Agulhas Current and the Agulhas Return Current in the retroflection region. The connection between a

growing normal mode (Figure 1) and weakly nonlinear transient anomalies (Figure 3) was explicitly demonstrated here; the transition toward fully nonlinear and self-propagating rings is implied by the resemblance with the Agulhas ring-shedding process as seen in observations. In particular, the frequency of this mode (6.6 per year) compares well with the observed ring-shedding frequency of 4–6 per year [*Schouten et al.*, 2000].

[17] In addition, we have established a connection between the retroflection mode and a Rossby basin mode of the South Indian/Atlantic Basin. Indeed, the theory of barotropic instability is closely linked to Rossby wave dynamics [e.g., *Talley*, 1983]. Although local flow conditions determine a preferred length scale of the instability, the modal character is established through association with a basin mode of that approximate wave length. In other words, the barotropic instability localizes the pattern of a global basin mode in the Agulhas retroflection region.

[18] Our standard solution shows only a weak retroflection, but it is the shear zone, not the retroflection per se, that is critical for the instability to develop [*LaCasce and Isachsen*, 2007]. Steady states with a more pronounced retroflection, obtained by unrealistically shifting the wind profile further north, still robustly feature the retroflection mode. However, other modes now are more unstable (for instance, an instability of the upstream Agulhas Current), making interpretation of the transient integrations less straightforward.

[19] The conclusion presented here is consistent with DdR01 and with the results of *Chassignet and Boudra* [1988], who studied Agulhas ring formation in a multi-layer isopycnic model. In their experiment with low Rossby number, ring formation in the Agulhas retroflection region appeared to be related to the propagation of a basin-scale Rossby basin mode in the lower layer. They found that for this simulation ring formation was dominantly related to a transfer from mean to eddy kinetic energy, pointing at barotropic instability. Energy transfers in additional simulations at higher Rossby numbers suggested the importance of mixed barotropic/baroclinic instabilities, a process that is not captured by our model. In conclusion, while baroclinic effects may come into play in a fully stratified setting, the barotropic instability mechanism is at the core of the Agulhas ring-shedding process.

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