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**Key Points:**
- A quantitative index for the Agulhas leakage has been developed
- Paleo-Agulhas leakage over the past 640,000 years has been quantified
- We provide reference points for further analyses and interpretations

**Supporting Information:**
- Readme
- Figure S1
- Figure S2
- Figure S3
- Figure S4
- Table S1

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# Quantitative estimate of the paleo-Agulhas leakage

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**Abstract** The Indian-Atlantic water exchange south of Africa (Agulhas leakage) is a key component of the global ocean circulation. No quantitative estimation of the paleo-Agulhas leakage exists. We quantify the variability in interocean exchange over the past 640,000 years, using planktic foraminiferal assemblage data from two marine sediment records to define an Agulhas leakage efficiency index. We confirm the validity of our new approach with a numerical ocean model that realistically simulates the modern Agulhas leakage changes. Our results suggest that, during the past several glacial-interglacial cycles, the Agulhas leakage varied by ~10 sverdrup and more during major climatic transitions. This lends strong credence to the hypothesis that modifications in the leakage played a key role in changing the overturning circulation to full strength mode. Our results are instrumental for validating and quantifying the contribution of the Indian-Atlantic water leakage to the global climate changes.

## 1. Introduction

Within the greater Agulhas Current system south of Africa, waters are exchanged between the Indian and South Atlantic Oceans. This process is known as the Agulhas leakage [*Gordon*, 1986; *De Ruijter et al.*, 1999; *Gordon*, 2003; *Lutjeharms*, 2006]. Estimates of the present-day magnitude of Agulhas leakage are not properly constrained, partly because of the logistical difficulty in accounting for the numerous features comprising leakage [*Beal et al.*, 2011]. The modern leakage is estimated around 15 sverdrup (Sv) ($1\ \mathrm{Sv} = 1 \times 10^6\ \mathrm{m^3 s^{-1}}$) [*Richardson*, 2007], compared to a mean transport of 70 Sv [*Bryden et al.*, 2005] for the Agulhas Current. It has been demonstrated that this interoceanic exchange is a key component of the global ocean "conveyor" circulation [*Gordon*, 1986; *De Ruijter et al.*, 1999; *Weijer et al.*, 2001, 2002; *Gordon*, 2003; *Knorr and Lohmann*, 2003; *Lutjeharms*, 2006; *Biastoch et al.*, 2008, 2009; *Beal et al.*, 2011]. Modeling studies suggest that (1) this exchange affects the buoyancy of Atlantic thermocline waters, potentially influencing North Atlantic deepwater formation on multidecadal time scale [*Weijer et al.*, 2002; *Knorr and Lohmann*, 2003; *Biastoch et al.*, 2009] and (2) perturbations of planetary waves by mesoscale eddies influence decadal variability of the Atlantic meridional overturning circulation (AMOC) [*Van Sebille and van Leeuwen*, 2007; *Biastoch et al.*, 2008]. It is thought that a larger leakage of warm and saline Agulhas waters leads to a positive density anomaly in the South Atlantic, which could in turn stimulate a stronger and more stable AMOC under future global warming scenarios.

Studies on marine cores also suggest that the efficiency of the Agulhas leakage was subjected to modulation with potential effects on climate changes at millennial, orbital, and glacial-interglacial changes over the Quaternary period [*Rau et al.*, 2002; *Peeters et al.*, 2004; *Bard and Rickaby*, 2009; *Dickson et al.*, 2010; *Martínez-Méndez et al.*, 2010; *Caley et al.*, 2011, 2012; *Marino et al.*, 2013]. It is not yet completely clear which mechanisms cause these modulations of Agulhas leakage. New model simulations suggest that there is a relation with the southern hemisphere westerlies [*Graham et al.*, 2012; *Durgadoo et al.*, 2013] that could additionally be associated and imprinted by the subtropical front across millennial to orbital time scales of the Quaternary [*Rau et al.*, 2002; *Peeters et al.*, 2004; *Bard and Rickaby*, 2009; *Caley et al.*, 2012; *Marino et al.*, 2013].

Fossil planktic foraminiferal assemblage variation [*Peeters et al.*, 2004] and the accumulation rate of *Globorotalia menardii* in marine sediment records [*Caley et al.*, 2012] have been used previously to qualitatively assess the changes in late Pleistocene strength of the Agulhas transfer of mass. A quantitative estimate of the interoceanic transfer on paleo time scales is not available but is important to modeling studies aiming to quantitatively assess the role of this leakage in the oceanic overturning circulation. Hence, quantitative reconstructions may provide reference points for future studies.

Here we propose a quantitative proxy index for the Agulhas leakage, referred to as the Agulhas leakage efficiency (ALE). Contrary to previous foraminiferal indices [*Peeters et al*., 2004; *Caley et al*., 2012] that were sensitive to the potentially changing composition of the source assemblage upstream within the Agulhas Current, the ALE is defined in such a way that it represents the transfer of Agulhas water from the Indian Ocean to the Atlantic independent of the variations in the source assemblage.

## 2. Material and Methods

### 2.1. Planktic Foraminiferal Assemblage From Core MD96-2048

Samples were dried, weighed, and washed through a 150 μm mesh sieve every 5–6 cm downcore. Planktic foraminiferal assemblage was analyzed using an Olympus SZH10 binocular microscope, and identifications were made following the taxonomy of *Hemleben et al*. [1989] and *Kennett and Srinivasan* [1983]. Approximately 350 specimens were counted in each sample after splitting with an Otto microsplitter. Details regarding the analyses of the planktic foraminiferal assemblage of the Cape Basin record were discussed by *Peeters et al*. [2004].

### 2.2. Age Models

The age models of cores MD96-2048 (26°10'S, 34°01'E, 660 m) and the Cape Basin record (35°08'/35°35', 17°33'/17°41', and 2840/3164 m) are taken from *Caley et al*. [2011]. They are based on the correlation between the $\delta^{18}$O of the benthic foraminifer *Planulina wuellerstorfi* and the LR04 stack [*Lisiecki and Raymo*, 2005]. The age models of cores MD96-2077 and ODP1087, as taken from *Bard and Rickaby* [2009] and *Caley et al*. [2012], respectively, have also been correlated to the LR04 age model [*Lisiecki and Raymo*, 2005].

### 2.3. Agulhas Leakage Efficiency: The ALE Index Calculation

Previous studies [*Bé and Tolderlund*, 1971; *Bé and Hutson*, 1977] and our new data from core MD96-2048 have shown that the Agulhas Current is characterized by a high dominance of tropical species. Subtropical, transitional, subpolar, and polar species are also present. Here we select the species characteristic of the tropical Indian Ocean, based on biogeographic maps [*Bé and Tolderlund*, 1971; *Bé and Hutson*, 1977]. The species selected here are slightly distinct from the species grouping of *Peeters et al*. [2004] (the Agulhas leakage fauna (ALF)). A stricter selection procedure is applied, with species including *Globigerinoides ruber*, *Globorotalia menardii*, *Globigerinoides sacculifer*, *Pulleniatina obliquiloculata*, *Globoquadrina hexagona*, and *Globigerinella aequilateralis*, hence defined in this paper as the Indian Ocean Tropical Group (IOTG). The species *Globorotalia inflata*, *Globorotalia truncatulinoides*, *Neogloboquadrina pachyderma dextral*, and *Globigerina bulloides* represent the colder transitional, subpolar water masses, here referred to as the Southern Ocean Group (SOG). Species that do not reflect either of these two specific oceanic regions or species found in very low abundances (<0.5%) in the sedimentary records selected here (e.g., *Globigerinita glutinata*, *Hastigerina pelagica*, *Orbulina universa*, and *Globorotalia scitula*) were excluded.

With these two groups or subsets of species, we formed the Indian Ocean tropical group index, which is considered to most strictly represent the Indian Ocean Agulhas water mass:

$$\text{IOTG}/(\text{IOTG} + \text{SOG}) = \text{Indian Ocean Tropical Group}/(\text{Indian Ocean Tropical Group} + \text{Southern Ocean Group})$$

By normalizing the characteristic Indian Ocean fauna found within the Indian Ocean tropical waters, we express the expatriated Indian Ocean tropical fossil group in the southeast Atlantic as a fraction of the upstream tropical Indian Ocean fauna found in the Agulhas Current.

Prior to the upstream normalization procedure, the planktic foraminiferal assemblages of each record (core MD96-2048 and the Cape Basin record) were linearly resampled. Resampling was done at 3500 year resolution, which corresponds to the lower mean resolution of the two data sets (i.e., the resolution of core MD96-2048).

The Agulhas leakage efficiency is defined as the ratio between the Indian Ocean tropical group index in the downstream and upstream regions of the Agulhas Current:

$$\text{ALE}\ (\%) = \left(\left(\text{IOTG}/(\text{IOTG}+\text{SOG})_{\text{downstream}}\right)/\left(\text{IOTG}/(\text{IOTG}+\text{SOG})_{\text{upstream}}\right)\right) \times 100$$

Error propagation calculation on foraminiferal counts follows the formula of *Press et al.* [1990]:

$$\sigma^2{}_Y = \sum_{i=1}^{n} (\partial f/\partial Xi)^2 \sigma^2{}_{Xi} \quad \text{if} \quad Y = f(X_1, X_2 \ldots X_n)$$

where $\sigma_Y$ represents the standard deviation of the function *Y*, $\partial f/\partial Xi$ denotes the partial derivative of the function with respect to the *Xi* variable, and $\sigma_{xi}$ represents the standard deviation of the *Xi* variable.

$$\sigma_{\text{ALE}} = \sqrt{\left(\left(\left(\text{IOTG}/(\text{IOTG}+\text{SOG})_{\text{upstream}}\right)^{-1}\right)^2 \times \left(\sigma_{\text{IOTG}/(\text{IOTG}+\text{SOG})_{\text{downstream}}}\right)^2 + \left(-\left(\text{IOTG}/(\text{IOTG}+\text{SOG})_{\text{dowstream}}\right)/\left(\text{IOTG}/(\text{IOTG}+\text{SOG})_{\text{upstream}}\right)^2\right)^2 \times \left(\sigma_{\text{IOTG}/(\text{IOTG}+\text{SOG})_{\text{upstream}}}\right)^2\right)} \times 100$$

With an error associated with the 95% confidence interval equal to

$$\sigma_{\text{IOTG}/(\text{IOTG}+\text{SOG})_{\text{downstream}}} = \left(\sqrt{((((\text{IOTG}/(\text{IOTG}+\text{SOG})_{\text{downstream}})/100) \times (1-((\text{IOTG}/(\text{IOTG}+\text{SOG})_{\text{downstream}})/100)))/\text{Total Planktonic Counts})} \times 100\right) \times 1.96$$

$$\sigma_{\text{IOTG}/(\text{IOTG}+\text{SOG})_{\text{upstream}}} = \left(\sqrt{\left(\left(\left(\left(\text{IOTG}/(\text{IOTG}+\text{SOG})_{\text{upstream}}\right)/100\right) \times \left(1-\left(\left(\text{IOTG}/(\text{IOTG}+\text{SOG})_{\text{upstream}}\right)/100\right)\right)\right)/\text{Total Planktonic Counts}\right)} \times 100\right) \times 1.96$$

### 2.4. Modern Distribution of Foraminifera

The modern distribution of planktic foraminifera in the Indian and South Atlantic Oceans was interpolated from the Multiproxy Approach for the Reconstruction of the Glacial Ocean Surface database, which contains a compilation of core top data [*Barrows and Juggins*, 2005; *Kucera et al.*, 2005] (Figure 1). The data were visualized using the ArcGIS Information System software.

### 2.5. Model and Simulations

INALT01 [*Durgadoo et al.*, 2013] is based on NEMO [*Madec*, 2008] and consists of global 1/2° ocean/sea ice model and a 1/10° nest covering the whole South Atlantic and western Indian Ocean up to the tropics (70°W–70°E, 50°S–8°N). Driven by interannually varying atmospheric forcing data for the period 1948–2007 [*Large and Yeager*, 2009], the model realistically simulates the Agulhas dynamics and leakage of the past decades [*Durgadoo et al.*, 2013].

Employing an off-line Lagrangian software (Ariane) [*Blanke et al.*, 1999], virtual particles were advected backward using the three-dimensional five daily velocity fields of INALT01. For each model year, 50 particles were continuously released every 10 days within each of the 10 × 10 km grid boxes of INALT01's nested domain. The particles were vertically distributed over the upper 100 m, representing a mean depth habitat of the foraminifera [*Hemleben et al.*, 1989]. Approximately $4.6 \times 10^6$ particles were released per model year. For each backwardly integrated particle, only 30 days were considered, representing the typical life span of an individual foraminifera [*Hemleben et al.*, 1989]. In contrast to the visual inspection of species, virtual particles required sorting into IOTG and SOG. This was undertaken based on the modeled temperatures at each particle's location. Owing to the nonunique temperature range, particles were sorted using a probability function that represented a statistical fit through the observations (Figure S1 in the supporting information). IOTG and SOG were mapped on the regular seeding grid, representing the 30 day life span at the particles' sampling locations. This procedure was repeated for each of the 60 years of model fields, and the ratio of IOTG/(IOTG + SOG) was calculated as annual averages (Figure 1b represents a long-term mean).

## 3. The Agulhas Leakage Efficiency as a Quantitative Index for the Leakage

Core MD96-2048 is located directly underneath the Agulhas Current and hence provides information on the faunal changes in the Agulhas source water region [*Caley et al.*, 2011] (Figures 1 and 2a). We compare the new faunal analysis of this core with the faunal analysis from sediment cores in the Cape Basin (Figures 1 and 2b). The Cape Basin record, composed of cores GeoB-3603-2 and MD96-2081, is located at the entrance of the leakage waters into the Atlantic Ocean [*Peeters et al.*, 2004] (Figure 1). Carbonate dissolution increases rapidly below the lysocline. The shallow depth of core MD96-2048 (660 m) is therefore prone to a good preservation of planktic foraminifera. Based on a fragmentation index, planktic foraminifera in the Cape Basin record have been found to be virtually unaffected by carbonate dissolution [*Peeters et al.*, 2004].

  

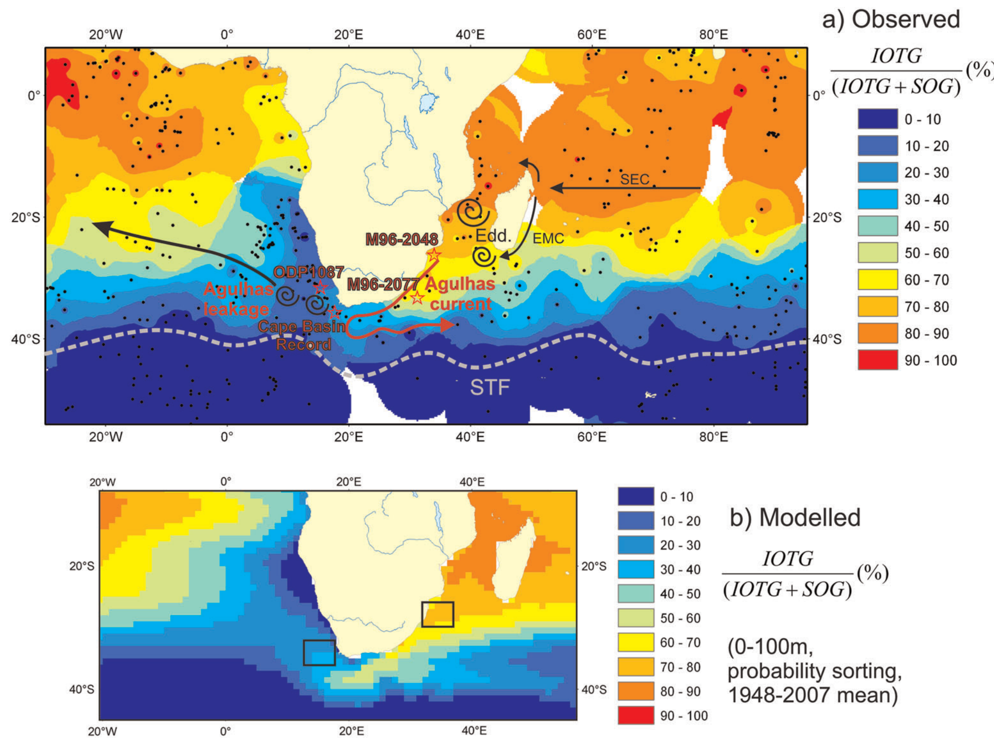


**Figure 1.** Indian Ocean tropical group index (groups of foraminifera species) reflecting the tropical Indian Ocean waters and hence the Agulhas current waters. (a) Current distribution of foraminiferal species (ratio IOTG/(IOTG + SOG) in percent) in core top sediments of the Indian and South Atlantic regions [*Barrows and Juggins*, 2005; *Kucera et al.*, 2005]. The location of core MD96-2048 and the Cape Basin record used in this study and schematic views of the Agulhas current system are indicated. The gray dashed line indicates the position of the subtropical front . Locations of sediment cores MD96-2077 [*Bard and Rickaby*, 2009] and ODP 1087 [*Caley et al.*, 2012] are also indicated. EMC refers to the East Madagascar Current, SEC to the South Equatorial Current, and Edd. to eddies. (b) Modeled ratio IOTG/(IOTG + SOG) (in percent), given as a time-mean over the 60 years of model integration.

The two faunal records on either side off south Africa (Figure 1) express changes in the downstream region relative to the upstream variations (Figures 1, 2a, and 2b). This allows us to derive the proportion of tropical fauna transported (ALE) from the Indian Ocean into the South Atlantic. Given that upstream compositional changes of the source assemblage may vary as a function of regional ocean/climate changes, a normalization procedure is used. This procedure allows us to minimize the regional climate effect and corrects the Agulhas leakage for the upstream variation in the source region fauna.

To test the validity of our leakage index, the ALE was simulated within the high-resolution ocean model (INALT01) [*Durgadoo et al.*, 2013] of the greater Agulhas system under modern climate conditions as previously explained. The resulting ALE time series (Figure 2c) is highly correlated at the interannual time scale ($R = 0.8$) with the independently calculated Agulhas leakage, which is directly computed as the volumetric amount of Agulhas Current waters ending up in the Atlantic Ocean. It also shows an upward trend over the full 60 year period [*Durgadoo et al.*, 2013].

We apply the ALE index to marine sedimentary paleorecords in order to derive the quantitative Agulhas leakage over the past 640 kyr with its associated uncertainties (Figure 2d and Figures S2 and S3 of the supporting information). In the following, we assume that the present-day regression between the ALE and the modeled leakage (Figure 2c) can be applied at paleotime scales. Currently, this is the only way to proceed since coarse-resolution models, typically used for paleostudies, strongly overestimate Agulhas leakage [*Durgadoo et al.*, 2013; *Weijer et al.*, 2012] and cannot deliver such a relationship. Furthermore, several lines of reasoning suggest that our assumption is reliable. Our calibration with the model relies on the relationship between two normalized end members (rather than an absolute value), downstream region relative to the upstream variations, and the leakage. During past periods, the tropical faunal component arriving at the Cape Basin record location cannot come from the South Atlantic subtropical gyre as those waters have to pass

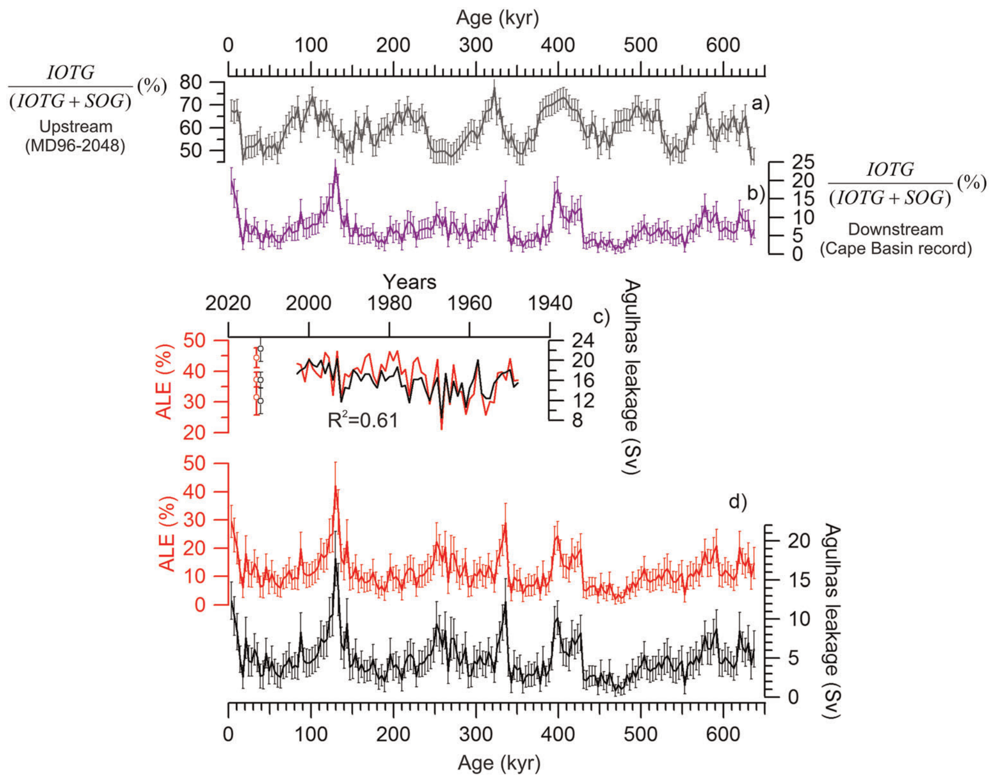


**Figure 2.** Present and past Agulhas leakage efficiency and quantitative estimate of Agulhas leakage (Sv). (a) Groups of foraminifera (IOTG/IOTG + SOG) forming the Indian Ocean tropical group index for the upstream record (MD96-2048) with associated uncertainties. (b) Groups of foraminifera (IOTG/IOTG + SOG) forming the Indian Ocean tropical group index for the downstream record (Cape Basin record) [*Peeters et al*., 2004] with associated uncertainties. (c) Modeled temporal variation of ALE (calculated from the difference of box averages in Figure 1b) and Agulhas leakage (in Sv) in INALT01 [*Durgadoo et al*., 2013]. The black and red dots with vertical bars represent range (mean +/−SD) of 10 years of sensitivity experiments [*Durgadoo et al*., 2013]. (d) Reconstructed variation of ALE over the last 640 kyr from marine sediment cores (Figures 2a and 2b)) with associated uncertainties (Figure 1 and Figure S2 in the supporting information and method) and corresponding estimate of changes in Agulhas leakage (Sv) based on model regression in Figure 2c).

along the sub-Antarctic zone and are not very likely to carry tropical faunas (Figure 1). In addition, southern Ocean fauna at the upstream location (Figure 2a) and at the Cape Basin record [*Peeters et al*., 2004] increase significantly in proportion during glacial periods. Our normalization procedure therefore prevents a potential dilution by such southern Ocean fauna of the ALE signal at the Cape Basin and hampers a potential bias linked to recirculation of tropical fauna in the Agulhas system. These arguments suggest that a change in ALE independently from leakage is not likely to occur. Furthermore, the ALE was simulated in sensitivity experiments under different atmospheric conditions [*Durgadoo et al*., 2013] (Figure 2c). The cases with 40% decreased or increased strength of the westerlies represent different levels of the Agulhas leakage. Although applied in an idealized sense, these give a fair range of variations as can be expected for westerly changes. In these experiments, the ALE was able to satisfyingly represent Agulhas leakage (Figure 2c).

## 4. Quantitative Agulhas Paleoleakage Over the Last 640,000 Years

### 4.1. Long-Term Changes Over the Late Quaternary

Our results indicate an increase in leakage during glacial-interglacial transitions, as was previously found in the qualitative ALF index [*Peeters et al*., 2004] and accumulation rate of *G. menardii* tracer [*Caley et al*., 2012] (Figure 3). The quantitative leakage index shows that, in general, the structure of previously identified events, e.g., the late glacial onset of increased leakage and maxima during terminations is conserved in the ALE reconstruction.

We performed a statistical test (*t* test) between the mean ALF and ALE records for each glacial/interglacial periods over the last 640 kyr (Table S1 in the supporting information). Differences can be observed for marine

  

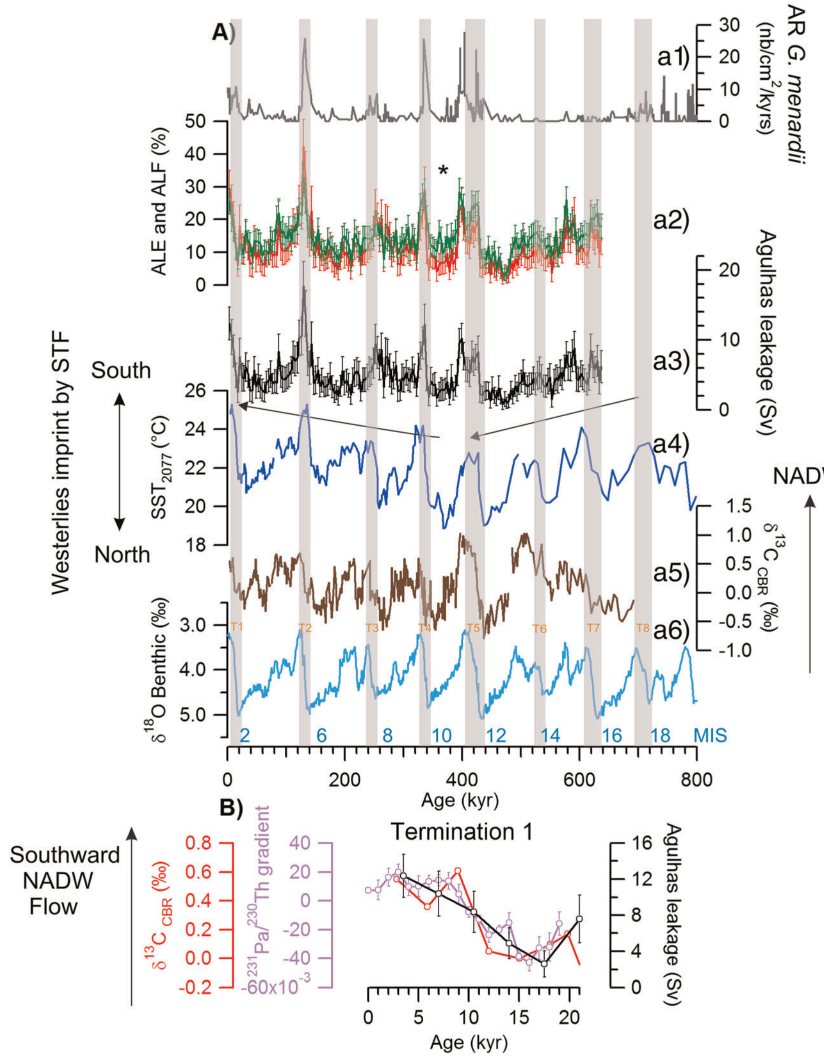


**Figure 3.** Role of Agulhas leakage variability on ocean overturning circulation. (a) Long-term changes over the late Quaternary. (a1) Qualitative index for the Agulhas leakage (accumulation rate of *G. menardii*) [*Caley et al.*, 2012]. (a2) Agulhas leakage fauna [*Peeters et al.*, 2004] and Agulhas leakage efficiency indices with associated uncertainties. The star indicates significant differences between the ALF index and the ALE index during MIS 10. (a3) Changes in Agulhas leakage (Sv) based on model regression. (a4) Position of the subtropical front, documented by sea surface temperature changes at site MD96-2077 [*Bard and Rickaby*, 2009]. (a5) Benthic $\delta^{13}C$ at the Cape Basin record (composed of core GeoB-3603-2 (2840 m depth) and core MD96-2081 (3164 m depth)) used as a proxy for the interplay between northern and southern component waters (SCW). The two arrows indicate the long-term changes in southern hemisphere westerlies imprinted by the subtropical front according to a 400 kyr periodicity and the corresponding changes in the Agulhas leakage. (a6) The $\delta^{18}O$ of benthic foraminifera (LR04 stack) as a proxy for ice volume changes [*Lisiecki and Raymo*, 2005]. MIS denotes marine isotopic stage during glacial periods. Tx denotes Terminations. Gray frames denote periods of increased Agulhas leakage during Terminations. (b) A focus on termination 1 showing the link between Agulhas leakage and change in the basin-scale deep Atlantic circulation. Radiogenic isotope pair $^{231}Pa$ and $^{230}Th$ gradient between northern and southern Atlantic [*Negre et al.*, 2010] as a quantitative proxy of the abyssal flow rate. During the Holocene, the $^{231}Pa/^{230}Th$ gradient reflect a southward flow of NADW. During the LGM, the situation is different with SCW that leave the southern Ocean to ventilate the deep Atlantic. The lower bathyal benthic $\delta^{13}C$ at the Cape Basin record and changes in Agulhas leakage are also indicated.

isotopic stages (MIS) 1, 8, 10, 11, and 16. Taking into account the error bars to both ALE and ALF indices, MIS 10 is the only period for which significant differences between the two indices can be observed (i.e., the differences exceed the bounds of the cumulative uncertainties) (Figure 3 and Figure S4 in the supporting information). The overall similarity of results obtained between the two different approaches (ALF and ALE index) suggests that faunal variations in marine sediment cores can be used as a robust proxy to characterized past Agulhas leakage.

Importantly, the long-term changes in quantitative leakage could coincide with potential changes of the southern hemisphere westerlies [*Bard and Rickaby*, 2009] (Figure 3). Indeed, an extreme northerly position of the southern hemisphere westerlies or wind intensity changes likely occurred during MIS 10 and 12 and conceivably acted to reduce the Agulhas leakage [*Sijp and England*, 2008; *Kohfeld et al*., 2013; *Sime et al*., 2013] (Figure 3). This could explain the different glacial amplitudes within a consistent range of atmospheric $pCO_2$ [*Bard and Rickaby*, 2009]. However, this potential effect was not immediately apparent from the ALF time series during MIS 10 [*Peeters et al*., 2004] but is now clearly visible in the ALE (Figure 3 and Figure S4 in the supporting information) as a result of the upstream normalization procedure.

The ALE increased on average by 20% across major glacial-interglacial transitions of the last 640 kyr leading to an estimated leakage change of $>$10 Sv (~70% volume transport) (Figures 2 and 3). It is thought that the interoceanic exchange is a key component of the global ocean conveyor circulation [*Gordon et al*., 1986; *De Ruijter et al*., 1999; *Weijer et al*., 2001, 2002; *Gordon*, 2003; *Knorr and Lohmann*, 2003; *Lutjeharms*, 2006; *Biastoch et al*., 2008, 2009; *Beal et al*., 2011], and we show here that the changes in leakage in the past were substantial. This may explain some of the variability in ocean circulation and climate that is documented in a range of paleoarchives. For instance, changes in benthic $\delta^{13}$C gradients between the Atlantic and the Pacific Oceans, used as a proxy for ventilation strength, mirror the changes in the leakage [*Bard and Rickaby*, 2009; *Caley et al*., 2012]. Here we use the $\delta^{13}$C of the Cape Basin record [*Acheson*, 2001] to avoid chronological problems than can emerge from the comparison of sedimentary records in different oceanic basin. Today, the Cape Basin record is located in the southern extension of the North Atlantic Deep Water (NADW, between 2000 and 3500 m), similarly to the records of *Martínez-Méndez et al*. [2008], and document the interplay between northern and southern component waters as the AMOC shifted between glacial and interglacial modes [*Martínez-Méndez et al*., 2008] (Figure 3). Long-term overturning changes and stimulation of the AMOC during terminations [*Knorr and Lohmann*, 2003] are therefore phased with modulation of the leakage in a quantitative sense (Figure 3). However, $\delta^{13}$C records do not unequivocally constrain the rate of meridional overturning [*Huybers et al*., 2007]. The conjunction with other circulation proxy can furnish a more robust link between the AMOC changes and leakage. We present such comparison for Termination 1 in the following part. Future model simulations at sufficient resolution must test and support the effect of large modifications in the Agulhas leakage on climate and ocean circulation.

### 4.2. A Focus on Specific Periods of Interest

Based on our study, the ALE during the late Holocene (i.e., 3500 years) is estimated as ~30 ± 6% (2$\sigma$). Model results for the present day give a mean ALE of 38 ± 12% (2$\sigma$) and a mean transport of ~16 ± 5 Sv (2$\sigma$) (Figure 2). By comparison, modern observations estimate this leakage as around 15 Sv, with strong interannual variations due to the intermittent ring shedding [*Richardson*, 2007]. Both the model and data estimations of transport for the recent period are therefore in good agreement.

The ALE during the Last Glacial Maximum (LGM, approximately 19,000–23,000 years ago) is 12 ± 8.5% suggesting a ~10 Sv reduction of the leakage from today (Figures 2 and 3). There is no clear consensus concerning a reduction or increase of the convective activity in the North Atlantic region during the LGM compared to present, but studies indicate profound changes in the basin-scale circulation of the Atlantic Ocean [*Lynch-Stieglitz et al*., 2007; *Negre et al*., 2010]. Numerical model results suggest, in general, a change (increase or decrease) of ~30% of the AMOC strength during the LGM [*Weber et al*., 2007] leading to a change of ~6 Sv compared to present observational estimates. Given that the reduction/increase of the Agulhas leakage could create density changes of upper thermocline waters in the South Atlantic, which extends into the North Atlantic in few decades [*Weijer et al*., 2002; *Van Sebille et al*., 2011; *Biastoch and Böning*, 2013; *Rühs et al*., 2013] the estimated amplitude changes in transport during Termination 1 (~10 Sv) would have a major impact on the global overturning circulation. To test this hypothesis, we compared with the radiogenic isotope pair $^{231}$Pa and $^{230}$Th gradient between a southern Atlantic record and a northern Atlantic record [*Negre et al*., 2010] (Figure 3). This proxy can be used to quantitatively assess the abyssal flow rate. The comparison lends a strong credence to the hypothesis that measurable modifications in the leakage played a key role in changing the overturning circulation to its full strength mode (Figure 3). Interestingly, Termination 1 does not correspond to the higher increase in leakage when compared to other past periods (Figures 2 and 3).

  

Qualitative salinity reconstructions in the Agulhas Current system suggest a strong leakage of salty waters during Termination 2 [*Martínez-Méndez et al*., 2010; *Caley et al*., 2011; *Marino et al*., 2013]. Based on our results, the major increase in leakage occurs during Termination 2 with >15 Sv of change (Figures 2 and 3). The estimate is higher than the present-day value and could therefore constitute an analogue for the increase in leakage and response of the AMOC under future global warming scenarios [*Beal et al*., 2011].

The most significant leakage reduction occurs during marine isotopic stage 12, for which we have reconstructed a leakage efficiency of 5 ± 10%, equivalent to a reduction of ~15 Sv compared to late Holocene/modern value (Figures 2 and 3). The mean estimate of the ALE is not equal to 0, indicating trace amounts of tropical fauna during MIS 12. Nonetheless, considering the error on the reconstruction, such trace amounts of tropical fauna are not a significant evidence of Agulhas leakage. If true, this suggests that the leakage plausibly ceased completely during MIS 12, in concordance with significant AMOC change (Figure 3).

## 5. Conclusions

A quantitative index for Agulhas leakage has been developed based on planktic foraminifera assemblage composition, here referred to as the Agulhas leakage efficiency. The presented 640,000 year long ALE record stresses the importance of the Agulhas leakage in the overturning circulation and the late Pleistocene ocean-climate change from a quantitative point of view. The data series suggests substantial changes of the Agulhas leakage volume transports during major climatic transitions (>10 Sv) and possibly a complete halt of the leakage during MIS12. Our new results therefore serve as a benchmark for climate models testing Agulhas leakage dynamics and AMOC sensitivity under paleoconditions. They also contribute to an improvement in predictions of the AMOC response to changes in Agulhas leakage in the future [*Beal et al*., 2011; *Biastoch and Böning*, 2013].

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