

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

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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 time-scales^{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},

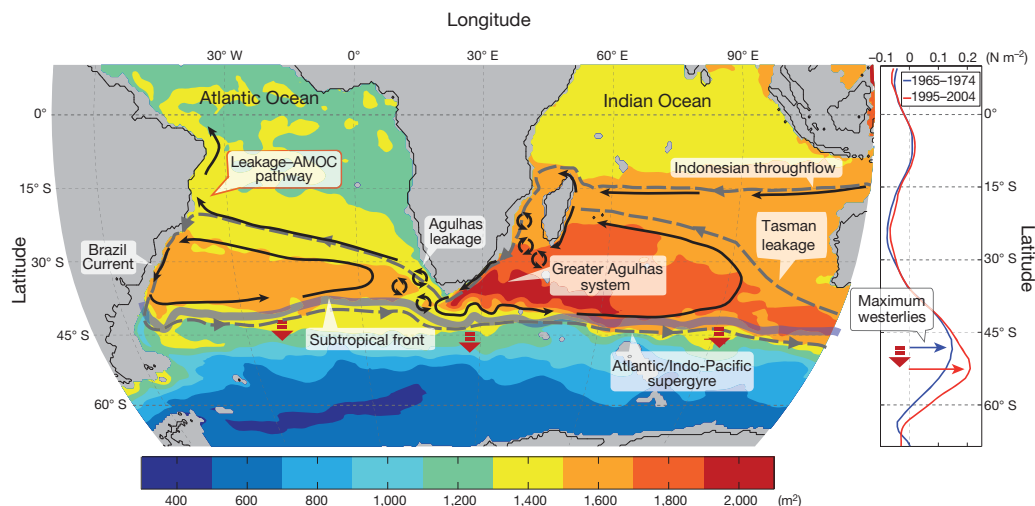


Figure 1 | Agulhas leakage affected by westerly winds and position of subtropical front. Schematic of the greater Agulhas system embedded in the Southern Hemisphere supergyre. Background colours show the mean subtropical gyre circulation, depicted by climatological dynamic height integrated between the surface and 2,000 dbar, from the CARS database³⁸. 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 stress⁹² 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.

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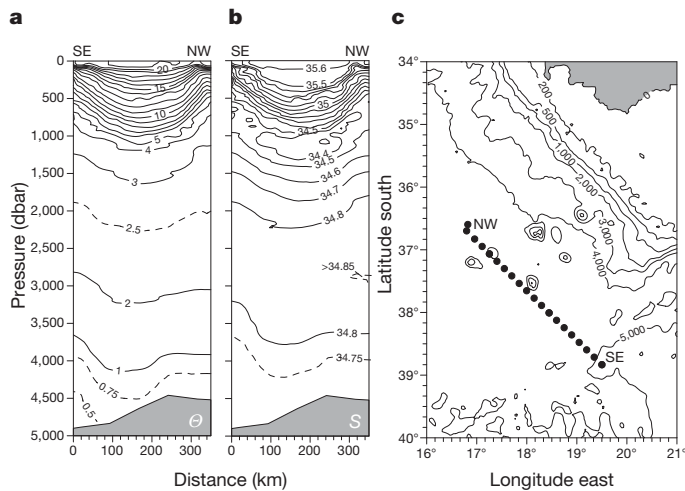


Figure 2 | Warm, saline Agulhas waters influence temperature and salinity in the Atlantic over the full depth of the water column. a, b, Vertical sections of the potential temperature (θ ; a) and salinity (S; b) of Agulhas ring Astrid, measured in the Cape basin off South Africa, March 2000⁵. Agulhas 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.

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 records¹⁷. 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 position¹⁸. 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 gyre²⁰ and a warming trend in the Agulhas system since the 1960s¹⁰, 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 leakage¹⁰. 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} ($1 \text{ Sv} = 1 \times 10^6 \text{ m}^3 \text{ s}^{-1}$), which could lead to a significant strengthening of the AMOC¹³. 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

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 supergyre⁸. 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 retroflexion 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 climate⁹⁹) 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 retroflexion 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 wrong¹⁰⁰. 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}.

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 westerlies³. 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 anti-clockwise south of Africa and feeding back into the Indian Ocean as the eastward Agulhas Return Current (Box 1). This loop, known as the

Agulhas Retroflection²³, 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 Ocean²⁶. 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 EMC³⁶, 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 dynamically⁸, 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 dominates⁴³, although some previous hydrographic studies concluded otherwise⁴¹. A careful model-data reanalysis⁴ 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

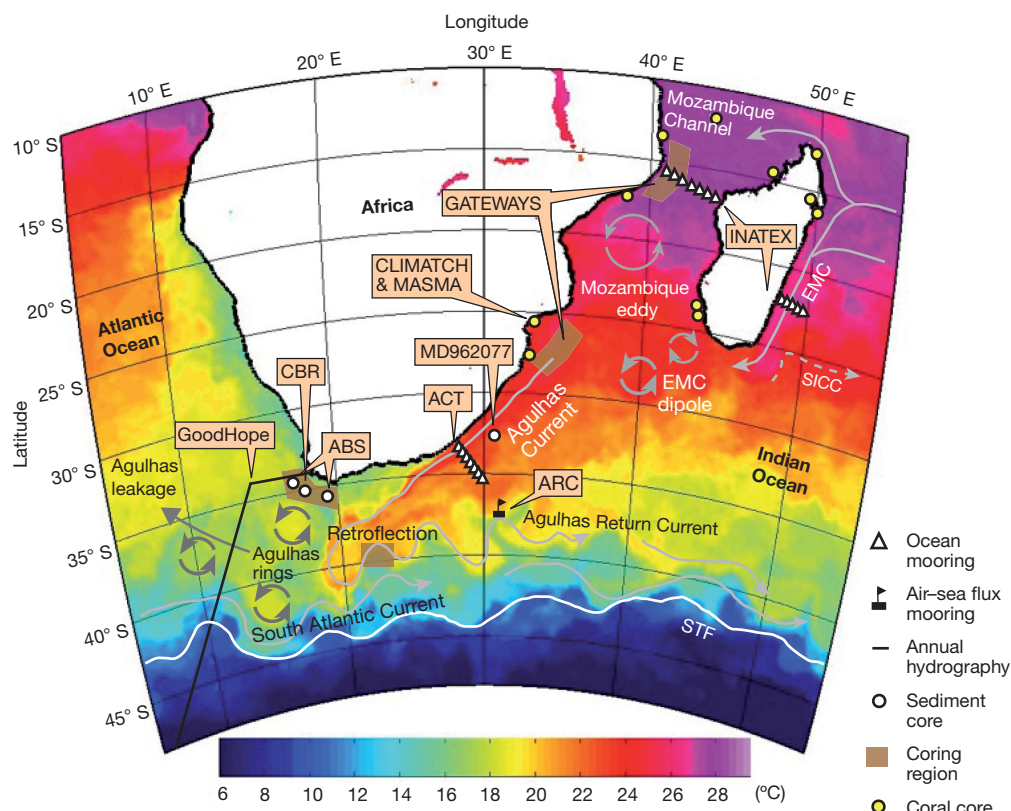


Figure 3 | Agulhas leakage advects warm, saline waters into the Atlantic, predominantly through Agulhas rings. Sea surface temperature (SST) for 23 May 2009, showing water at 23–25 °C in the Agulhas Current and Retroflection. North–south migrations of the STF (related to wind curl changes) and/or the 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 programmes 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 record¹⁷ (CBR), MD962077¹² and Agulhas Bank splice⁹⁰ (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 GHRSSST project⁹³. 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 instance⁴⁵, but are also integrated into interannual-to-decadal oscillations in the AMOC¹⁵, 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 AMOC¹³; 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 effect⁴⁹). 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 dioxide⁵⁴. 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 variability⁵⁷; 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, Retroflexion and Return Current⁵⁸. 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 Africa⁶³. 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 Oscillation⁶⁶.

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 retroflexion, 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 retroflexion. In model simulations, the resulting fluctuations in Agulhas leakage cause decadal-scale variability in the AMOC¹⁵.

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 dioxide⁷³. 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 dioxide¹⁷. During the last deglaciation, the delay in and then abrupt warming of the North Atlantic (transition from Heinrich event 1 to the Bolling warm event) has been attributed to changes in the AMOC⁷⁴, and a high-resolution sediment core¹⁹ 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 ceased¹² (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}.

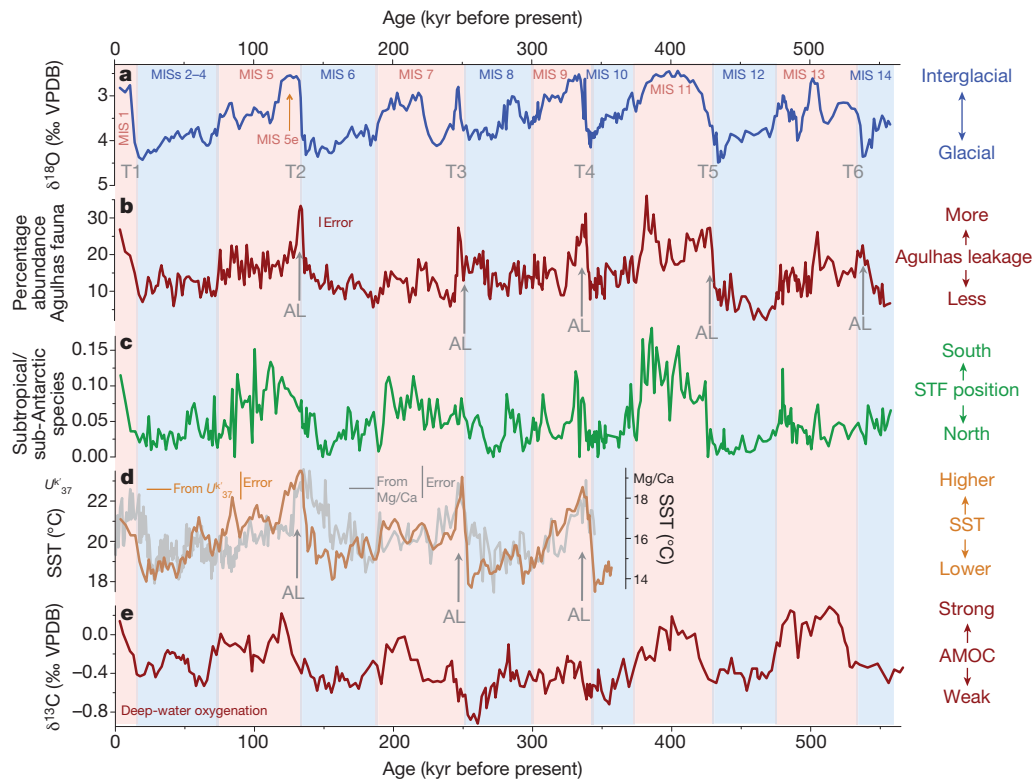


Figure 4 | Palaeoceanographic time series from the Agulhas leakage corridor spanning the last 570,000 yr. **a**, Stable oxygen isotope profile ($\delta^{18}\text{O} = (^{18}\text{O}/^{16}\text{O})_{\text{sample}} / (^{18}\text{O}/^{16}\text{O})_{\text{VPDB}} - 1$; Vienna PeeDee Belemnite (VPDB) standard) of benthic foraminifera from the CBR¹⁷ 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 CBR¹⁷ 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 CBR¹⁷, thought to be related to north–south migrations of the STF. **d**, SST derived from temperature-sensitive

biomarkers (U_{37}^k) produced by prymnesiophyceae algae along the CBR¹⁷ (brown line), and Mg/Ca ratios in planktonic foraminifera from the ABS record⁹⁰ (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 $\delta^{13}\text{C}$ ($(^{13}\text{C}/^{12}\text{C})_{\text{sample}} / (^{13}\text{C}/^{12}\text{C})_{\text{VPDB}} - 1$) from ODP Site 846 in the deep Pacific⁹⁴ is thought to be linked to ventilation of the deep Pacific⁷², 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 leakage⁹.

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 westerlies⁵⁰ 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 convection⁴⁸. 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 study⁴⁸ 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 palaeorecord¹². 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 climatologies⁸⁶. 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 feedback⁸⁷. 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 AMOC⁸⁷ 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 effect⁵⁰. 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 superglacials⁸⁹ (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 terminations⁹⁰. Radiogenic isotopes that serve as a fingerprint in sea-floor sediments of overlying Agulhas water suggest that the position of the Agulhas Retroflexion at the Last Glacial Maximum was the same as today⁹¹. 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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