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Advective timescales and pathways of Agulhas leakage

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[1] Current research indicates an increase in Agulhas leakage for the past and coming decades. This change potentially alters the strength of the Atlantic meridional overturning circulation, in particular, through advection of positive density anomalies into the North Atlantic. To explore the fate of Agulhas leakage, results from a Lagrangian analysis were evaluated, with virtual floats advected within an eddy-permitting ocean model (ORCA025). A considerable fraction of Agulhas leakage reached the subtropical North Atlantic: of a mean Agulhas leakage transport of 15.3 Sv entering the South Atlantic, 9.7, 7.7, and 6.1 Sv crossed sections at 6°S, 6°N, and 26°N, respectively. The most probable transit time of leakage to reach the respective latitudes is one to two decades. We suggest that changes in Agulhas leakage could manifest in the Gulf Stream regime most probably within two decades. These results were supported by an eddy-resolving implementation of the ocean model (INALT01). **Citation:** Rühs, S., J. V. Durgadoo, E. Behrens, and A. Biastoch (2013), Advective timescales and pathways of Agulhas leakage, *Geophys. Res. Lett.*, *40*, 3997–4000, doi:10.1002/grl.50782.

1. Introduction

[2] South of Africa warm and salty Indian Ocean water enters the Atlantic through "Agulhas leakage" [*De Ruijter et al.*, 1999]. This process is key for the global circulation since it feeds the upper limb of the Atlantic meridional overturning circulation (AMOC) [*Beal et al.*, 2011]. Dominated by mesoscale variations, such as the formation and shedding of Agulhas rings, the flow from the Indian Ocean to the Atlantic is subject to high temporal variability [*De Ruijter et al.*, 1999; *Biastoch et al.*, 2008b]. Changes in the Agulhas region have the potential to influence the strength of the AMOC through different processes on various timescales [*Weijer et al.*, 2002; *Van Sebille and van Leeuwen*, 2007; *Biastoch et al.*, 2008a; *Van Sebille et al.*, 2011]. Of particular interest in the climate change discussion is the input of salt through Agulhas leakage and its northward advection [*Gordon et al.*, 1992]; an additional supply could alter the density structure of the Atlantic [*Biastoch and Böning*, 2013] and lead to a strengthening of the AMOC [*Weijer et al.*, 2002]. Model hindcasts simulated an increase of leakage in the past decades [*Biastoch et al.*, 2009a; *Rouault et al.*, 2009]. As yet, no conclusive observational confirmation is available [*Backeberg et al.*, 2012].

[3] The indicated changes south of Africa lead to particular questions on the fate of Agulhas leakage in the Atlantic: How much of Agulhas leakage is entering the northern hemisphere? What are the associated advective timescales from the Agulhas region towards the North Atlantic? And what are the predominant pathways?

[4] Due to the lack of sufficient observations, models have to be used to investigate the fate of Agulhas leakage. Here, we used results of two ocean general circulation models in a Lagrangian framework to show that approximately half of Agulhas leakage reaches the subtropical North Atlantic most probably on decadal timescales.

2. Model Data and Methods

[5] Data used in this study stem from 5 day mean model outputs of two configurations of the NEMO ocean/sea-ice model (v3.1.1) [*Madec*, 2008] implemented on a global tripolar grid and with 46 z levels. ORCA025, eddy-permitting at nominal 1/4° resolution [*The DRAKKAR Group*, 2007], was forced with atmospheric fields from CORE-IAF.v2 [*Large and Yeager*, 2009] over the period 1965–2007. Even though ORCA025 already simulates Agulhas rings [*Barnier et al.*, 2006], a complete representation of mesoscale Agulhas dynamics necessitates upstream variability representation that requires higher resolution [*Biastoch et al.*, 2008b]. Therefore, to address the reliability of ORCA025, 30 years of the eddy-resolving configuration, INALT01, under repeated year forcing were employed. INALT01 is a 1/10° high-resolution model of the Agulhas region and South Atlantic (70°W–70°E, 50°S–8°N), nested within a half-degree global ocean model [*Durgadoo et al.*, 2013].

[6] To follow the fate of Agulhas leakage, a Lagrangian analysis using the ARIANE software [*Blanke et al.*, 1999] was applied to the five daily model data, similar to *Speich et al.* [2001] and *Biastoch et al.* [2008b, 2009b]. The analysis consists of releasing virtual particles (floats) and advecting them using the models' 3-D time-varying velocity fields. For INALT01, the application was restricted to the high-resolution domain. During the first 10 model years, floats were seeded over the full depth range at a five daily interval within the Agulhas Current at 32°S (Figure 1). Each float represented a partial transport of ≤1 Sv (1 Sv = 10^6 m^3 s^{-1}). Trajectories were calculated cycling two and three times, respectively, through the ORCA025 and INALT01 simulation periods to allow 3-D pathways with maximum transit times of 86 years (Note that most probable transit times fall well within the first cycle). Following *Biastoch et al.* [2008b], Agulhas leakage was defined by the sum of floats exiting west of the retroflection towards the South Atlantic (red section in Figure 1) within the first 4 years after their release. Using this definition for

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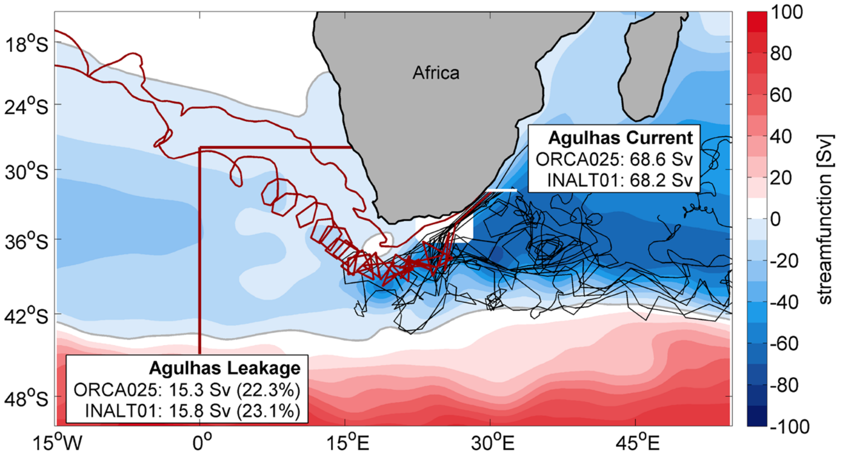

Figure 1. Lagrangian Analysis. The white line at 32°S marks the section of the Agulhas Current where virtual floats were released; floats were defined as Agulhas leakage after crossing the red sections. Values are provided as 10 *y* mean and as a fractional Agulhas Current transport. Example trajectories of leakage (red) and "no leakage" (black) floats are shown. Background colors show a smoothed horizontal stream function from INALT01.

Agulhas leakage, we obtained ~40,000 (~90,000) floats accounting for 15.3 Sv (15.8 Sv) or 22.3% (23.1%) of the Agulhas Current transport within ORCA025 (INALT01). These transport values agree well with observations [*Richardson*, 2007]. In the following, only leakage floats were considered.

[7] Leakage floats were tracked towards sections at 6°S, 6°N, and 26°N in the Atlantic. Transit time distributions were used to infer the most probable propagation time to the chosen sections. To visualize pathways of Agulhas leakage, a method to compute the total number of float counts per predefined grid cells at 1° horizontal resolution was used following *Gary et al.* [2011]. The resulting value for each grid cell depends on the number of passing floats and on their residence time within the cell (including possible reoccurrences).

3. Results

3.1. Advective Timescales

[8] The first arrival transit time of each float at a given latitude was calculated with a temporal resolution of 5 days. The resulting cumulative distributions of relative occurrence show that in both models, more than half of the floats reaching 6°S, 6°N, and 26°N needed less than 10, 14, and 24 years, respectively (Figure 2). The most probable transit times belong to the steepest slopes of the cumulative distributions and were estimated from the modes of histograms of relative occurrences. In ORCA025, the most probable transit times are 6–7, 8–9, and 12–13 years for 6°S, 6°N, and 26°N, respectively (Figure 2). It is noteworthy that the majority (~60%) of the floats that reached 26°N needed less than 4 years to pass the equatorial region between 6°S and 6°N (not shown). Floats that did not reach 26°N stayed twice as long in the equatorial regime compared to floats that reached 26°N. INALT01 confirmed the results of ORCA025 but showed a slight preference to shorter transit times (Figure 2). At 6°N, the most probable transit time of INALT01 is ~2 years faster.

3.2. Pathways and Volume Transport

[9] The occurrence of a distinct mode for every transit time distribution (Figure 2) points to the existence of dominant pathways for the spreading of Agulhas leakage into the North Atlantic. The broadening distribution with increasing latitude, however, also indicates an increasing number of possible deviations from the main track.

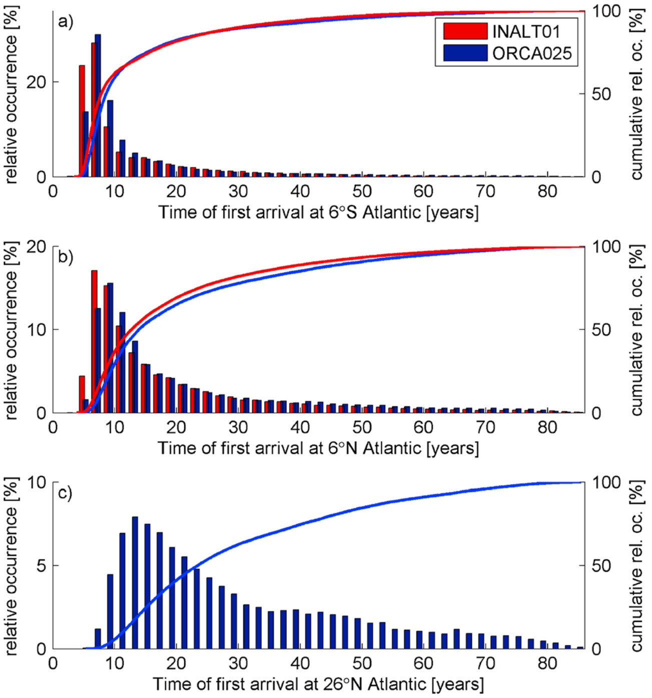

Figure 2. Transit time distributions of leakage floats. Individual transit times were computed as the time needed by a float to first reach (a) 6°S, (b) 6°N, and (c) 26°N, respectively. Line graphs represent the resulting cumulative distributions referring to the total number of leakage floats that reached the respective latitude within the simulation period. Histograms of relative occurrence are added to visualize the most probable transit times represented by the modes (note that the bin width was set to 2 years to get smooth distributions even for 26°N).

[10] From the evaluation of the fate of Agulhas leakage in ORCA025 (Figure 3), of its depth expression (Figure S2 of the supporting information), and of the partitioning into

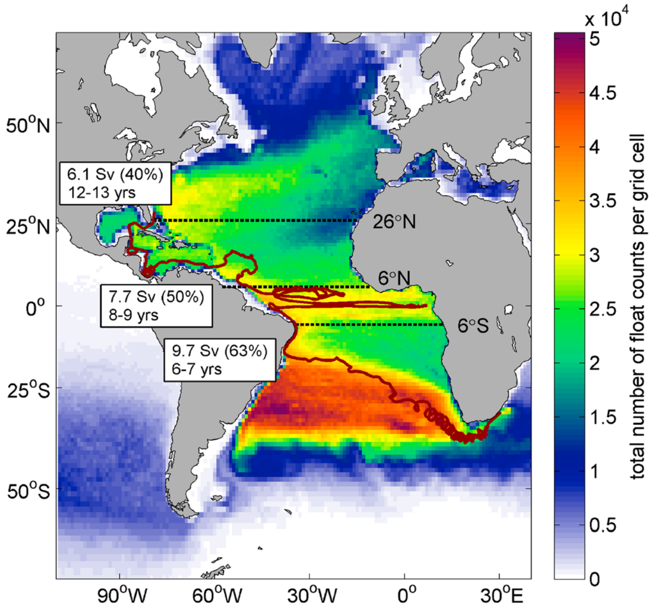

Figure 3. Spreading of Agulhas leakage in ORCA025 based on the Lagrangian analysis of ~40,000 virtual floats, representing a mean leakage transport of 15.3 Sv. Background colors show the total number of float counts per 1° × 1° grid cell. Numbers give mean volume transport of Agulhas leakage through marked sections, its fraction of the leakage transport, and the most probable (modal) transit times. An exemplary float trajectory with the most probable transit time is shown. A global version is provided as Figure S1.

subsets of floats reaching and not reaching 26°N in the Atlantic within the simulation period (Figure 4), the following can be deduced. After having entered the South Atlantic, the majority of leakage floats followed the upper branch of the AMOC through the Benguela Current and the South Equatorial Current (SEC) into the tropical South Atlantic. A subset recirculated in the South Atlantic subtropical gyre, primarily those floats not reaching 26°N within the simulation period (Figure 4b). More than half of the leakage floats continued into the equatorial Atlantic, mainly via the North Brazil Current (NBC) (Figures S5 and S6 demonstrate a good comparison with observations [e.g., *Schott et al.*, 2005]). At 6°S, they accounted for a mean volume transport of 9.7 Sv (63% of the total leakage transport), which is comparable to the 69% reported by *Donners and Drijfhout* [2004]. With that amount, Agulhas leakage is representative of ~55% of the AMOC strength (17.5 Sv) at 6°S. In the tropics, trajectories were likely to be influenced and "trapped" by the zonal circulation; 7.7 Sv (50%) exited the equatorial regime at 6°N. With dominant pathways through the Caribbean Sea and the Straits of Florida, the majority (6.1 Sv or 40%, Figure 3) arrived, still concentrated in the upper ocean, at 26°N. After having passed 26°N for the first time, floats were likely to recirculate in the North Atlantic subtropical gyre such that comparable numbers of float counts were found on either side of the Antilles (Figure 3). INALT01 gave slightly higher transport numbers than ORCA025, 10.2 Sv (65%) for 6°S and 8.6 Sv (55%) for 6°N. Pathways further north could not be estimated due to the termination of the high-resolution nest.

4. Summary and Discussion

[11] Results of Lagrangian analyses within an eddy-permitting and an eddy-resolving ocean model showed that about half of the volume transport entering the South Atlantic through the process of Agulhas leakage is advected into the subtropical North Atlantic within the 86 year simulation period. En route on a relatively direct way through the Benguela Current, the SEC, and the NBC, most of leakage waters reach the tropics within one decade. Eventual, zonal detours into the equatorial current regime and other interior pathways do not alter the modal structure of the transit time distributions but instead, delay the flow towards the North Atlantic into the second decade and reduce the amount of arriving Agulhas leakage within the simulation period. About 40% of the original Agulhas leakage (though with different temperature/salinity characteristics) arrives in the Gulf Stream regime, most likely via the Florida Straits after 12–13 years; more than half of the water arrives after 23.5 years.

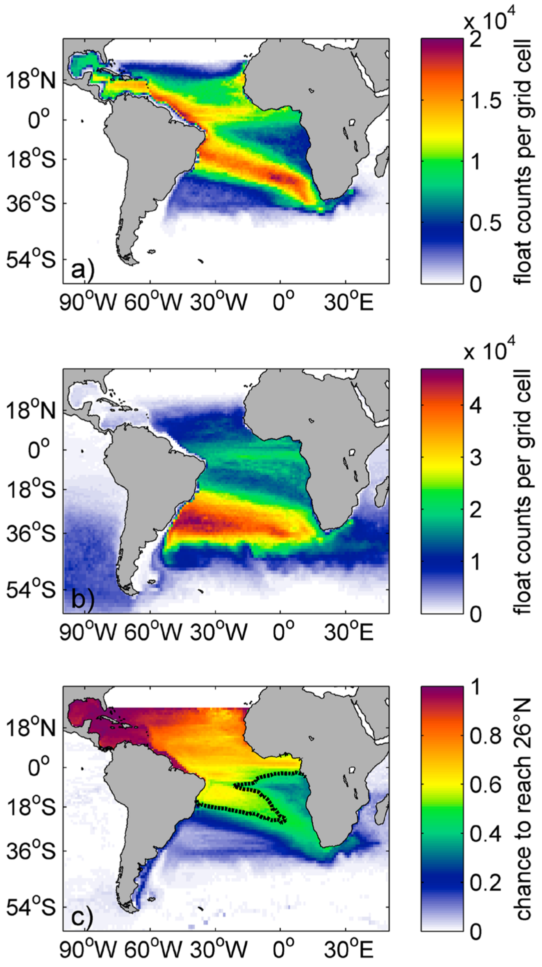

Figure 4. Spreading of leakage floats that (a) reach and (b) do not reach 26°N in the Atlantic. For a better visualization of the pathways into the North Atlantic (and in contrast to Figure 3), trajectories in Figure 4a are cropped after their first arrival at 26°N. (c) Local chances for floats passing a certain grid cell to reach 26°N (number of floats that later reach 26° N, divided by total number of floats). The dashed line represents the 50% chance.

[12] Our results confirm and refine the estimate of *Weijer et al.* [2002] who also showed a decadal spreading based on an Eulerian calculation in a coarse resolution model with strongly idealized Agulhas Leakage. In comparison with *Van Sebille et al.* [2011], our timescales appear longer, but a detailed comparison is difficult due to different methodologies and foci of the analysis. However, repeating our calculation without accounting for recirculations (not shown here), we found similar pathways in the subtropical and tropical Atlantic to those reported by *Van Sebille et al.* [2011]. The comparison between ORCA025 and INALT01 suggests that the horizontal model resolution plays a minor role for assessing the advective pathways. However, timescales are faster if mesoscale eddies are represented; background flow in the subtropical South Atlantic within INALT01 is generally stronger than ORCA025 by a few cm s^{-1} (not shown). This would explain the slightly faster timescales. Nevertheless, the precise pathway through the tropics depends on the detailed representation of the western portion of the equatorial current regime [*Kirchner et al.*, 2009].

[13] Considering that the mean calculated volume transport of Agulhas leakage of 6.1 Sv through 26°N is mainly restricted to the western boundary, we conclude that Agulhas Leakage accounts for about 20% of the Florida Strait transport (30.8 Sv in ORCA025, 32.2 Sv in the observed long-term mean [*Baringer and Larsen*, 2001]) which is the major contributor to the upper limb of the AMOC at this latitude. This amount can be considered as the coherent and direct part of the warm water route into the North Atlantic circulation.

[14] Model-based studies show strong trends in Agulhas leakage during the past four decades with a 25% increase in Agulhas leakage volume transport [*Biastoch et al.*, 2009a; *Rouault et al.*, 2009]. Under global warming conditions, Agulhas leakage is likely to further increase [*Biastoch and Böning*, 2013]. Assuming that the general fate of Agulhas leakage is mainly unaffected by these changes and follows the pathways and timescales presented here, our results suggest that the positive trend in leakage could invoke a corresponding increase of leakage waters in the western boundary current regime of the subtropical North Atlantic. Of particular importance will be the changes of the thermohaline properties along the pathway of (increased) leakage, not only into the deepwater formation areas of the North Atlantic but also through the equatorial Atlantic. A coupled model has shown that Agulhas leakage changes have been associated with substantial changes in tropical precipitation [*Haarsma et al.*, 2009].

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