LETTERS

Increase in Agulhas leakage due to poleward shift of Southern Hemisphere westerlies

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The transport of warm and salty Indian Ocean waters into the Atlantic Ocean—the Agulhas leakage—has a crucial role in the global oceanic circulation[1] and thus the evolution of future climate. At present these waters provide the main source of heat and salt for the surface branch of the Atlantic meridional overturning circulation (MOC)[2]. There is evidence from past glacial-to-interglacial variations in foraminiferal assemblages[3] and model studies[4] that the amount of Agulhas leakage and its corresponding effect on the MOC has been subject to substantial change, potentially linked to latitudinal shifts in the Southern Hemisphere westerlies[5]. A progressive poleward migration of the westerlies has been observed during the past two to three decades and linked to anthropogenic forcing[6], but because of the sparse observational records it has not been possible to determine whether there has been a concomitant response of Agulhas leakage. Here we present the results of a high-resolution ocean general circulation model[7,8] to show that the transport of Indian Ocean waters into the South Atlantic via the Agulhas leakage has increased during the past decades in response to the change in wind forcing. The increased leakage has contributed to the observed salinification[9] of South Atlantic thermocline waters. Both model and historic measurements off South America suggest that the additional Indian Ocean waters have begun to invade the North Atlantic, with potential implications for the future evolution of the MOC.

The Agulhas leakage is the result of a complex, highly nonlinear interplay between the strong western boundary current (WBC) along the South African coast, the Agulhas Current[10], and vigorous mesoscale activity arising in its source regions[11] and south of Africa where the bulk of the Agulhas Current waters are retroflected back into the Indian Ocean. As part of the retroflection process, the intermittent formation of intense oceanic eddy structures—Agulhas rings—carries warm and salty Indian Ocean water into the South Atlantic. The leakage can affect the MOC in two ways. (1) The mesoscale activity in the retroflection regime induces wave processes in the South Atlantic that dynamically modulate the MOC on decadal timescales[7]. (2) On longer timescales, it has been demonstrated in idealized studies[12] that the northward advection of salinity anomalies from the Agulhas regime influences deep-water formation in the northern North Atlantic.

Owing to its mean latitudinal position south of Africa, the zero line of the wind stress curl permits an interoceanic connection of the subtropical gyres of the South Indian and the Atlantic Ocean, a 'supergyre'[13] (Fig. 1a). Studies of atmospheric observations and reanalyses have noted a poleward intensification of the westerly winds during the last decades[6], a trend that is projected to continue during the twenty-first century[14]. How have these changes to the wind field affected the Agulhas system[10], in particular interoceanic transport? We used a high-resolution (1/10°) model of the greater Agulhas region (green box in Fig. 2) that has been demonstrated to realistically simulate the complicated circulation around South Africa[7,8,15]. The model is nested into a global ocean/sea-ice model which by itself would significantly over-estimate the Agulhas leakage owing to its coarse (1/2°) resolution[8]. In addition to the reference experiment (AG01-R) which provides a hindcast simulation subject to the atmospheric forcing variability of the last decades[16], two sensitivity experiments are considered: AG01-C is driven by a repeated-year forcing, so it inherently explicitly excludes any inter-annual (and anthropogenic) forcing trend; AG01-S[8] uses a variant of the high-resolution nesting domain, exploring the sensitivity of the leakage behaviour to an omission of the mesoscale activity in the upstream regions of the Agulhas Current.

The model hindcast shows that during the past decades the supergyre has extended poleward by about 2° of latitude, a direct consequence of the poleward shift of the westerlies (Fig. 1b). Such behaviour is not produced by the sensitivity experiment under

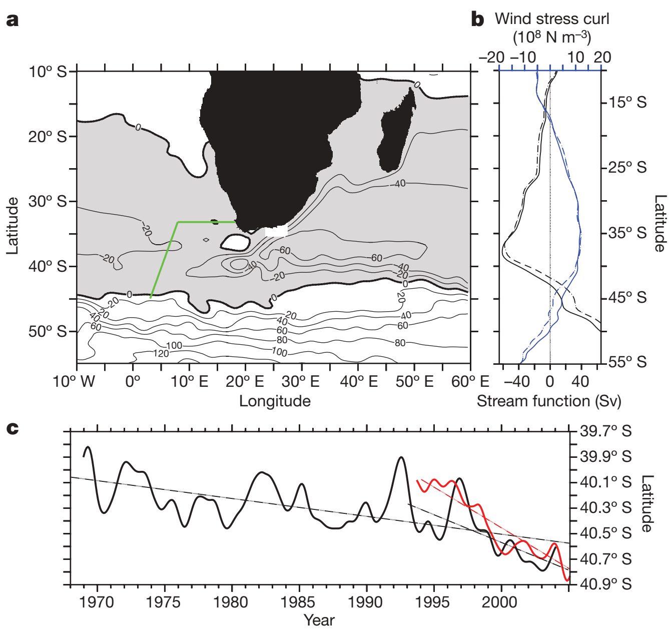

Figure 1 | Large-scale circulation changes south of Africa. a, Time-mean (1995–2004) horizontal streamfunction in the Agulhas region (contours marked in Sverdrups) in AG01-R, with grey shading denoting anticyclonic circulation. The GoodHope section used for the quantification of Agulhas leakage is marked by the green line. **b**, Latitudinal dependence of zonal averages (20°–60° E) of the streamfunction (black) and zonally averaged wind stress curl over the Indian Ocean (20°–110° E, blue) for periods 1965–1974 (dashed) and 1995–2004 (solid). **c**, Latitude of zero sea surface height in AG01-R (0°–40° E zonal average, black) and a corresponding constant sea surface height line in satellite data (Aviso, red). Dashed lines indicate linear trends over full time range and over the past decade.

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repeated-year forcing (AG01-C), confirming that we can neglect possible effects of spurious model trends and attribute the shift to the decadal changes in the external forcing. An observational test of the change in the geometry of the super-gyre is provided by satellite altimeter data, available since the beginning of the 1990s: the observed sea surface height pattern shows a southward migration, similar to that of the model simulation (Fig. 1c), with a clear increase in the past decade.

As a consequence of the trend in the atmospheric forcing, and consistent with studies of regional ocean observations[17], the waters in the southwest Indian Ocean exhibit warming and salinification tendencies (Fig. 2; Supplementary Fig. 1). The model simulation captures the observed trends[18], and indicates the regional changes as part of a larger pattern that zonally extends into the South Atlantic. The warming/salinification can be explained by a southward shift (Supplementary Fig. 2) of the boundary between the subtropical gyre circulation and the Antarctic Circumpolar Current, and thus considered to be part of the hemispheric-scale poleward migration of this frontal zone[19]. (Note that the warming pattern is absent in the sensitivity experiment under repeated-year forcing, AG01-C.)

Another, potentially even more important, consequence of the forcing trend occurs in the Agulhas leakage (Fig. 3). For a rigorous determination of Agulhas leakage we trace the amount of water originating in the Agulhas Current at 32° S and arriving at the GoodHope section (see ref. 20 and green line in Fig. 1a) using a Lagrangian tracking technique[8,21,22]. Partially masked by a strong year-to-year variability, there has been a significant trend of 1.2 Sv ($1\ \mathrm{Sv} = 1 \times 10^6\ \mathrm{m^3\ s^{-1}}$) per decade, resulting in a total increase of more than 5 Sv over the course of the integration.

Of potential relevance to ocean monitoring efforts[20,23] is the manifestation of circulation changes in the WBC system east of Africa. The model simulation demonstrates that it is not possible to infer the WBC changes from linear vorticity dynamics, as attempted in previous calculations[6,18] (Fig. 4a): there is no simple relation between the Sverdrup transport variability calculated from the wind stress curl over the Indian Ocean and the actual transport variability, presumably because of the strong topographic effects shielding the Agulhas region from the east[24] and the inherent nonlinearities of eddy–mean flow interaction in the WBC[15]. The importance of the WBC nonlinearities for the generation of inter-annual to decadal transport variability is elucidated by the sensitivity experiments (Fig. 4b). AG01-C, although forced without inter-annual variability, exhibits low-frequency transport variations of similar intensity (but different phase). In contrast, AG01-S, a sensitivity experiment with a smaller nesting domain excluding Mozambique eddies[11], produces, although under identical forcing, a temporal variation differing from the reference experiment. The sequence demonstrates that inter-annual transport variations in

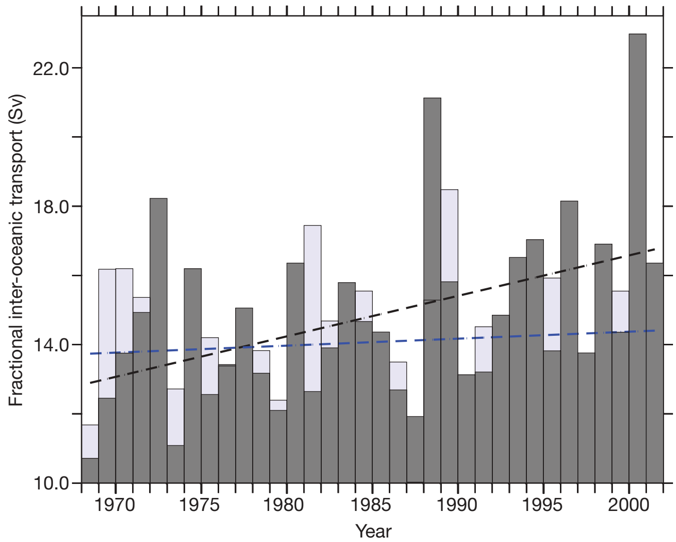

Figure 3 | Increase of Agulhas leakage. Inter-oceanic transport as obtained by float releases within the southward-flowing Agulhas Current at 32° S: fractional transports (in Sverdrups) across the GoodHope line in the Cape Basin (green line in Fig. 1a) in the reference experiment (AG01-R, grey bars) and the repeated-year (AG01-C, light-blue bars) experiment. The dashed lines mark the linear trend of 1.2 Sv per decade in AG01-R (black) and 0.2 Sv in AG01-C (blue).

the Agulhas regime are largely decoupled from the large-scale wind field and governed primarily by the internal dynamics in the WBC regime. Only on longer, decadal timescales does the effect of these eddies appear to fade, and transport changes with (AG01-R) and without (AG01-S) Mozambique eddies begin to exhibit a clear correlation ($r = 0.95$, Supplementary Fig. 3). The model results have implications for ongoing ocean-monitoring efforts at the western boundary: they suggest that observations of a few years' duration are of limited value as an index of inter-annual gyre-scale transport changes in the southern Indian Ocean.

As suggested by theoretical arguments[25], an increase (decrease) in the strength of the Agulhas Current should translate into a decrease (increase) of the leakage; a corresponding behaviour was noted for the present model[22]. It also holds for the long-term trend in which the increasing transport from the Indian to the Atlantic Ocean (1.2 Sv per decade) is linked to a multi-decadal decrease of the Agulhas Current transport (−1.4 Sv per decade). The observed warming south of Africa is therefore an expression of the large-scale frontal changes, rather than an advective effect of the Agulhas Current[18] (Supplementary Fig. 4). The simulation suggests that this 10% reduction of the WBC can be

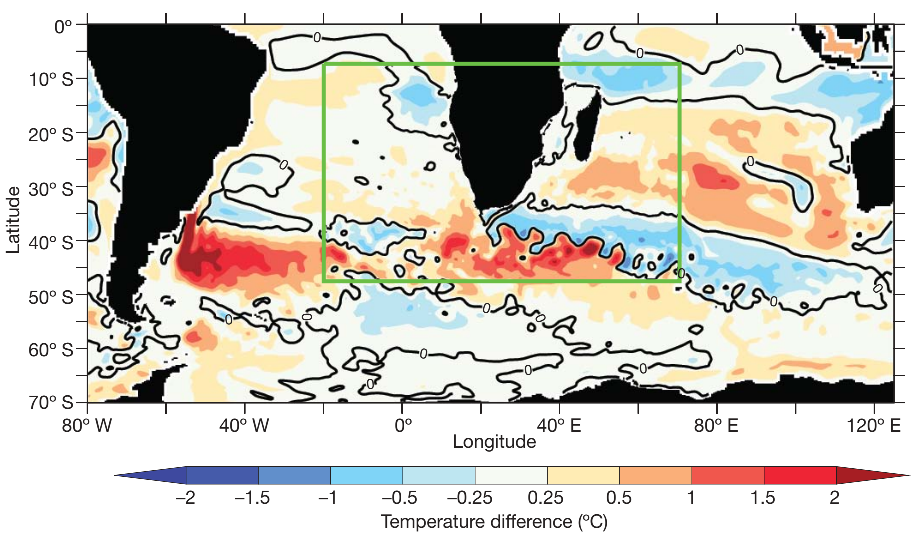

Figure 2 | Thermocline changes in the Southern Hemisphere. The colour scale shows the difference (2000–2004 minus 1968–1972) in the upper ocean (0–200 m) temperature (in °C), simulated in AG01-R. The green box denotes the boundaries of the high-resolution nest. The zero contour line (black) separates cooling from warming areas.

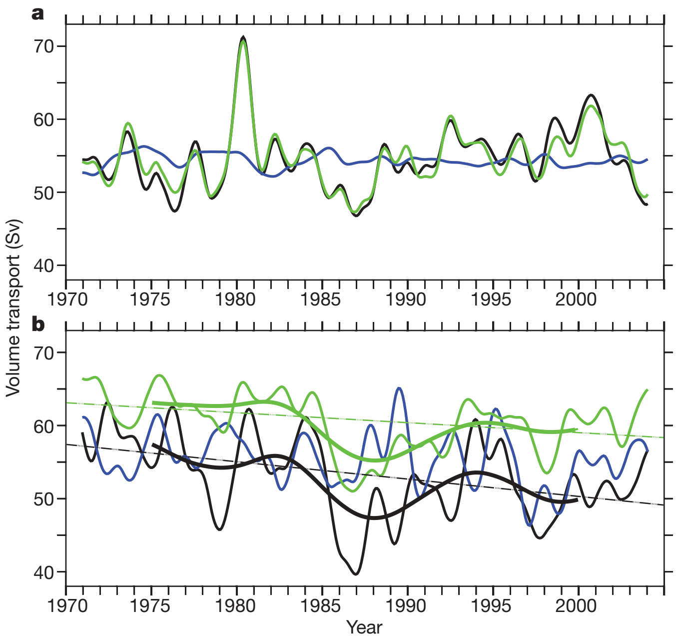

Figure 4 | Inter-annual to decadal variability in the Agulhas Current. **a**, Inter-annual variability of the Sverdrup transport at 32° S, calculated from the atmospheric wind stress (CORE[16]), for AG01-R (black), AG01-C (blue) and AG01-S (green). **b**, Agulhas Current transport at 32° S, calculated across the WBC and its first recirculation (line colours as in **a**), and filtered with a 23-month (thin curves) and 121-month Hanning window (bold). Long-term linear trend (dashed) of the strength of the WBC. (For alternative calculations of the WBC transport, see Supplementary Fig. 3.)

attributed to a combination of decreased transport through the Mozambique Channel (Supplementary Fig. 5), which is sensitive to shifts in the wind fields[26], and a reduced recirculation in the Southwest Indian Ocean subgyre[10].

What are the consequences of the increased Agulhas leakage for the large-scale circulation in the Atlantic Ocean? The present model series does not permit the effect of the leakage trend on the MOC transport to be isolated because the model includes other potential effects of changes in the westerlies, which may affect the MOC via changes in the Antarctic Circumpolar Current and its associated deep- and intermediate-water formation processes in the Southern Ocean[27]. However, by using the Lagrangian tracking technique we can follow and inspect the properties of the waters that enter the South Atlantic across the GoodHope section (Fig. 5). Consistent with the comparison of Agulhas leakage in the stand-alone base model and the nested model[8], the net volume transport towards the North Atlantic did not change from the 1970s to the 2000s; the increased leakage instead led to an enhanced horizontal super-gyre. However, there has been a striking trend in the freshwater transport: the inter-hemispheric export of salt originating from Agulhas leakage has increased by 25% over the course of the integration.

In the South Atlantic, almost all of the inter-hemispheric, northward volume transport (that is, the upper-layer branch of the MOC) is channelled through the North Brazil Current[1]. Corresponding to the increase in the northward salt transport, the model simulation reveals an increasing trend in the salinity of the North Brazil Current core. We have assessed this behaviour by performing an analysis of salinity profiles collected in historic ocean data archives (Fig. 5 inset). The observed records show a salinity increase in the North Brazil Current during the 1970s and 1980s, corresponding to the observed salinification of the subtropical thermocline waters during the past decade, which has been attributed to changes in the hydrological cycle[9]. The model simulation suggests that the majority of this salinification can be traced to the increased invasion of Indian Ocean waters as a result of wind-driven changes.

The suite of model experiments highlights a far-reaching consequence of the anthropogenic shifts in the Southern Hemisphere westerlies—the salinity increase described above—which is projected to continue and accelerate during the twenty-first century[14]. An increased import of salty water into the northward branch of the inter-hemispheric MOC could eventually become a significant factor for the freshwater budget of the deep-water formation regions in the subpolar North Atlantic[12]. To what degree it could help to stabilize a potentially declining 'Gulf Stream system' caused by subarctic freshening in a warming climate[28] needs to be investigated using coupled

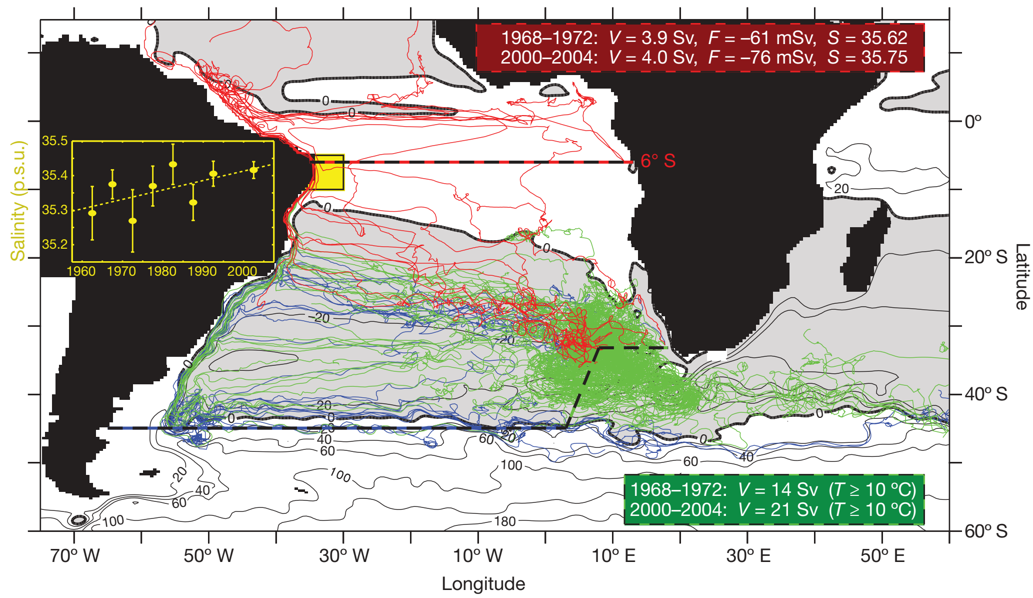

Figure 5 | Pathways of the Agulhas leakage into the North Atlantic. Example trajectories of virtual floats released with temperature $T \geq 10$ °C along the GoodHope section and leaving the South Atlantic towards the Indian Ocean (green), the Southern Ocean (blue) or the North Atlantic (red). For statistical numbers see Supplementary Table 1. Volume (V) and freshwater (F) transports (negative numbers indicate salt advection to the north) are shown for the full 6° S (red-black dashed line) and GoodHope (black dashed) sections for the indicated periods, and the mean salinity (S) of floats leaving the domain in the core of the North Brazil Current (depth range, 100–600 m). The inset shows an analysis of historic salinity profiles (in practical salinity units, p.s.u.) averaged over the same depth range off the east coast of South America (yellow box). The error bars depict 2σ errors (95% confidence intervals). The shading and the contour lines depict the streamfunction as in Fig. 1a.

ocean–atmosphere models and dedicated sensitivity studies. Our model results emphasize the need to capture realistically the mesoscale processes of the Agulhas leakage regime in climate model projections of future MOC evolution, and the importance of ocean-monitoring programmes in key areas for inter-ocean and inter-hemispheric transports.

METHODS SUMMARY

For a realistic model simulation of the Agulhas Current system the horizontal resolution is a critical factor. Here we use a high-resolution (1/10°) model (green box in Fig. 2) nested[29] into a coarser (1/2°) global ocean/sea-ice model based on the NEMO code (v2.3)[30], developed by the DRAKKAR collaboration. Previous studies demonstrated the success of this set-up in reproducing the salient circulation features of the Agulhas system[8,15] and its dynamic impact on the Atlantic MOC[7]. In addition to the reference experiment (AG01-R) in which surface forcing fields[16] were applied over the period 1958–2004, two sensitivity experiments have been performed. AG01-C, without inter-annual variability in the forcing fields, allows us, by comparison with AG01-R, to isolate the internal variability and a possible spurious model drift from the changes by the forcing fields. In AG01-S, the high-resolution nest terminates at 27° S, thus excluding mesoscale eddies in the source regions of the Agulhas Current[8].

A Lagrangian method[21] was used to quantify the Agulhas leakage. Virtual floats, each seeded as a fraction of the Agulhas Current transport at 32° S, were advected by the time-dependent three-dimensional flow field. Summing up their individual transports at the GoodHope section[20] resulted in a total number for the leakage transport. Another float integration elucidated the longer-term paths of the leakage towards the North Atlantic by seeding at the GoodHope section and advecting with the velocities of two different pentads (five-year periods) from the model. The model fields are compared with gridded time series of sea surface height (http://www.aviso.oceanobs.com) based on satellite altimeter data, produced by Ssalto/Duacs and distributed by Aviso, with support from CNES. The mean dynamic topography Rio05 was produced by the CLS Space Oceanography Division. To assess temporal changes in salinity fields in the North Brazil Current near 6° S, we used an extensive compilation of historical observations by BLUElink (ftp://ftp.marine.csiro.au/pub/omas/BOA) and CARS (http://www.marine.csiro.au/~dunn/cars2006).

Full Methods and any associated references are available in the online version of the paper at www.nature.com/nature.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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Author Contributions A.B. and C.W.B. conceived the experimental concept. A.B. implemented and conducted the experiments, and carried out the analysis. F.U.S. performed the observational analysis. All authors discussed the results and jointly wrote the manuscript.

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METHODS

For a realistic model simulation of the greater Agulhas Current system the horizontal resolution is essential. The nested model configurations used here build on the ocean/sea-ice numerical framework of the 'Nucleus for European Modelling of the Ocean' (NEMO, v2.3)[30] and 'Adaptive Grid Refinement in Fortran' (AGRIF)[29], developed in the framework of the DRAKKAR collaboration.

The base model uses the global ORCA05 configuration, a tripolar, quasi-isotropic grid with a nominal resolution of 1/2°; its cell size of 45–50 km in the Agulhas region is not resolving the mesoscale. In the vertical dimension 46 levels (with ten levels in the upper 100 m, and 250-m resolution at the deepest levels) are used, whereby the bottom cells are allowed to be partially filled. This improved representation of topographic slopes, in combination with a refined, energy- and enstrophy-conserving advection scheme, has led to marked improvements in the global circulation features[31]. Additional subgrid-scale mixing parameterizations include a representation of mixed layer dynamics by a 1.5-level turbulent kinetic energy closure, a bi-Laplacian viscosity, and an iso-neutral Laplacian scheme. For tracer advection a total variance dissipation scheme[32]—a second-order, two-step monotonic scheme with moderate numerical diffusion—is used.

The model is driven at the surface by a consistent data set, CORE[16], which is a combination of the NCEP/NCAR atmospheric reanalysis[33] and independent observations used to correct known biases, and to globally balance the heat and freshwater budgets. Turbulent fluxes are computed via bulk formulae, allowing some feedback of the ocean on the atmospheric fluxes[16,34]. Data are prescribed at six-hourly (wind speed, humidity and atmospheric temperature), daily (short- and long-wave radiation) and monthly (rain and snow) resolution, with inter-annual variability over the time range 1958–2004. To avoid an artificial model drift due to an excess of freshwater[34], the CORE precipitation field has been replaced north of 30° N by observational values[35]; in addition common practice[34] has been followed by damping sea surface salinity towards monthly-mean climatological values with a piston velocity of 50 m per 300 days (about a one-month timescale) poleward of 70° N and 50° S. Equatorward of these latitudes (and in the high-resolution nest) a very weak damping (more than a one-year timescale) was used, leaving the evolution within the Agulhas area almost unaffected. Several studies have demonstrated the fidelity of this ORCA05 set-up in simulating the salient features of the Atlantic MOC[36,37].

The experiments were initialized from rest using temperatures and salinities from a global climatology[38,39] and integrated over 20 years using the repeated-year version of the CORE forcing data. After that time all prognostic model fields were interpolated onto the 1/10° nest in the greater Agulhas region (20° W–70° E, 47°S–7° S, green box in Fig. 2). The fivefold refinement of the original ORCA05 grid, with an average grid cell of 9.5 km at 30° S, resolves the baroclinic Rossby radius of ~30 km in this regime. Apart from some resolution-dependent scaling the same parameterizations have been used. Both base and nested model were then integrated over the full period of 1958–2004. The nesting approach acts in two ways so that not only is the regional model continually receiving information from the outside ocean, but also it feeds the effect of the mesoscale dynamics in the leakage regime back to the base model at all timescales. This feature enabled us to isolate the effect of the Agulhas dynamics onto the Atlantic MOC[7].

Previous studies demonstrated the success of the model set-up in reproducing all the important circulation features of the greater Agulhas Current system, including a realistic WBC structure off Africa[15], the upstream perturbations arising from the Mozambique Channel[11], and their interplay with the shedding of Agulhas rings[8]. In addition to the reference experiment (AG01-R) using the inter-annually varying CORE forcing fields, two sensitivity experiments have been performed: AG01-C, without inter-annual variability in the forcing fields, allows us to isolate the internal variability and a possible spurious model drift from the changes due to the forcing fields by comparison with AG01-R. In AG01-S the high-resolution nest terminates at 27° S, thus excluding the mesoscale eddies in the source regions of the Agulhas Current from the model solution[8].

Similar to a previous analysis[8] a Lagrangian method[21] was used, in which a large number (typically 10^5–10^6) of virtual floats was seeded continuously over a year into the Agulhas Current at 32° S. Each float represents a fraction (~0.1 Sv) of the total volume transport, is advected by the time-dependent flow field and is counted when crossing the GoodHope section[20] (green line in Fig. 1a) in the Atlantic within three years of release. The algorithm uses all velocity components and analytically calculates a three-dimensional streamfunction for any given five-daily averages, thereby avoiding spurious diffusion. A second float integration elucidated the longer-term paths of the Agulhas leakage towards the North Atlantic by seeding fractional transports (~0.01 Sv) crossing the GoodHope section with temperatures exceeding 10 °C and advecting those with the five-daily base model flow fields for two different pentads (1968–1972 and 2000–2004). About a third of the floats do not reach one of the control sections within five years (especially the ones looping in the subtropical gyre); so to draw out the path differences, the float integration was elongated by repeatedly cycling through these pentads until ~95% of the floats had crossed one of the sections (Fig. 5). Comparison with float experiments over ten-year periods and different repetitions led to similar conclusions for the volume and freshwater transports arriving at 6° S (Supplementary Table 1).

The model fields were compared with gridded time series of sea surface height (http://www.aviso.oceanobs.com) based on satellite altimeter data, produced by Ssalto/Duacs and distributed by Aviso, with support from CNES. The mean dynamic topography Rio05 was produced by the CLS Space Oceanography Division.

To assess temporal changes in salinity fields in the North Brazil Current near 6° S, we used an extensive compilation of historical shipboard hydrographic cast and high-quality buoy data provided by the BLUElink Ocean Archive (BOA, ftp://ftp.marine.csiro.au/pub/omas/BOA). Our model-data comparison focused on the region 40° W–30° W, 5° S–10° S. The irregularly distributed BOA profiles constitute the basis for the high-resolution, gridded 'CSIRO Atlas of Regional Seas' (CARS, http://www.marine.csiro.au/~dunn/cars2006)[40] climatology. Following previous studies[19] we minimized the potential spatial aliasing arising from the temporally varying distributions of sampling points by subtracting the climatological mean from the individual BOA profiles. The resulting salinity values were averaged over the individual pentads and the depth range of the North Brazil Current (100–600 m). Error bars were drawn using 95% confidence intervals, given by doubling the population standard deviation divided by the square root of the number of degrees of freedom.

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