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A weaker Agulhas Current leads to more Agulhas leakage

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[1] Time series of transports in the Agulhas region have been constructed by simulating Lagrangian drifter trajectories in a 1/10 degree two-way nested ocean model. Using these 34 year long time series it is shown that smaller (larger) Agulhas Current transport leads to larger (smaller) Indian-Atlantic inter-ocean exchange. When transport is low, the Agulhas Current detaches farther downstream from the African continental slope. Moreover, the lower inertia suppresses generation of anti-cyclonic vorticity. These two effects cause the Agulhas retroflection to move westward and enhance Agulhas leakage. In the model a 1 Sv decrease in Agulhas Current transport at 32°S results in a 0.7 ± 0.2 Sv increase in Agulhas leakage. **Citation:** van Sebille, E., A. Biastoch, P. J. van Leeuwen, and W. P. M. de Ruijter (2009), A weaker Agulhas Current leads to more Agulhas leakage, *Geophys. Res. Lett.*, *36*, L03601, doi:10.1029/2008GL036614.

1. Introduction

[2] The transport of thermocline and intermediate water between the Indian and Atlantic ocean is largely controlled by the dynamics of the Agulhas system [*De Ruijter et al.*, 1999; *Lutjeharms*, 2006]. This highly non-linear system has a profound role in global climate as it connects the meridional overturning circulation of the Pacific-Indian Ocean system with that of the Atlantic [*Gordon*, 1986; *Weijer et al.*, 1999; *Knorr and Lohmann*, 2003]. *Peeters et al.* [2004] showed that changes in Indian-Atlantic inter-ocean exchange are related to (de)glaciations and *Biastoch et al.* [2008b] showed that variability in inter-ocean exchange influences the variability of the Atlantic thermohaline circulation. Accurate knowledge of the mechanisms governing inter-ocean variability is therefore important.

[3] The Agulhas Retroflection system is fed from the north by the Agulhas Current. From in-situ measurements *Bryden et al.* [2005] estimated the Agulhas Current volume transport at 32°S to be 70 Sv (1 Sv $\equiv 10^6$ m^3 s^{-1}). Water entering the Agulhas system can exit through two major pathways. One is eastward through the Agulhas Return Current. This current reconnects to the Indian Ocean subtropical gyre, thereby recirculating the water in the Indian Ocean. The second pathway for water to leave the Agulhas system is westward into the Atlantic Ocean through Agulhas leakage. Agulhas leakage occurs predominantly in rings, filaments and other meso- to small-scale features [e.g., *Reason et al.*, 2003]. Its magnitude is an estimated 5–15 Sv [*de Ruijter et al.*, 1999; *Richardson*, 2007], 10–20% of the inflow transport. The Agulhas retroflection dynamics is a control on the ratio of eastward and westward transport.

[4] *de Ruijter* [1982] argued from an asymptotic analysis that the inertia of the Agulhas Current plays a key role in the strength of the retroflection. A weaker Agulhas Current would then result in a reduced inertial overshoot and a consequent increase in Agulhas leakage. This was supported by a series of numerical experiments [*de Ruijter and Boudra*, 1985; *Boudra and Chassignet*, 1988]. An anti-correlation between Agulhas Current transport and the westward extent of the retroflection loop was derived in an adiabatic reduced gravity model by *Ou and de Ruijter* [1986].

[5] In a steady-state model *Dijkstra and de Ruijter* [2001] showed that the anti-correlation between Agulhas Current strength and Agulhas leakage is valid only if the flow is in low lateral Ekman number regime, when inertia dominates over viscosity. However, the relations determined by these authors have never been explored in large-scale high-resolution diabatic Ocean General Circulation Models (OGCMs). Although there have been quite a few studies on the variability and strength of the Agulhas Current in OGCMs [e.g., *Matano*, 1996; *Penven et al.*, 2006] none have quantified the strength of the Agulhas Current in relation to the inter-ocean exchange. Moreover, the efficiency of the mechanism has not been investigated. In this study we use two coupled OGCMs in a nested configuration, in combination with numerical drifter trajectories, to assess the sensitivity of the Agulhas leakage to changes in Agulhas Current transport.

2. Model

[6] In order to compute transports in the Agulhas system, Lagrangian drifters are tracked within a set of two coupled OGCMs. The models are a 1/10° model of the Agulhas region (20°W–70°E; 47°S–7°S), nested into a 1/2° global ocean-sea-ice model [*Biastoch et al.*, 2008a]. Both models are based on NEMO (version 2.3 [*Madec*, 2006]). The models are two-way nested, allowing for information to cross the open boundaries both ways [*Debreu et al.*, 2008]. In this way, the local Agulhas dynamics are affected by the global circulation and vice versa. The models are forced for 34 years with the CORE data set of daily wind and surface forcing fields [*Large and Yeager*, 2004].

[7] Lagrangian drifter trajectories are computed using the ARIANE package [*Blanke and Raynaud*, 1997]. Every five days, the number of drifters released in the Agulhas Current is related to the instantaneous transport in such a way that each drifter represents a transport with a maximum of 0.1 Sv. The drifters are released according to the southward velocity at 32°S between the coast and 32.1°E. Only 0.2% of all drifters are released in the most eastern grid cell, implying that the Agulhas Current core is well captured by

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constraining the release longitude to 32.1°E. The drifter paths are integrated for five years. Over a period of 34 years (1968–2002) $5.5 \cdot 10^6$ drifter are released, a mean transport at 32°S of 64.1 Sv. The ability of the model and drifters to accurately simulate Agulhas Current transport and Agulhas leakage has been demonstrated by *Biastoch et al.* [2008a, 2008b].

3. Relating Agulhas Inflow and Outflow

[8] Using the drifters, time series are constructed of the Agulhas Current volume transport T_{AC}. The instantaneous transport varies between 30 Sv and 128 Sv, largely related to passing mesoscale eddies. Because we are interested in inter-annual variability, biennial averages are taken of the transport time series yielding 17 individual transport estimates.

[9] Similar to the time series for the Agulhas Current transport, time series are constructed for the Agulhas leakage T_{AL} and the Agulhas Return Current transport T_{ARC}. Due to the turbulent nature of the flow in the Cape Basin T_{AL} should be measured far enough from the retroflection area [*Boebel et al.*, 2003]. Therefore, a drifter contributes to T_{AL} the last time it crosses the Good Hope line (the dashed black line in Figure 2 [*Swart et al.*, 2008]). In a similar way T_{ARC} is measured over the 40°E line south of Madagascar. In the model, 26% (16.5 Sv) of the drifter transport exits the Agulhas system as T_{AL}, whereas 71% (45.4 Sv) exits as T_{ARC}. Approximately 3% (2.2 Sv) of the drifters have not left the domain through one of these sections after the five year integration period and they constitute T_R. Mass conservation leads to a relation between the transports

$$T_{AC} = T_{AL} + T_{ARC} + T_R \qquad (1)$$

[10] It is important to note that, by construction, a drifter's exit from the Agulhas system is synchronized to its release. In this way, the local dynamics in the Agulhas system is ignored. This is done because the time lags between drifter inflow and outflow are highly variable and depend on where a drifter leaves the system. The median time it takes a drifter to exit the Agulhas system as either T_{AL} or T_{ARC} is less then a year, and more than 85% of the drifters exit within two years. By eliminating the influence of the lags, equation (1) is always true and the transport sensitivities, which are based on this relation, are better confined.

[11] In the model, the ratio between the outflow fluxes T_{AL} and T_{ARC} is approximately 1:3. If the Agulhas system were linear, a 1 Sv decrease in the inflow flux T_{AC} would therefore yield a 0.25 Sv decrease in T_{AL} and a 0.75 Sv decrease in T_{ARC}. This linear hypothesis is tested using the drifter data. The sensitivities of the outflow fluxes to changes in T_{AC} are obtained from the slope of the best linear fits in Figure 1. They are -0.73 ± 0.21 for T_{AL}, 1.78 ± 0.23 for T_{ARC}, and 0.05 ± 0.04 for T_R, emphasizing the non-linear nature of the Agulhas system with the main result that a weaker Agulhas Current leads to more Agulhas leakage. These sensitivities depend on the width of the averaging bins taken, but beyond a width of two years the sensitivity parameters vary within the standard deviations of the biennial bin. When time lags are incorporated in the transport time series the signs of the sensitivities remain unchanged but the correlations decrease.

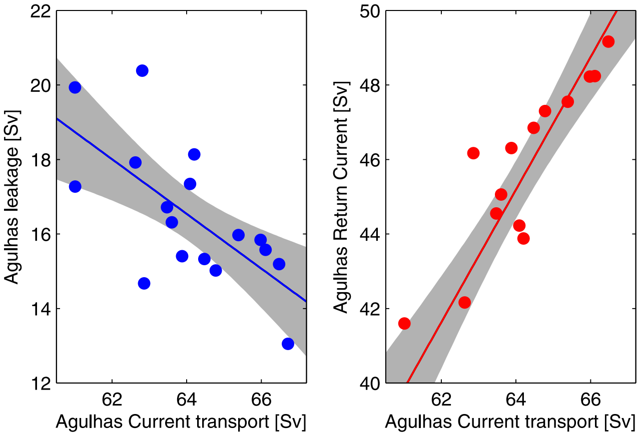

Figure 1. The correlations between Agulhas Current transport and (left) Agulhas leakage and (right) Agulhas Return Current transport. The dots are biennial transport values, the lines represent the best linear fit, and the gray areas are the 95% confidence interval of these fits. There is an anti-correlation between Agulhas Current transport and Agulhas leakage ($R = -0.67$), whereas Agulhas Current transport correlates positively with Agulhas Return Current transport ($R = 0.89$).

4. Inertial Outcropping

[12] As mentioned in the introduction, the negative correlation between Agulhas Current strength and Agulhas leakage found here has been suggested before. A stronger Agulhas Current has more inertia so the potential for stretching is larger (related to conservation of the Bernouilli function [*Ou and de Ruijter*, 1986]). The current can then more easily detach from the continental slope by interface outcropping, creating a free streamline. Due to the convex curvature of the African coast a stronger Agulhas Current detaches more upstream. In part aided by the local bottom topography (in particular the Agulhas plateau [*Matano*, 1996; *Speich et al.*, 2006]) the separated current then flows southward, where it is able to attach to the Agulhas Return Current.

[13] The mean drifter trajectories (Figure 2) show that the flow is more coast-bound when T_{AC} is low, as predicted by the inertial outcropping mechanism. Moreover, the drifter trajectory distributions are shifted westward for low T_{AC}.

[14] The model Agulhas Current detaches from the continent by means of outcropping of the isotherms (Figure 3; due to the biennial averaging, the strength of the outcropping is masked somewhat). In the model, a weaker Agulhas Current outcrops farther downstream (with a correlation coefficient $R = 0.5$) and the strength of the upwelling is reduced ($R = 0.6$). Moreover, a weaker Agulhas Current has less inertia ($R = 0.5$).

[15] Apart from reducing outcropping, inertia also controls the eastward current loop after outcropping because it generates anticyclonic vorticity through the strength of the planetary vorticity advection [*Boudra and Chassignet*, 1988]. A more upstream separation leads, in agreement

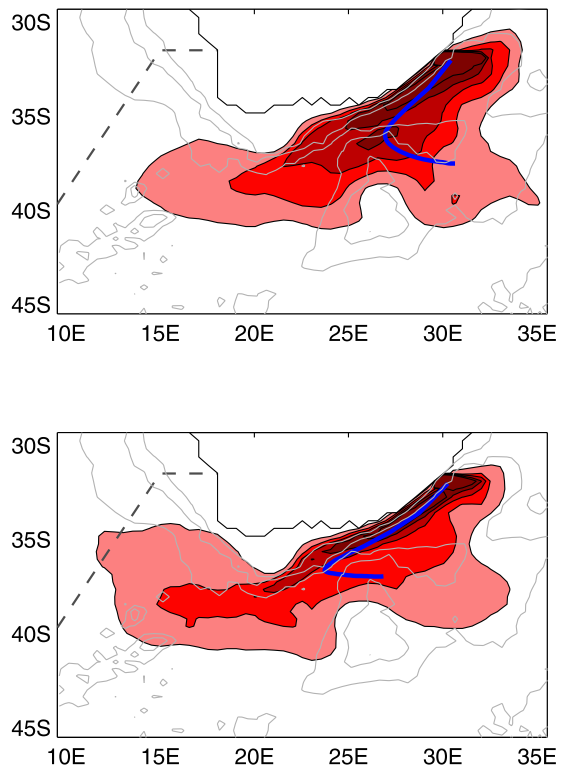

Figure 2. The density of drifter transport (red, 1 Sv contour interval) in the first six months after release for all drifters released in (top) 1986–1987 (a mean Agulhas Current transport of 65.4 Sv) and (bottom) 1988–1989 (a mean Agulhas Current transport of 61.0 Sv). The blue lines are the transport-weighted mean trajectories. The bathymetry is shown in gray (1500 m contour interval). The dashed line is the location of the GoodHope line over which the Agulhas leakage is calculated. For lower Agulhas Current transports (1988–1989), the current detaches from the continental slope farther downstream. The retroflection is consequently moved westward and Agulhas leakage is increased.

with the results of *Ou and de Ruijter* [1986], to a more southward-oriented inertial overshoot (Figure 2). This change in overshoot direction causes a better matching with the wind-curl forced subtropical Indian Ocean, which is located around 40°S [*de Ruijter and Boudra*, 1985; *Zharkov and Nof*, 2008]. The increased matching leads to a smaller Agulhas leakage. Although the three individual correlations are not very strong, the combination of reduced outcropping and inertia for a weaker Agulhas Current may explain the anti-correlation found between T_{AL} and T_{AC}.

5. Conclusions and Discussion

[16] Using the transports determined from Lagrangian numerical drifters over a 34 year period, we have shown in a high-resolution model study that there is an anti-correlation between the strength of the Agulhas Current at 32°S and the Agulhas leakage into the Atlantic Ocean. A decrease in Agulhas leakage is compensated by an increase in the Agulhas Return Current transport. The inertial outcropping mechanism proposed by *Ou and de Ruijter* [1986] is consistent with these findings. A weaker Agulhas Current experiences less outcropping and generates less anti-cyclonic vorticity, thereby moving the location of the retroflection southwestward. The larger southward overshoot results in a better matching to the latitude of zero wind stress curl [*Dijkstra and de Ruijter*, 2001]. This causes the Agulhas leakage to increase.

[17] Inertial outcropping is only one of the mechanisms that can affect the location of the Agulhas retroflection. Another one is offshore migration of the Agulhas Current due to Natal pulses, which are solitary cyclonic meanders on the inshore edge of the current [*Lutjeharms and Roberts*, 1988]. As Natal pulses may be accompanied by an anti-cyclone on the seaward side of the current, local transport can be increased. However, although Natal pulses trigger early retroflections on intra-annual time scales in the model [*Biastoch et al.*, 2008a], there is no correlation between Natal pulses and T_{AC} or T_{AL} in the model on the biennial time scale.

[18] The range of biennial variation of Agulhas Current transports used here is almost 6 Sv. Although this range is large enough to draw conclusions on present-day climate sensitivity, it is unsure how robust these sensitivities are to larger changes in T_{AC}. The determined sensitivity implies

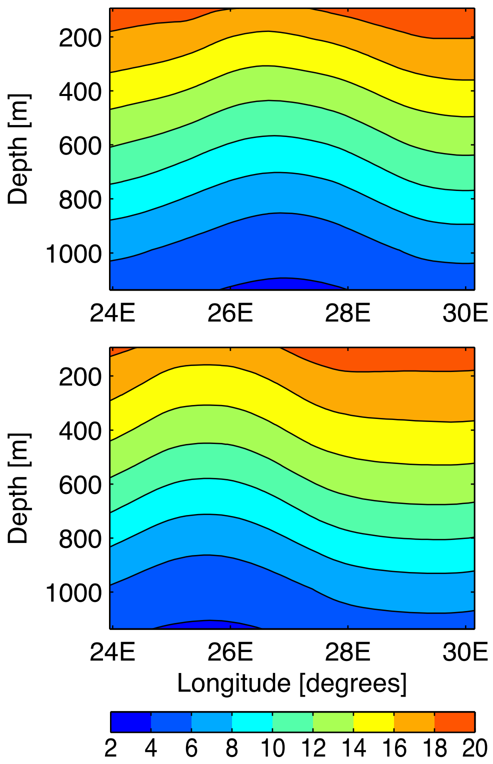

Figure 3. Modeled near-coastal temperature distribution as a function of longitude and subthermocline depth in °C for (top) 1986–1987 (a mean Agulhas Current transport of 65.4 Sv) and (bottom) 1988–1989 (a mean Agulhas Current transport of 61.0 Sv). For lower Agulhas Current transports the outcropping, the upward shift of isotherms, occurs more downstream. The strength of the outcropping is masked due to the biennial averaging. True outcropping, where the 12°C isotherm is lifted to depths of 150 m, appears in individual model snapshots.

that at $T_{AC} \approx 37$ Sv Agulhas leakage equals Agulhas Current transport and $T_{ARC} = 0$. At $T_{AC} \approx 87$ Sv Agulhas leakage would become negative. Clearly, the derived sensitivity is only valid within an (unknown) range of Agulhas Current transport in which the present day system resides.

[19] However, the sign of the sensitivity between Agulhas leakage and Agulhas Current transport is robust, also in view of the dynamics. The negative correlation might play a role in the Agulhas leakage on glacial time scales. The latitude of zero wind stress curl plays an important role in the magnitude of Agulhas leakage. This is also found by *Zharkov and Nof* [2008], who calculated that the slant of the African continent can choke the formation of Agulhas rings when the latitude of zero wind stress curl is too northward.

[20] Measuring the Agulhas leakage in-situ in the south-eastern Atlantic Ocean is complicated, due to the turbulent nature of the "Cape Cauldron" [*Boebel et al.*, 2003] and the vicinity of the varying Antarctic Circumpolar Current. In order to better assess the inter-ocean exchange, the measurements of the GoodHope section [*Swart et al.*, 2008] could be augmented by a monitoring of the (much more confined) Agulhas Current. The Agulhas Current transports could then be converted into Agulhas leakage by utilizing the relation presented here.

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