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On the role of the Agulhas system in ocean circulation and climate

Lisa M. Beal[1], Wilhelmus P. M. De Ruijter[2], Arne Biastoch[3], Rainer Zahn[4] & SCOR/WCRP/IAPSO Working Group 136*

The Atlantic Ocean receives warm, saline water from the Indo-Pacific Ocean through Agulhas leakage around the southern tip of Africa. Recent findings suggest that Agulhas leakage is a crucial component of the climate system and that ongoing increases in leakage under anthropogenic warming could strengthen the Atlantic overturning circulation at a time when warming and accelerated meltwater input in the North Atlantic is predicted to weaken it. Yet in comparison with processes in the North Atlantic, the overall Agulhas system is largely overlooked as a potential climate trigger or feedback mechanism. Detailed modelling experiments—backed by palaeoceanographic and sustained modern observations—are required to establish firmly the role of the Agulhas system in a warming climate.

The greater Agulhas system around southern Africa forms a key component of the global ocean circulation[1–3] (Fig. 1). This system feeds the upper arm of the Atlantic meridional overturning circulation (AMOC) through the leakage of warm, saline waters from the Indian Ocean to the Atlantic[1,4] (Fig. 2). From year to year, Agulhas leakage is dominated by nonlinear, mesoscale dynamics: it is carried by Agulhas rings (formed by an occlusion of the Agulhas Retroflection; Fig. 2), eddies and filaments[5–7]. Over longer periods, theory suggests its variability is associated with the large-scale wind field, in particular with the position of the maximum Southern Hemisphere westerly winds[2,8–10]. These winds are related to the latitude of the oceanic subtropical front (STF), which separates the subtropical gyre from the Antarctic Circumpolar Current. In essence, if the westerlies shift southwards, as recent data suggest in a warming climate (Fig. 1), then the oceanic 'gateway' between the African continent and the STF expands and leakage from the Indian Ocean to the Atlantic increases[8,9] (Fig. 1 and Box 1). Similarly, a northward shift, as inferred from palaeorecords during glacial periods, would reduce the leakage[11,12].

Model simulations suggest that variability in Agulhas leakage can impact the strength of the Atlantic overturning on a number of timescales[13–15]. Most significantly, a persistent change in leakage could impact the thermohaline properties of the Atlantic, changing its stratification and its potential for deep convection, and thus altering the AMOC to a new stable state over a period of several hundred years[13,16],

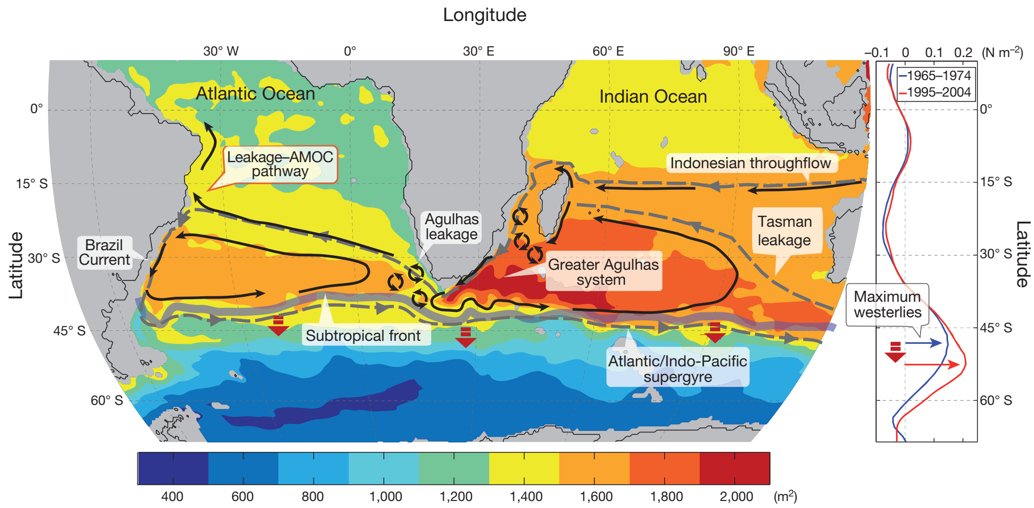

Figure 1 | Agulhas leakage affected by westerly winds and position of subtropical front. Schematic of the greater Agulhas system embedded in the Southern Hemisphere supergyre. Background colours show the mean subtropical gyre circulation, depicted by climatological dynamic height integrated between the surface and 2,000 dbar, from the CARS database[38]. Black arrows and labels illustrate significant features of the flow. An outline of the Southern Hemisphere supergyre is given by the grey dashed line. The plot on the right shows the southward expansion of the Southern Hemisphere westerlies over a 30-yr period, from the CORE2 wind stress[92] averaged between longitudes 20° E and 110° E (Indian Ocean sector). The expected corresponding southward shift of the subtropical front (STF) is illustrated by red dashed arrows and would affect Agulhas leakage (shown as eddies) and the pathway between leakage and the AMOC, which is highlighted with a red box.

[1]Rosenstiel School of Marine and Atmospheric Science, University of Miami, 4600 Rickenbacker Causeway, Florida 33149, USA. [2]Institute for Marine and Atmospheric Research, Utrecht University, Princetonplein 5, 3584 CC Utrecht, The Netherlands. [3]Leibniz-Institut für Meereswissenschaften (IFM-GEOMAR), Düsternbrooker Weg 20, 24105 Kiel, Germany. [4]Institució Catalana de Recerca i Estudis Avançats (ICREA), Institut de Ciència i Tecnologia Ambientals (ICTA), Departament de Física, Universitat Autònoma de Barcelona, Bellaterra E-08193, Spain.
*Lists of authors and affiliations appear at the end of the paper.

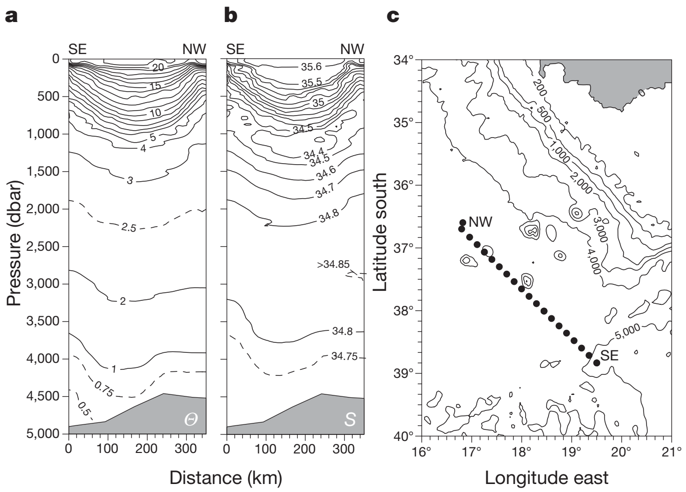

Figure 2 | Warm, saline Agulhas waters influence temperature and salinity in the Atlantic over the full depth of the water column. **a**, **b**, Vertical sections of the potential temperature (*Θ*; **a**) and salinity (*S*; **b**) of Agulhas ring Astrid, measured in the Cape basin off South Africa, March 2000[5]. Agulhas waters trapped in the ring displace otherwise flat surfaces of *Θ* and *S* by up to 500 m. The sea bed is shaded grey. **c**, Hydrographic station positions are indicated by dots on the chart, where the African continent is shaded grey.

BOX 1

Dynamics of Agulhas leakage

As a western boundary current, the Agulhas Current is primarily driven by positive wind stress curl over the subtropical Indian Ocean. However, beyond the tip of Africa, there is no western boundary to steer the current southwards, towards the latitude where the westerlies are a maximum and the wind stress curl is zero (Fig. 1). Hence, without inertia the full Agulhas Current would turn west into the Atlantic and feed the Southern Hemisphere supergyre[8]. Conversely, for large inertia, or with the latitude of zero wind stress curl much closer to the continent, the full Agulhas Current would loop back into the Indian Ocean. In this case, there is no leakage, owing to 'inertial choking'. Lower inertia would lead to partial leakage. Hence, the main controls on retroflection and leakage are the latitude of maximum westerlies and the southward inertia of the Agulhas Current at separation, which are both largely determined by the strength and position of the wind field over the Indian Ocean. Instabilities, interaction with bathymetry and other mesoscale, nonlinear dynamics are also important, generating Agulhas rings that propagate westwards, conveying most of the leakage into the Atlantic[2,95,96].

When interpreting glacial–interglacial cycles in the Agulhas system implied from palaeoproxy data, or present-day changes implied from model simulations, the combination of these controls should be taken into account. For instance, if the wind pattern is fixed but its strength reduced, then a weaker Agulhas Current would result in more leakage, owing to the smaller inertial overshoot[97,98]. Similarly, for increased wind strength a stronger Agulhas Current combines with less leakage. But if the wind pattern shifts northwards and weakens (for example in relation to glacial climate[99]) then the Agulhas Current would be weaker at separation, and the latitude of zero wind stress curl would simultaneously be closer to Africa. The weaker Agulhas Current may then still have enough inertia to reach the closer wind curl change, so that a weaker Agulhas Current combines with less leakage[17,91]. In present-day climate change, global wind data point to a southward expansion of the wind pattern (a southward shift of the westerlies) but no robust trend in wind curl over the Indian Ocean. In such a situation, the latitude of zero wind stress curl or maximum westerlies is farther south and leakage increases, but the response of the Agulhas Current and its change in inertia is unclear[9,10].

To simulate Agulhas leakage correctly, it is essential that inertial mechanisms and ring formation—that is, nonlinear dynamics—are resolved. However, most Intergovernmental Panel on Climate Change (IPCC)-type simulations have coarse resolution (large eddy viscosity). Agulhas retroflection appears, but as a result of 'viscous choking' instead of inertial choking. As a result, the amplitudes of Agulhas transport and leakage and their sensitivity to change may be completely wrong[100]. An effective resolution of at least 0.1° is necessary to resolve Agulhas leakage and could be achieved by a range of regional and global numerical grids[15,70].

with direct implications for climate. According to these simulations, a stronger Agulhas leakage (saltier Atlantic) sustains a stronger and more stable AMOC.

Fluctuations in the strength of Agulhas leakage over the late-Pleistocene epoch have been inferred through an assemblage of planktonic foraminifera characteristic of modern Agulhas waters in marine sediment records[17]. The reconstructions suggest that there was less Agulhas water leaking into the South Atlantic during glacial periods, when the STF was shifted several degrees northwards of its present-day position[18]. Furthermore, leakage started to increase during late-glacial conditions, several thousand years before the glacial ice volume fully disappeared[11,17,18]. This maximum during glacial terminations suggests that Agulhas leakage may have had a role in the rapid resumption of interglacial climate, presumably through its influence on the AMOC[14,17,19].

There is evidence that Agulhas leakage is increasing under anthropogenic climate change. Satellite and hydrographic data show a southward expansion of the Indian Ocean subtropical gyre[20] and a warming trend in the Agulhas system since the 1960s[10], in correspondence with a southward shift of the STF. There has also been an increase in eddy kinetic energy in the southeast Atlantic since the early 1990s, indicative of more rings and eddies associated with increased leakage[10]. Hindcast simulations suggest that these observed changes may accompany an increase in Agulhas leakage of the order of 1.4–4 Sv per decade[9,10] ($1\ \mathrm{Sv} = 1 \times 10^6\ \mathrm{m^3\ s^{-1}}$), which could lead to a significant strengthening of the AMOC[13]. This is a profound finding, because it presents a plausible mechanism to stabilize the AMOC at a time when anthropogenic warming and accelerated Greenland ice-sheet melting is predicted to weaken it[21,22].

In this Review, we focus on the past decade of research on the Agulhas system, highlighting its potential global climate impacts in particular. We find observational and palaeoproxy evidence that Agulhas leakage is enhanced in a warming climate and could precipitate rapid increases in the AMOC and atmospheric carbon dioxide. Theory and simulations show how Agulhas leakage is mechanistically linked to the strength of the Indian Ocean subtropical gyre, to changes in Southern Hemisphere winds and to changes in the AMOC. There are large uncertainties in our current understanding and we suggest that sustained observations, as well as climate process studies with high resolution in the Agulhas region, are badly needed. A careful method for simulating changes in leakage (accounting for both temperature and salinity fluxes) is critically important in regards to the response of the AMOC, as is an exploration into the interplay of Southern Hemisphere winds and Agulhas leakage in forcing a double response of the ocean in a changing climate.

The Agulhas system and ocean circulation

The Agulhas Current is the western boundary current of the southern Indian Ocean subtropical gyre (Fig. 1), and is primarily driven by the large-scale pattern of wind stress curl between the southeast trade winds and the Southern Hemisphere westerlies[3]. The STF at a latitude of about 45° S demarks the southern extent of the gyre and lies well south of the tip of the African continental shelf at 37° S. The Agulhas Current flows to the southwest along the east coast of South Africa as a narrow, fast boundary current until it separates from the continent, looping anticlockwise south of Africa and feeding back into the Indian Ocean as the eastward Agulhas Return Current (Box 1). This loop, known as the

Agulhas Retroflection[23], sheds rings, eddies and filaments to the west, representing a leakage of Indo-Pacific waters into the Atlantic down to depths of more than 2,000 m (refs 1, 5–7; Figs 2 and 3).

The Agulhas Current is fed in the main by recirculating subtropical gyre waters, but also by waters from the Red and Arabian seas, from the Indonesian throughflow and from the equatorial Indian Ocean via Mozambique Channel eddies and the East Madagascar Current (EMC)[24,25] (Fig. 3). Long-term moorings in the narrows of the Mozambique Channel show that four or five large (350-km) anticyclonic eddies drift southwards through the channel per year, carrying a mean transport of 17 Sv (ref. 26). Interannual variability is high (9 Sv), owing to upstream variations related to the phase of the Indian Ocean Dipole mode, an intrinsic mode of coupled climate variability in the tropical Indian Ocean[26]. The EMC is less well measured. At 20° S there is an estimated transport of 20 Sv (refs 27, 28), whereas close to the southern tip of Madagascar the geostrophic transport is increased to about 35 Sv (ref. 29). The Agulhas Current itself has a mean transport of 70 Sv at 32° S (ref. 30). Its variability on seasonal to longer timescales remains unknown. Estimates of Agulhas leakage are highly uncertain, ranging between 2 and 15 Sv, with about four to six Agulhas rings shed per year[1,2,31].

There has been conflicting evidence over the years for the existence of an EMC retroflection[32–36]. Dynamically, the large-scale wind field does not require the EMC to feed an eastward interior flow as it does at the latitude of the Agulhas Retroflection. Most recent research points to the EMC linking to the Agulhas Current by means of westwards-drifting eddies and dipoles shed off the tip of Madagascar[34,35]. Although there is a shallow (<200-m) eastward flow (the South Indian Countercurrent; Fig. 3) around 25° S (ref. 37) that may connect intermittently with the EMC[36], mean dynamic topography, satellite and water mass measurements show it to be part of a basin-wide recirculation to the south and east of Madagascar that is fed by waters from the southwest[29,37–39].

Observations have recently shown, as predicted dynamically[8], that the Agulhas system and the southern Indian Ocean subtropical gyre are embedded in a Southern Hemisphere supergyre that connects the Atlantic, Indian and Pacific basins[31,38,40] (Fig. 1). The Atlantic and Indian oceans are connected south of Africa by westward Agulhas leakage and the eastward South Atlantic Current. Hence, a proportion of Agulhas leakage remains in the South Atlantic subtropical gyre, some ends up in the supergyre, circulating back into the Indo-Pacific via the South Atlantic Current, and the remainder feeds into the surface arm of the AMOC and crosses the equator.

The strength of the connectivity between Agulhas leakage and the AMOC is important for global climate impacts but is beyond direct observations. As a source of the AMOC, Agulhas leakage (warm-water route) competes with intermediate waters from the Drake Passage (cold-water route)[41,42]. Several hydrographic inverse models have implied that the cold-water route dominates[43], although some previous hydrographic studies concluded otherwise[41]. A careful model-data reanalysis[4] suggests that the AMOC is largely fed by Agulhas leakage and that inverse models deal poorly with large, opposing flows such as those found south of Africa (Figs 1 and 3). This is because hydrographic inverse models work

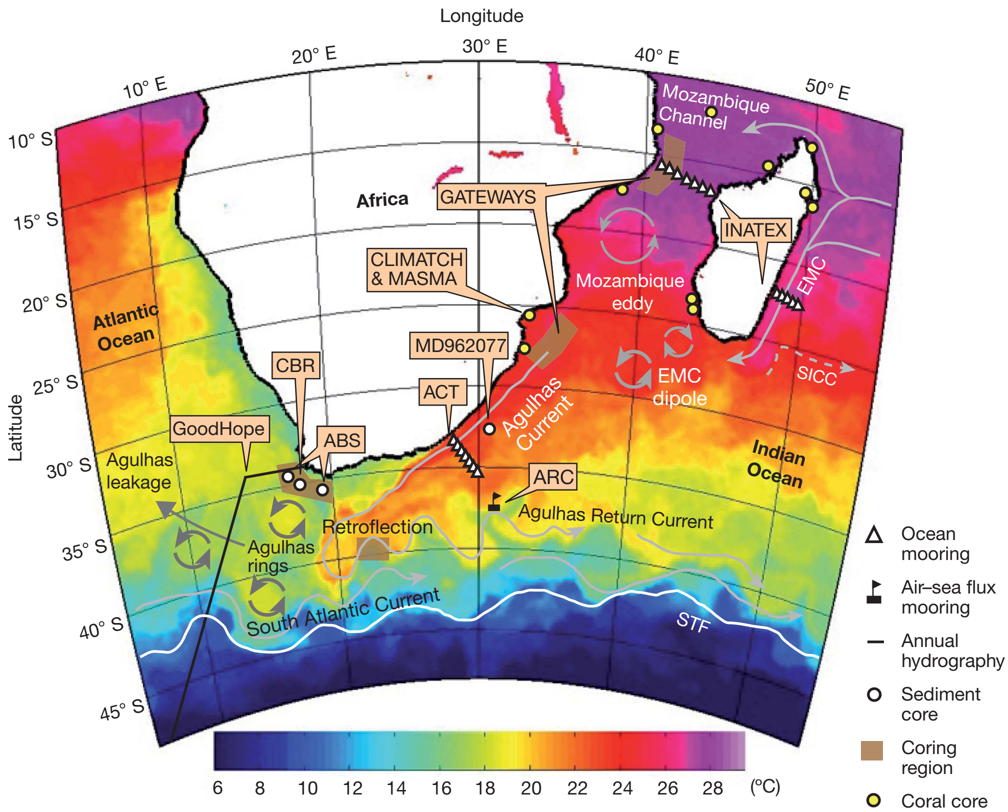

Figure 3 | Agulhas leakage advects warm, saline waters into the Atlantic, predominantly through Agulhas rings. Sea surface temperature (SST) for 23 May 2009, showing water at 23–25 °C in the Agulhas Current and Retroflection. North–south migrations of the STF (related to wind curl changes) and/or the retroflection loop (related to varying Agulhas strength) can choke or open the "leakage gap" between Africa and the STF. Leakage takes place largely by means of Agulhas rings. Main circulation features and observation programs are highlighted. Monitoring and repeat measurement programmes in the region include Agulhas Current Time-series (ACT), Indian–Atlantic Exchange in Present and Past Climate (INATEX), the Agulhas Return Current (ARC) air–sea flux buoy and the GoodHope repeat-hydrography line. Palaeoceanographic measurements are being collected in four (coring) regions under the European GATEWAYS programme. Individual sediment core locations are marked for the Cape Basin record[17] (CBR), MD962077[12] and Agulhas Bank splice[90] (ABS). Coral cores are being collected under the Climate and Anthropological Change (CLIMATCH) and Marine and Coastal Science for Management (MASMA) programmes. SICC is the shallow South Indian Countercurrent. SST data are from the NAVOCEANO K10 analysis with combined satellite infrared and microwave measurements, made available through the GHRSST project[93]. EMC, East Madagascar Current.

to balance net section-wide fluxes (and are underdetermined); hence, Agulhas leakage is obscured by the large throughflow of the Antarctic Circumpolar Current. Maps of mean dynamic height from the Argo database also support a direct pathway for Agulhas leakage from the Cape basin to the equator (Fig. 1).

Mechanistic linkages to climate

The mechanisms by which the Agulhas Current and its leakage may be linked to AMOC and global climate have been explored in several ocean and coupled climate models. Variability in Agulhas leakage can impact the strength of the AMOC in a number of different ways: through buoyancy forcing, associated wind stress changes and planetary-wave perturbations.

The depression of density surfaces associated with anticyclonic Agulhas rings entering the Atlantic basin instigates the propagation of planetary waves that perturb the AMOC[15,44]. Such perturbations can contribute to short-term variability in the AMOC, as might be seen in the time series at 26° N for instance[45], but are also integrated into interannual-to-decadal oscillations in the AMOC[15], perhaps because Agulhas ring shedding is modulated by Indian Ocean Dipole modes and El Niño/Southern Oscillation modes[34,46].

Simulations show that buoyancy forcing associated with warm and saline Agulhas leakage waters acts to strengthen the AMOC by enhancing the Atlantic meridional pressure gradient and preconditioning the North Atlantic for deep convection[13,16]. Although Agulhas heat and salt anomalies are largely density compensated as they enter the South Atlantic, progressive atmospheric heat loss creates an increasing positive density anomaly as salt is left behind and waters are advected northwards[13,47]. In this way, an increase in leakage initiates an increase in overturning strength 15–30 yr later, the advective timescale for the excess salt to reach the North Atlantic[13,47]. It takes another several hundred years for the AMOC to adjust fully to a new stable state, as buoyancy fluxes and (irreversible) mixing rates re-establish a balance[13,48].

It is difficult to separate the impact of wind forcing on the AMOC from the buoyancy effect of Agulhas leakage, because model studies show that the strength and position of the Southern Hemisphere wind systems seem to affect the strengths of both Agulhas leakage and the AMOC directly[2,8,9,49,50]. For example, in a warming climate the Southern Hemisphere westerlies would tend to shift polewards and the AMOC will have a double response: (1) an expansion of the gateway between Africa and the STF allows increased Agulhas leakage that, through buoyancy forcing, increases the AMOC[13]; and (2) increased northward surface-layer Ekman transport in the Southern Ocean increases upwelling that theoretically pulls directly on the southward deep arm of the AMOC (Drake Passage effect[49]). Climate model experiments of coarse resolution, where the wind systems are shifted to emulate glacial–interglacial cycles or projected anthropogenic warming, suggest that a warmer climate is associated with a stronger AMOC (and a saltier Atlantic) and that a cooler climate is associated with a weaker AMOC, presumably through an unknown combination of mechanisms (1) and (2) and others (for example sea ice and air–sea fluxes) that are unrelated to the Agulhas system[50,51].

Changes in Southern Ocean winds and buoyancy fluxes are also thought to regulate the ocean's ability to store carbon[52,53], through their impact on deep upwelling (ventilation) and the AMOC. Hence, Agulhas leakage could influence atmospheric carbon dioxide concentrations through its link to the AMOC, or through a direct impact on the density distribution in the sub-Antarctic region. So far, simulations have produced conflicting results regarding the relative importance of wind and buoyancy in governing atmospheric carbon dioxide[54]. The broader picture is further complicated by the role of eddies, which are unresolved in climate models but can carry significant buoyancy fluxes and are clearly important in controlling Agulhas leakage. In the Southern Ocean, eddies can short-circuit the link between Ekman transport, deep upwelling and the AMOC, thereby significantly reducing the sensitivity of the AMOC and carbon dioxide to winds[55,56]. This means that climate models overestimate the control winds have over the AMOC and carbon dioxide variability[57]; hence, Agulhas leakage and buoyancy fluxes may have a more important role than presently recognized.

Observed interactions with climate

Western boundary current systems support the highest air–sea fluxes in the world, and the Agulhas system is no exception. Latent and sensible heat fluxes increase three to five times over the SST fronts associated with the Agulhas Current, Retroflection and Return Current[58]. There is a clear impact on surface winds and clouds, with higher wind stress, a deeper marine–atmospheric boundary layer and convective clouds over the warmer waters[59,60]. As a result of enhanced atmospheric baroclinicity, the Agulhas system influences storm development, storm tracks and the regional atmospheric circulation[61,62]. It can also contribute to extreme rainfall events and tornadoes over southern Africa[63]. Increased rainfall events are correlated with warm anomalies in the Agulhas system associated with subtropical Indian Ocean Dipole and El Niño/Southern Oscillation cycles[64,65]. A 300-yr coral record suggests that overall warming of the Agulhas system since the 1970s may have increased the sensitivity of the African hydrological cycle to El Niño/Southern Oscillation[66].

Agulhas leakage may also be modulated by interannual modes of variability in the Indian and Pacific oceans. The Indian Ocean tropical and subtropical gyres shift in latitude and strengthen during a negative Indian Ocean Dipole phase (La Niña) and weaken during a positive phase (El Niño) through planetary-wave teleconnection processes[46,67], as observed in satellite data. These gyre changes strengthen or weaken the sources of the Agulhas Current, affecting the frequency of Mozambique Channel and EMC eddies (anticyclonic anomalies) that can propagate downstream into the retroflection, where they tend to trigger Agulhas rings[34,46]. Along the Agulhas Current, these anomalies manifest as strongly barotropic solitary meanders that propagate downstream with a mirrored cyclone on the inshore side[30,68–70] and destabilize the retroflection. In model simulations, the resulting fluctuations in Agulhas leakage cause decadal-scale variability in the AMOC[15].

Observations of interactions between the Agulhas system and climate over longer periods are based on palaeoceanographic records that currently span the past 570,000 yr (Fig. 4). Systematic changes in the abundance of planktonic foraminiferal species associated with modern-day Agulhas waters are recorded in marine sediment cores positioned along the Agulhas ring corridor and used as a proxy for leakage strength[17,71] (Agulhas fauna). Leakage events can be linked to glacial–interglacial cycles using oxygen isotope stratigraphy and to variations in deep-ocean ventilation using carbon isotope ratios and opal fluxes[12,17,72,73]. Variations in the ratio of subtropical to subpolar planktonic species taken from sites close to the modern-day STF can be used as a proxy for its latitudinal position in the past. Together, these palaeoproxies point to three conclusions: Agulhas leakage peaks at glacial terminations, changes in leakage are accompanied by latitudinal migrations of the STF by several degrees, and changes in leakage seem to be accompanied by changes in deep-ocean ventilation, suggesting that the AMOC strengthens during glacial–interglacial transitions[72,73]. Enhanced ventilation through Southern Ocean upwelling has also been correlated with the deglacial rise in concentrations of atmospheric carbon dioxide[73]. Importantly, peaks in Agulhas leakage appear during deglaciation, while ice volume is still substantial, suggesting that leakage may have had a role in triggering the associated resumption of the AMOC and the relatively rapid rise in carbon dioxide[17]. During the last deglaciation, the delay in and then abrupt warming of the North Atlantic (transition from Heinrich event 1 to the Bølling warm event) has been attributed to changes in the AMOC[74], and a high-resolution sediment core[19] supports model studies[13,14] that point to Agulhas leakage as the trigger. Furthermore, during two of the most severe glacials 340,000 and 420,000 yr ago (MISs 10 and 12), the STF seemed to have shifted northwards by about 7°, to reach its lowest latitude in the past 800,000 yr, and Agulhas fauna suggests that leakage was weaker than ever and possibly ceased[12] (Fig. 4). This implies that Agulhas leakage may have a role in modulating the severity of glacial periods through its influence on the AMOC[7,75].

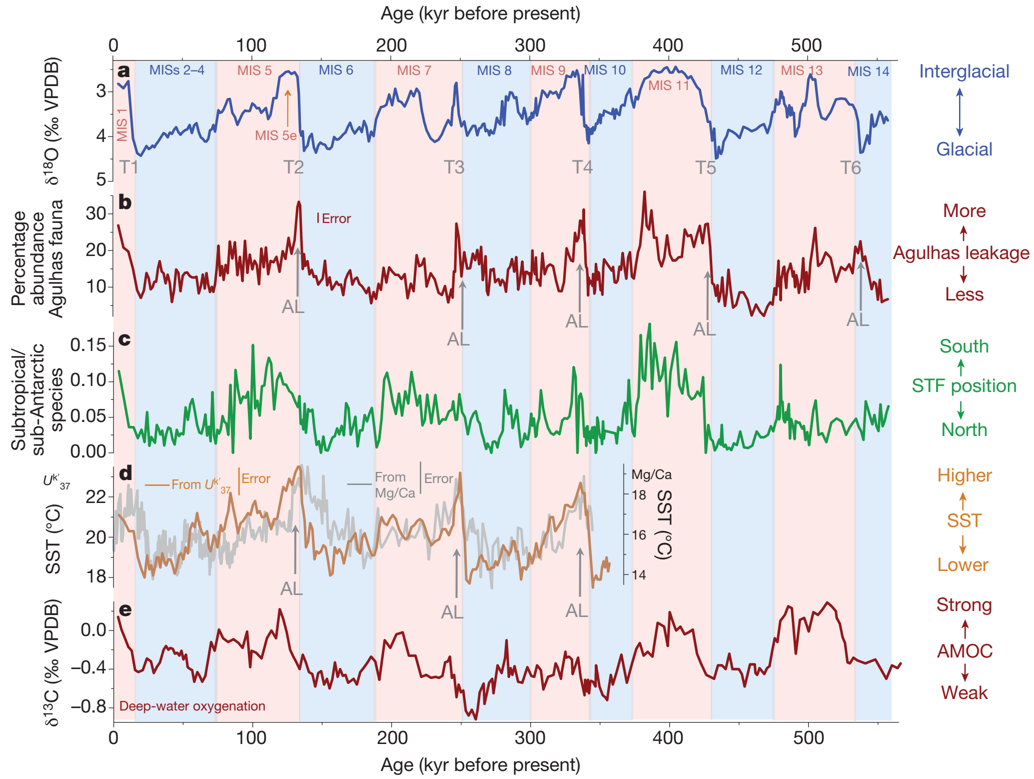

Figure 4 | Palaeoceanographic time series from the Agulhas leakage corridor spanning the last 570,000 yr. **a**, Stable oxygen isotope profile ($\delta^{18}O = (^{18}O/^{16}O)_{sample}/(^{18}O/^{16}O)_{VPDB} - 1$; Vienna PeeDee Belemnite (VPDB) standard) of benthic foraminifera from the CBR[17] represents a proxy for glacial–interglacial variations in global climate (highlighted by vertical blue/red shading). Marine Isotope Stages (MISs) are labelled. T1–T6 mark terminations of the past six glacial periods (MISs 2, 6, 8, 10, 12 and 14). **b**, Abundance of tropical planktonic foraminiferal marker species along the CBR[17] indicate maximum Agulhas leakage (AL) during glacial terminations T2–T6. Standard error (1.73%) is illustrated. **c**, Ratio of subtropical to sub-Antarctic planktonic marker species along the CBR[17], thought to be related to north–south migrations of the STF. **d**, SST derived from temperature-sensitive biomarkers ($U^{k'}_{37}$) produced by prymnesiophyceae algae along the CBR[17] (brown line), and Mg/Ca ratios in planktonic foraminifera from the ABS record[90] (grey line). Both reconstructions show maximum SST during glacial terminations, coinciding with Agulhas leakage events. SST reconstructions diverge during glacial periods, possibly corresponding to changes in seasonality. Error bars represent a combination of analytical and calibration errors. **e**, Record of benthic $\delta^{13}C$ ($(^{13}C/^{12}C)_{sample}/(^{13}C/^{12}C)_{VPDB} - 1$) from ODP Site 846 in the deep Pacific[94] is thought to be linked to ventilation of the deep Pacific[72], which is related to the strength of the AMOC. With this interpretation, AMOC strength seems to increase at each glacial termination, leading to the hypothesis that Agulhas leakage may stimulate the AMOC. All records are synchronized using standard oxygen isotope stratigraphy.

There is recent evidence pointing to a trend of increasing Agulhas leakage[9,10] concomitant with a polewards shift in the westerly winds over the past three decades, which is projected to continue over the twenty-first century under anthropogenic forcing[51,76]. This evidence is based on satellite data, far-field hydrographic data and hindcast simulations (ocean models with prescribed atmospheric forcing over the past 50 yr), because no modern *in situ* observations of Agulhas leakage exist. The Agulhas system seems to have been warming since the 1960s[10,20], and increased eddy kinetic energy in the southeast Atlantic, together with saltier water in the North Brazil Current and crossing the equator, is suggestive of increased leakage[9].

Facing uncertainties

We have seen that Agulhas leakage may have an important role in climate transitions, but it cannot act in isolation from other processes in the climate system. Models suggest that the AMOC also adjusts to the shifting of the Southern Hemisphere westerlies[50] and to Northern Hemisphere ice melt[14,77]. Southern Ocean sea-ice extent and carbon dioxide outgassing are further likely feedbacks[52,78]. The relative importance and timing of these effects, and the interactions among them, are largely unknown. Climate models tend to overestimate wind effects because of unresolved eddies[56,57], and to underestimate surface buoyancy fluxes as a result of parameterizations that suppress deep convection[48]. Moreover, most do not resolve the nonlinear dynamics that control Agulhas leakage (Box 1).

There is ongoing debate about the relative roles of surface buoyancy forcing and wind (and tide) forcing on the AMOC. From energy considerations, it has been argued that buoyancy fluxes have only some kind of organizational role[79,80] by setting water mass stratification, and that wind and tides drive the AMOC by providing the energy needed for the (irreversible, diapycnal) mixing that brings deep water back to the surface. The implication of this conceptual model is that Agulhas leakage is merely a passive respondent, and that AMOC changes are forced elsewhere by changing winds. However, a new study[48] shows that the rate at which energy is transferred within the system is more important than the quantity of available energy, and that the background stratification essentially dictates these rates. In other words, wind and tides represent the fuel of the system and stratification represents the efficiency, such that the rate at which mixing can redistribute mass is key, not the total amount of mixing per se. Hence, in a steady state, the redistribution of mass by surface buoyancy fluxes is balanced by the redistribution of mass by mechanical mixing. In this case, buoyancy fluxes are important and we might expect Agulhas leakage and wind changes to force a double response of the AMOC, as discussed earlier[13,50]. Each acts to strengthen the AMOC in a warming climate and weaken it in a cooling climate, which perhaps explains why the Southern Hemisphere leads in glacial–interglacial transitions. In contrast, Northern Hemisphere ice melt acts in the opposite sense, reducing the AMOC in response to warming. Overall, Southern Hemisphere forcing may dominate the glacial cycle, causing the AMOC to increase during deglaciation[14,72].

Simulations show that the strength and pathway of warm, saline Agulhas leakage through the South Atlantic profoundly affects the sensitivity of the AMOC to leakage changes. Like other subtropical gyres, the South Atlantic gyre has a poleward salt flux via the Brazil Current (reflecting an excess in evaporation over precipitation over the subtropics), but the superposed AMOC has an equatorward salt flux, representing Agulhas leakage waters at the surface and a return of fresher North Atlantic Deep Water below[4,81,82]. Several model studies demonstrate that the AMOC is bistable if it imports its own salt, because this 'salt–advection feedback' allows a collapsed AMOC (as well as an active one) as a stable state[83–85]—although there is no evidence for a completely collapsed AMOC in the palaeorecord[12]. In all these models, the South Atlantic gyre exports salt from the Atlantic basin and the overturning component of the circulation imports a little less salt, such that overall the Atlantic Ocean is evaporative, consistent with air–sea flux climatologies[86]. However, hydrographic data point to a small import of salt (AMOC dominant), inconsistent with an evaporative basin[81,82], whereas most IPCC climate models show AMOC salt export, inconsistent with both the oceanic data and salt–advection feedback[87]. These inconsistencies could represent a serious flaw in predictions of the AMOC response to changes in Agulhas leakage. Theoretically, in a monostable state, if the AMOC shuts down it will eventually recover because it is not stable in a collapsed state. In a bistable state, a shutdown can be permanent, leading us to an altogether different climate state. The lack of salt–advection feedback in IPCC models (and by inference an incorrect Agulhas leakage) could be the reason why these models do not show multiple stable states of the AMOC[87] and may render their predictive capabilities inadequate.

Wind-shift experiments in coarse-resolution climate models seem to suggest that the AMOC has an asymmetric response under present-day climate, such that a northward shift in the Southern Hemisphere westerlies decreases the AMOC by several sverdrups whereas a southward shift seems to have little effect[50]. An explanation could be that the larger Agulhas leakage for a southward wind shift mostly recirculates in the supergyre and does not force the AMOC in the model. The response of the AMOC to changes in leakage is profoundly shaped by the evolution of leakage waters, their associated density anomaly and whether they are transported northwards in the Atlantic[13,81]. It is important that both temperature and salinity anomalies (and their vertical distributions; Fig. 2) are simulated accurately, and with realistic air–sea fluxes, to correctly predict the sensitivity of the AMOC to leakage. For instance, introducing only surface salinity (a positive density anomaly) into the South Atlantic as a proxy for Agulhas leakage initially destabilizes the meridional pressure gradient and slows (or even halts) the AMOC, an effect not present when appropriate temperature–salinity anomalies are used[13,16,88]. For the same reasons, oceanic turbulent buoyancy fluxes initiated by eddy–eddy and eddy–mean flow interactions in the leakage region are important, as is the mean path of the leakage. So far, climate models do not accurately resolve the processes controlling leakage and its pathways into the supergyre and the AMOC.

The palaeorecord likewise has inconsistencies, such as the indication of an anomalous SST increase in the southeast Atlantic during one of the superglacials[89] (MIS 10), alluding to the advection of subtropical waters well into the sub-Antarctic zone during a period when Agulhas fauna suggests leakage was at a minimum. A core at the northern edge of the Agulhas ring corridor suggests that leakage may have increased much earlier than during glacial terminations[90]. Radiogenic isotopes that serve as a fingerprint in sea-floor sediments of overlying Agulhas water suggest that the position of the Agulhas Retroflection at the Last Glacial Maximum was the same as today[91]. Despite these inconsistencies in detail, the palaeorecord (Fig. 4) provides the strongest evidence yet for a connection between Agulhas leakage, the AMOC and changing climate.

Outlook

Many of the uncertainties in our current understanding of the linkages between the Agulhas system and climate can be addressed with carefully placed observations and well-designed numerical experiments. Observational programmes to capture long-term transport of the Agulhas Current and air–sea fluxes over the Agulhas Return Current began in 2010 (Fig. 3), and extensive hydrographic observations over the greater Agulhas system have been obtained over the past three years under the auspices of the Agulhas and Somali Current Large Marine Ecosystems Project. However, although there are annual hydrographic occupations across the Cape basin (French/Russian/South African GoodHope programme), direct continuous measurements of Agulhas leakage are very difficult because of its intermittent nature and variable location. Monitoring of the leakage embedded in the South Atlantic close to 25° S seems appropriate, as this is far enough north that difficult-to-capture eddy fluxes are small and the AMOC signal (and salt flux) may be clearer above a weaker gyre signal (weak Brazil Current). The international South Atlantic Meridional Overturning Circulation group is developing a proposal for a basin-wide AMOC array for the South Atlantic, similar to that at 26° N.

Long-term *in situ* observations of the Agulhas Current and its sources in the Mozambique Channel and EMC are underway through the US ACT and Dutch INATEX programmes (Fig. 3). In support of these observations, closer explorations of the link between Indian Ocean variability, Agulhas Current and Agulhas leakage under different simulated wind regimes are needed. Ongoing efforts to collect palaeoproxy data (European GATEWAYS Programme) aim to cover the trajectory of the Agulhas Current and its sources to be able to discern between local dynamical effects, large-scale wind effects and upstream variability (Fig. 3). Coral cores from the Dutch CLIMATCH and WIOMSA MASMA programmes will provide information about changes in upstream ocean temperature and the hydrological cycle on centennial timescales. A range of numerical simulations of (resolved) leakage under warming conditions (and shifting winds), also beginning with both glacial and interglacial climate conditions, could further help us understand the links among Agulhas Current, Agulhas leakage and the AMOC and its dependence on the background climate state.

Numerical experiments that explore the sensitivity of the AMOC to Agulhas leakage (with realistic temperature–salinity distributions) in the absence of Southern Hemisphere wind effects are also needed. This might be done by changing the easterly winds over the Indian Ocean or by prescribing leakage, although it is not clear how the latter might be achieved. High resolution over the Agulhas region is a necessity. In terms of palaeorecords, resolution on millennial timescales and higher is needed to examine the sequence of changes in warming, leakage, AMOC, atmospheric carbon dioxide and ice volume, to try to unravel cause and effect.

To identify potential drivers of climate change, we need to understand better the relative strengths and interactions between AMOC forcing in the Northern Hemisphere and that in the Southern Hemisphere. Current efforts largely concentrate on the North Atlantic as the presumed driver of the AMOC. It is time to take a more holistic approach and in particular consider the Southern Ocean and Agulhas leakage as potentially powerful modulators of the AMOC and climate.

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1. Gordon, A. L., Weiss, R. F., Smethie, W. M. & Warner, M. J. Thermocline and intermediate water communication between the South Atlantic and Indian Oceans. *J. Geophys. Res.* **97,** 7223–7240 (1992).
2. De Ruijter, W. P. M. *et al.* Indian-Atlantic inter-ocean exchange: dynamics, estimation, and impact. *J. Geophys. Res.* **104,** 20885–20910 (1999).
This work reviews the dynamics and variability of the Indian–Atlantic connection and sets the stage for further research into its wider impacts.
3. Lutjeharms, J. R. E. *The Agulhas Current* (Springer, 2006).
4. Donners, J. & Drijfhout, S. S. The Lagrangian view of South Atlantic interocean exchange in a global ocean model compared with inverse model results. *J. Phys. Oceanogr.* **34,** 1019–1035 (2004).
5. Van Aken, H. M. *et al.* Observations of a young Agulhas ring, Astrid, during MARE in March 2000. *Deep-Sea Res. II* **50,** 167–195 (2003).
6. Schouten, M. W., De Ruijter, W. P. M., van Leeuwen, P. J. & Lutjeharms, J. R. E. Translation, decay, and splitting of Agulhas Rings in the south-eastern Atlantic Ocean. *J. Geophys. Res.* **105,** 21913–21925 (2000).

7. Boebel, O. *et al.* The Cape Cauldron, a regime of turbulent inter-ocean exchange. *Deep-Sea Res. II* **50,** 57–86 (2003).
This work describes the mesoscale turbulent regime in the Cape basin for the first time, where important eddy mixing and air–sea interaction transform Agulhas leakage waters into those that take part in the AMOC.
8. De Ruijter, W. P. M. Asymptotic analysis of the Agulhas and Brazil current systems. *J. Phys. Oceanogr.* **12,** 361–373 (1982).
9. Biastoch, A., Böning, C. W., Lutjeharms, J. R. E. & Schwarzkopf, F. U. Increase in Agulhas leakage due to pole-ward shift of the Southern Hemisphere westerlies. *Nature* **462,** 495–498 (2009).
This was the first global hindcast simulation, with an eddy-resolving Agulhas nest, to show that Agulhas leakage is likely to have increased under anthropogenic forcing.
10. Rouault, M., Penven, P. & Pohl, B. Warming in the Agulhas Current system since the 1980's. *Geophys. Res. Lett.* **36,** L12602 (2009).
In this work, satellite observations and a regional model are used to show that the Agulhas system has been warming, consistent with increased Agulhas Current transport.
11. Berger, W. H. & Wefer, G. in *The South Atlantic: Present and Past Circulation* (eds Wefer, G., Berger, W. H. & Webb, D. J.) 363–410 (Springer, 1996).
12. Bard, E. & Rickaby, R. E. M. Migration of the subtropical front as a modulator of glacial climate. *Nature* **460,** 380–383 (2009).
13. Weijer, W., De Ruijter, W. P. M., Sterl, A. & Drijfhout, S. S. Response of the Atlantic overturning circulation to South Atlantic sources of buoyancy. *Global Planet. Change* **34,** 293–311 (2002).
This work is the only rigorous exploration of the effect of Agulhas waters on the stability of the AMOC (in the absence of changed wind forcing).
14. Knorr, G. & Lohmann, G. Southern Ocean origin for the resumption of Atlantic thermohaline circulation during deglaciation. *Nature* **424,** 532–536 (2003).
Using an ocean model, the authors of this work find that abrupt resumption of the interglacial AMOC mode is triggered by increased mass transport from the Pacific and Indian (Agulhas leakage) oceans into the South Atlantic.
15. Biastoch, A., Böning, C. W. & Lutjeharms, J. R. E. Agulhas Leakage dynamics affects decadal variability in Atlantic overturning circulation. *Nature* **456,** 489–492 (2008).
16. Weijer, W., De Ruijter, W. P. M. & Dijkstra, H. A. Stability of the Atlantic overturning circulation: competition between Bering Strait freshwater flux and Agulhas heat and salt sources. *J. Phys. Oceanogr.* **31,** 2385–2402 (2001).
17. Peeters, F. J. C. *et al.* Vigorous exchange between the Indian and Atlantic oceans at the end of the past five glacial periods. *Nature* **430,** 661–665 (2004).
This work links glacial terminations with increased Agulhas leakage using an assemblage of subtropical foraminifera to trace changes in leakage over the past 550,000 yr.
18. Flores, J. A., Gersonde, R. & Sierro, F. J. Pleistocene fluctuations in the Agulhas Current Retroflection based on the calcareous plankton record. *Mar. Micropaleontol.* **37,** 1–22 (1999).
19. Chiessi, C. M. *et al.* South Atlantic interocean exchange as the trigger for the Bølling warm event. *Geology* **36,** 919–922 (2008).
20. Alory, G., Wijffels, S. & Meyers, G. Observed temperature trends in the Indian Ocean over 1960–1999 and associated mechanisms. *Geophys. Res. Lett.* **34,** L02606 (2007).
21. Gregory, J. M. *et al.* A model intercomparison of changes in the Atlantic thermohaline circulation in response to increasing atmospheric CO_2 concentration. *Geophys. Res. Lett.* **32,** L12703 (2005).
22. Stammer, D. Response of the global ocean to Greenland and Antarctic ice melting. *J. Geophys. Res.* **113,** C06022 (2008).
23. Gordon, A. L. The brawniest retroflection. *Nature* **421,** 904–905 (2003).
24. Song, Q., Gordon, A. L. & Visbeck, M. Spreading of the Indonesian Throughflow in the Indian Ocean. *J. Phys. Oceanogr.* **34,** 772–792 (2004).
25. Beal, L. M., Chereskin, T. K., Lenn, Y. D. & Elipot, S. The sources and mixing characteristics of the Agulhas Current. *J. Phys. Oceanogr.* **36,** 2060–2074 (2006).
26. Ridderinkhof, H. *et al.* Seasonal and interannual variability in the Mozambique Channel from moored current observations. *J. Geophys. Res.* **115,** C06010 (2010).
27. Swallow, J., Fieux, M. & Schott, F. The boundary currents east and north of Madagascar 1: geostrophic currents and transports. *J. Geophys. Res.* **93,** 4951–4962 (1988).
28. Donohue, K. A. & Toole, J. M. A near-synoptic survey of the Southwest Indian Ocean. *Deep-Sea Res. II* **50,** 1893–1931 (2003).
29. Nauw, J. J., van Aken, H. M., Webb, A., Lutjeharms, J. R. E. & De Ruijter, W. P. M. Observations of the southern East Madagascar Current and undercurrent and countercurrent system. *J. Geophys. Res.* **113,** C08006 (2008).
30. Bryden, H. L., Beal, L. M. & Duncan, L. M. Structure and transport of the Agulhas Current and its temporal variability. *J. Oceanogr.* **61,** 479–492 (2005).
In this work, the first time series of Agulhas Current transport finds a dominant meander mode at 50–70 d.
31. Richardson, P. L. Agulhas Leakage into the Atlantic estimated with subsurface floats and surface drifters. *Deep-Sea Res. I* **54,** 1361–1389 (2007).
32. Lutjeharms, J. R. E. Remote sensing corroboration of retroflection of the East Madagascar Current. *Deep-Sea Res. I* **35,** 2045–2050 (1988).
33. Quartly, G. D. & Srokosz, M. A. SST observations of the Agulhas and East Madagascar retroflections by the TRMM microwave imager. *J. Phys. Oceanogr.* **32,** 1585–1592 (2002).
34. De Ruijter, W. P. M. *et al.* Eddies and dipoles around South Madagascar: formation, pathways and large-scale impact. *Deep-Sea Res. I* **51,** 383–400 (2004).
This work shows that both anticyclones and cyclones are commonly shed around Madagascar and propagate into the Agulhas system.
35. Quartly, G. D., Buck, J. J. H., Srokosz, M. A. & Coward, A. C. Eddies around Madagascar: the retroflection reconsidered. *J. Mar. Syst.* **63,** 115–129 (2006).
36. Siedler, G. *et al.* Modes of the southern extension of the East Madagascar Current. *J. Geophys. Res.* **114,** C01005 (2009).
37. Palastanga, V., van Leeuwen, P. J., Schouten, M. W. & De Ruijter, W. P. M. Flow structure and variability in the subtropical Indian Ocean: instability of the South Indian Ocean Countercurrent. *J. Geophys. Res.* **112,** C01001 (2007).
38. Ridgway, K. R. & Dunn, J. R. Observational evidence for a Southern Hemisphere oceanic supergyre. *Geophys. Res. Lett.* **34,** L13612 (2007).
This work reports observation of the Atlantic/Indo-Pacific supergyre in which a large proportion of Agulhas leakage takes part.
39. Palastanga, V., Dijkstra, H. A. & De Ruijter, W. P. M. Inertially induced connections between subgyres in the South Indian Ocean. *J. Phys. Oceanogr.* **39,** 465–471 (2009).
40. Speich, S., Blanke, B. & Cai, W. Atlantic meridional overturning circulation and the Southern Hemisphere supergyre. *Geophys. Res. Lett.* **34,** L23614 (2007).
41. Gordon, A. L. Interocean exchange of thermocline water. *J. Geophys. Res.* **91,** 5037–5046 (1986).
42. Rintoul, S. R. South Atlantic interbasin exchange. *J. Geophys. Res.* **96,** 2675–2692 (1991).
43. Sloyan, B. M. & Rintoul, S. R. The Southern Ocean limb of the global deep overturning circulation. *J. Phys. Oceanogr.* **31,** 143–173 (2001).
44. Van Sebille, E. & van Leeuwen, P. J. Fast northward energy transfer in the Atlantic due to Agulhas Rings. *J. Phys. Oceanogr.* **37,** 2305–2315 (2007).
45. Cunningham, S. A. *et al.* Temporal variability of the Atlantic meridional overturning circulation at 26.5° N. *Science* **317,** 935–938 (2007).
46. Schouten, M. W., De Ruijter, W. P. M. & Van Leeuwen, P. J. Upstream control of Agulhas ring shedding. *J. Geophys. Res.* **107,** 3109 (2002).
This work is an observational study (satellite altimetry data) showing remote control of Agulhas ring formation by eddies from the Mozambique Channel and EMC, which in turn are triggered by westwards-propagating Rossby waves along 10° S and 24° S. Interannual modulations seem to be connected to the Indian Ocean Dipole.
47. Haarsma, R. J., Campos, E. J. D., Drijfhout, S., Hazeleger, W. & Severijns, C. Impacts of interruption of the Agulhas Leakage on the tropical Atlantic in coupled ocean-atmosphere simulations. *Clim. Dyn.* **36,** 989–1003 (2009).
48. Hughes, G. O., Hogg, A., McC. & Griffiths, R. W. Available potential energy and irreversible mixing in the meridional overturning circulation. *J. Phys. Oceanogr.* **39,** 3130–3146 (2009).
49. Toggweiler, J. R. & Samuels, B. Effect of Drake Passage on the global thermohaline circulation. *Deep-Sea Res. I* **42,** 477–500 (1995).
50. Sijp W. P. & England, M. H. Southern hemisphere westerly wind control over the ocean's thermohaline circulation. *J. Clim.* **22,** 1277–1286 (2009).
51. Sen Gupta, A. *et al.* Projected changes to the Southern Hemisphere ocean and sea-ice in the IPCC AR4 climate models. *J. Clim.* **22,** 3047–3078 (2009).
52. Toggweiler, J. R., Russell, J. L. & Carson, S. R. Midlatitude westerlies, atmospheric CO_2, and climate change during the ice ages. *Paleoceanography* **21,** PA2005 (2006).
53. Watson, A. J. & Naviera Garabato, A. C. The role of Southern Ocean mixing and upwelling in glacial-interglacial atmospheric CO_2 change. *Tellus* **58B,** 73–87 (2006).
54. Tschumi, T., Joos, F. & Parekh, P. How important are Southern Hemisphere wind changes for low glacial carbon dioxide? A model study. *Paleoceanography* **23,** PA4208 (2008).
55. Speer, K., Rintoul, S. R. & Sloyan, B. The diabatic deacon cell. *J. Phys. Oceanogr.* **30,** 3212–3222 (2000).
56. Naviera Garabato, A. C., Stevens, D. P., Watson, A. J. & Roether, W. Short-circuiting of the overturning circulation in the Antarctic Circumpolar Current. *Nature* **447,** 194–197 (2007).
57. Farneti, R. & Delworth, T. L. The role of mesoscale eddies in the remote oceanic response to altered Southern Hemisphere winds. *J. Phys. Oceanogr.* **40,** 2348–2354 (2010).
58. Jury, M. & Walker, N. Marine boundary layer modification across the edge of the Agulhas Current. *J. Geophys. Res.* **93,** 647–654 (1988).
59. Rouault, M., Lee-Thorp, A. M. & Lutjeharms, J. R. E. The atmospheric boundary layer above the Agulhas Current during along-current winds. *J. Phys. Oceanogr.* **30,** 40–50 (2000).
60. Liu, W. T., Xie, X. & Niiler, P. P. Ocean–atmosphere interaction over Agulhas Extension meanders. *J. Clim.* **20,** 5784–5797 (2007).
61. Reason, C. J. C. Evidence for the influence of the Agulhas Current on REGIONAL atmospheric circulation patterns. *J. Clim.* **14,** 2769–2778 (2001).
62. Nakamura, H. & Shimpo, A. Seasonal variations in the Southern Hemisphere storm tracks and jet streams as revealed in reanalysis datasets. *J. Clim.* **17,** 1828–1844 (2004).
63. Rouault, M., White, S. A., Reason, C. J. C., Lutjeharms, J. R. E. & Jobard, I. Ocean-atmosphere interaction in the Agulhas Current region and a South African extreme weather event. *Weather Forecast.* **17,** 655–669 (2002).
64. Behera, S. K. & Yamagata, T. Subtropical SST dipole events in the southern Indian Ocean. *Geophys. Res. Lett.* **28,** 327–330 (2001).
65. Hermes, J. C. & Reason, C. J. C. Ocean model diagnosis of interannual coevolving SST variability in the South Indian and South Atlantic oceans. *J. Clim.* **18,** 2864–2882 (2005).
66. Zinke, J., Dullo, W.-C., Heiss, G. A. & Eisenhauer, A. ENSO and Indian Ocean subtropical dipole variability is recorded in a coral record off southwest Madagascar for the period 1659 to 1995. *Earth Planet. Sci. Lett.* **228,** 177–194 (2004).

67. Palastanga, V., van Leeuwen, P. J. & De Ruijter, W. P. M. A link between low-frequency mesoscale eddy variability around Madagascar and the large-scale Indian Ocean variability. *J. Geophys. Res.* **111,** C09029 (2006).
68. Beal, L. M. A time series of Agulhas Undercurrent transport. *J. Phys. Oceanogr.* **39,** 2436–2450 (2009).
69. Biastoch, A., Beal, L. M., Casal, T. G. D. & Lutjeharms, J. R. E. Variability and coherence of the Agulhas Undercurrent in a high-resolution ocean general circulation model. *J. Phys. Oceanogr.* **39,** 2417–2435 (2009).
70. Tsugawa, M. & Hasumi, H. Generation and growth mechanism of a Natal Pulse. *J. Phys. Oceanogr.* **40,** 1597–1612 (2010).
71. Rau, A. J., Rogers, J. & Chen, M.-T. Late Quaternary palaeoceanographic record in giant piston cores off South Africa, possibly including evidence of neotectonism. *Quaternary Int.* **148,** 65–77 (2006).
72. Lisiecki, L. E., Raymo, M. E. & Curry, W. B. Atlantic overturning responses to Late Pleistocene climate forcings. *Nature* **456,** 85–88 (2008).
73. Anderson, R. F. *et al.* Wind-driven upwelling in the Southern Ocean and the deglacial rise in atmospheric CO_2. *Science* **323,** 1443–1448 (2009).
74. Thornalley, D. J. R., Elderfield, H. & McCave, N. Reconstructing North Atlantic deglacial surface hydrography and its link to the Atlantic overturning circulation. *Global Planet. Change.* (in the press).
75. Zahn, R. Beyond the CO_2 connection. *Nature* **460,** 335–336 (2009).
76. Cai, W. Antarctic ozone depletion causes an intensification of the Southern Ocean super-gyre circulation. *Geophys. Res. Lett.* **33,** L03712 (2006).
77. Vellinga, M. & Wood, R. A. Global climatic impacts of a collapse of the Atlantic thermohaline circulation. *Clim. Change* **54,** 251–267 (2005).
78. Stephens, B. B. & Keeling, R. F. The influence of Antarctic sea ice on glacial-interglacial CO_2 variations. *Nature* **404,** 171–174 (2000).
79. Wunsch, C. & Ferrari, R. Vertical mixing, energy, and the general circulation of the oceans. *Annu. Rev. Fluid Mech.* **36,** 281–314 (2004).
80. Kuhlbrodt, T. *et al.* On the driving processes of the Atlantic meridional overturning circulation. *Rev. Geophys.* **45,** RG2001 (2007).
81. Weijer, W., De Ruijter, W. P. M., Dijkstra, H. A. & van Leeuwen, P. J. Impact of interbasin exchange on the Atlantic overturning circulation. *J. Phys. Oceanogr.* **29,** 2266–2284 (1999).
82. McDonagh, E. L. & King, B. A. Oceanic fluxes in the South Atlantic. *J. Phys. Oceanogr.* **35,** 109–122 (2005).
83. Rahmstorf, S. On the freshwater forcing and transport of the Atlantic thermohaline circulation. *Clim. Dyn.* **12,** 799–811 (1996).
84. DeVries, P. & Weber, S. L. The Atlantic freshwater budget as a diagnostic for the existence of a stable shut down of the meridional overturning circulation. *Geophys. Res. Lett.* **32,** L09606 (2005).
85. Dijkstra, H. A. Characterization of the multiple equilibria regime in a global ocean model. *Tellus* **59A,** 695–705 (2007).
86. Romanova, V., Kohl, A., Stammer, D., Klepp, C. & Andersson, A. Sea surface freshwater flux estimates from GECCO, HOAPS and NCEP. *Tellus* **62,** 435–452 (2010).
87. Huisman, S. E., den Toom, M., Dijkstra, H. A. & Drijfhout, S. An indicator of the multiple equilibria regime of the Atlantic meridional overturning circulation. *J. Phys. Oceanogr.* **40,** 551–567 (2010).
88. Marsh, R., Hazeleger, W., Yool, A. & Rohling, E. J. Stability of the thermohaline circulation under millennial CO_2 forcing and two alternative controls on Atlantic salinity. *Geophys. Res. Lett.* **34,** L03605 (2007).
89. Cortese, G. & Abelmann, A. Radiolarian-based paleotemperatures during the last 160 kyr at ODP Site 1089 (Southern Ocean, Atlantic Sector). *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **182,** 259–286 (2002).
90. Martinez-Mendez, G. *et al.* Contrasting multi-proxy reconstructions of surface ocean hydrography in the Agulhas Corridor and implications for the Agulhas Leakage during the last 345,000 years. *Paleoceanography* **25,** PA4227 (2010).
91. Franzese, A. M., Hemming, S. R. & Goldstein, S. L. Use of strontium isotopes in detrital sediments to constrain the glacial position of the Agulhas Retroflection. *Paleoceanography* **24,** PA2217 (2009).
92. Large, W. G. & Yeager, S. G. *Diurnal to Decadal Global Forcing for Ocean and Sea-Ice Models: The Data Sets and Flux Climatologies*. NCAR Tech. Note NCAR/TN-460+STR (NCAR, 2004).
93. Donlon, C. *et al.* The global ocean data assimilation experiment high-resolution sea surface temperature pilot project. *Bull. Am Meteorol. Soc.* **88,** 1197–1213 (2007).
94. Mix, A. C., Le, J. & Shackleton, N. J. Benthic foraminiferal stable isotope stratigraphy of Site 846: 0–1.8 Ma. *Proc. ODP Sci. Results* **138,** 839–854 (1995).
95. Speich, S., Lutjeharms, J. R. E., Penven, P. & Blanke, B. Role of bathymetry in Agulhas Current configuration and behaviour. *Geophys. Res. Lett.* **33,** L23611 (2006).
96. Zharkov, V. & Nof, D. Retroflection from slanted coastlines – circumventing the "vorticity paradox". *Ocean Sci. Discuss.* **4,** 293–306 (2008).
97. Dijkstra, H. A. & de Ruijter, W. P. M. On the physics of the Agulhas Current: steady retroflection regimes. *J. Phys. Oceanogr.* **31,** 2971–2985 (2001).
98. Van Sebille, E., Biastoch, A., van Leeuwen, P. J. & De Ruijter, W. P. M. A weaker Agulhas Current leads to more Agulhas Leakage. *Geophys. Res. Lett.* **36,** L03601 (2009).
99. Rojas, M. *et al.* The Southern Westerlies during the last glacial maximum in PMIP2 simulations. *Clim. Dyn.* **32,** 525–548 (2009).
100. Banks, H. T., Stark, S. & Keen, A. B. The adjustment of the coupled climate model HadGEM1 toward equilibrium and the impact on global climate. *J. Clim.* **20,** 5815–5826 (2007).

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Meghan Cronin[1], Juliet Hermes[2], Johann Lutjeharms[3], Graham Quartly[4], Tomoki Tozuka[5], Sheekela Baker-Yeboah[6], Thomas Bornman[7], Paolo Cipollini[4], Henk Dijkstra[8], Ian Hall[9], Wonsun Park[10], Frank Peeters[11], Pierrick Penven[12], Herman Ridderinkhof[13] & Jens Zinke[13]

[1]NOAA Pacific Marine Environmental Laboratory, 7600 Sand Point Way NE, Seattle, Washington 98115, USA. [2]South African Environmental Observation Network, Private Bag X2, Roggebaai 8012, South Africa. [3]Department of Oceanography, University of Cape Town, 7700 Rondebosch, South Africa. [4]National Oceanography Centre, Southampton, European Way, Southampton SO14 3ZH, UK. [5]Department of Earth and Planetary Science, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan. [6]Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, Massachusetts 02139, USA. [7]South African Institute for Aquatic Biodiversity, Private Bag 1015, Grahamstown 6140, South Africa. [8]Institute for Marine and Atmospheric Research, Utrecht University, Princetonplein 5, 3584 CC Utrecht, The Netherlands. [9]School of Earth and Ocean Sciences, Cardiff University, Park Place, Cardiff CF10 3AT, UK. [10]Leibniz-Institut für Meereswissenschaften (IFM-GEOMAR), Düsternbrooker Weg 20, 24105 Kiel, Germany. [11]Faculty of Earth and Life Sciences, Section Marine Biogeology, Vrije Universiteit Amsterdam, De Boelelaan 1085, 1081 HV Amsterdam, The Netherlands. [12]Laboratoire de Physique des Oceans (UMR 6523 CNRS, IFREMER, IRD, UBO), LMI ICEMASA, Department of Oceanography, University of Cape Town, Cape Town, 7700 Rondebosch, South Africa. [13]NIOZ Royal Netherlands Institute for Sea Research, PO Box 59, 1790 AB Den Burg, The Netherlands.