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LETTERS

Agulhas leakage dynamics affects decadal variability in Atlantic overturning circulation

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Predicting the evolution of climate over decadal timescales requires a quantitative understanding of the dynamics that govern the meridional overturning circulation (MOC)[1]. Comprehensive ocean measurement programmes aiming to monitor MOC variations have been established in the subtropical North Atlantic[2,3] (RAPID, at latitude 26.5° N, and MOVE, at latitude 16° N) and show strong variability on intraseasonal to interannual timescales. Observational evidence of longer-term changes in MOC transport remains scarce, owing to infrequent sampling of transoceanic sections over past decades[4,5]. Inferences based on long-term sea surface temperature records, however, supported by model simulations, suggest a variability with an amplitude of ±1.5–3 Sv ($1\,Sv = 10^6\,m^3\,s^{-1}$) on decadal timescales in the subtropics[6]. Such variability has been attributed to variations of deep water formation in the sub-arctic Atlantic, particularly the renewal rate of Labrador Sea Water[7]. Here we present results from a model simulation that suggest an additional influence on decadal MOC variability having a Southern Hemisphere origin: dynamic signals originating in the Agulhas leakage region at the southern tip of Africa. These contribute a MOC signal in the tropical and subtropical North Atlantic that is of the same order of magnitude as the northern source. A complete rationalization of observed MOC changes therefore also requires consideration of signals arriving from the south.

The Agulhas leakage around South Africa[8] is the main source of the warm and salty waters carried towards the subpolar North Atlantic as the upper limb of the MOC. The Agulhas leakage region is characterized by vigorous variability on intraseasonal to interannual timescales[9] shedding the largest mesoscale eddies in the world ocean[10], which are the dominating vehicles transporting and releasing the Indian Ocean waters into the Atlantic[11]. Observational palaeoclimate studies have suggested a broken inter-ocean exchange on centurial to millennial timescales[12], and ocean climate model studies[13,14] have elucidated the potential of the inter-ocean exchange of heat and salt to alter the long-term MOC response. However, large uncertainties in those studies remain, owing to unresolved mesoscale processes[15] that govern the dynamics and strength of the Agulhas leakage[16]; the present study focuses on those effects on decadal timescales.

The methodology used here is to assess the effect of mesoscale processes in the Agulhas leakage by adopting a two-way nesting scheme that selectively increases the grid resolution in the region of interest in a global model simulation. More specifically, we use the following approach. We start with a global ocean/sea-ice model with a nominal grid resolution of 0.5° (ORCA05) that reasonably resolves western boundary current structures and captures the different processes of deep-water formation due to the thermohaline and wind forcing, but that does not resolve mesoscale processes. ORCA05 has been demonstrated[17] to capture the decadal MOC variability (Fig. 1) simulated in more highly resolved, eddying models; it thus serves as a meaningful basis for the present study. In a second configuration (AG01), we selectively refine the resolution (to 0.1°) of the Agulhas region in this model by adopting a 'two-way nesting' scheme (Fig. 2a). The high-resolution nest provides a realistic simulation of the mesoscale dynamics of the Agulhas retroflection (Fig. 2b, c), including the upstream perturbations originating in the source regions of the Agulhas current[15] that control the frequency of the inter-ocean exchange[16]. The effect of these processes is fed back to the global model[16,18], allowing the global circulation to respond to the mesoscale dynamics introduced by this limited region. Comparison of the two model simulations, one with an Agulhas nest (AG01) and one without (ORCA05), thus provides us with an effective means of identifying the impact of the mesoscale Agulhas dynamics on the basin-scale MOC. The alternative, that is, analysis of a globally eddying model[19], would provide a comprehensive hindcast of MOC variability, but would not allow us to discriminate effects due to the mesoscale processes of an individual region (the Agulhas leakage region in this case) from those arising in other areas. In addition, local variability[17] would further complicate the interpretation.

Although the introduction of the high-resolution Agulhas nest has little effect on the time-mean MOC transport (differences are less than 1 Sv; Supplementary Fig. 2), despite the large difference in the mean inter-oceanic transport from the Indian Ocean to the Atlantic with realistic[11] transport of 12 Sv in AG01 and an over-estimation of 21.5 Sv in ORCA05[16], there is a marked difference in the MOC variability (Fig. 3): an isolation of the MOC variability induced by the mesoscale fluctuations in the Agulhas (that is, the 'Agulhas-induced MOC anomalies' found by comparing the experiments with and

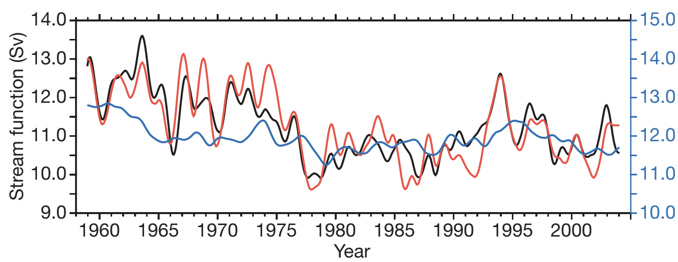

Figure 1 | Strength of the interhemispheric transport in the Atlantic Ocean. Shown is the low-pass-filtered (23-month Hanning filter) maximum stream function value of the North Atlantic Deep Water cell in the global coarse-resolution model without (ORCA05, black) and with (AG01, red) a high-resolution Agulhas nest (left-hand scale). The blue curve (right-hand scale (Sv)) shows a sensitivity experiment with the global coarse-resolution model in which only heat fluxes varied interannually (HEAT[17]). For wind stress and freshwater fluxes, a repeated year was used (that is, still with daily forcing, but without interannual variation). We note the slightly different strength of the stream function in the sensitivity experiment, which is due to a general off-set between the climatological and interannually varying forcing[27].

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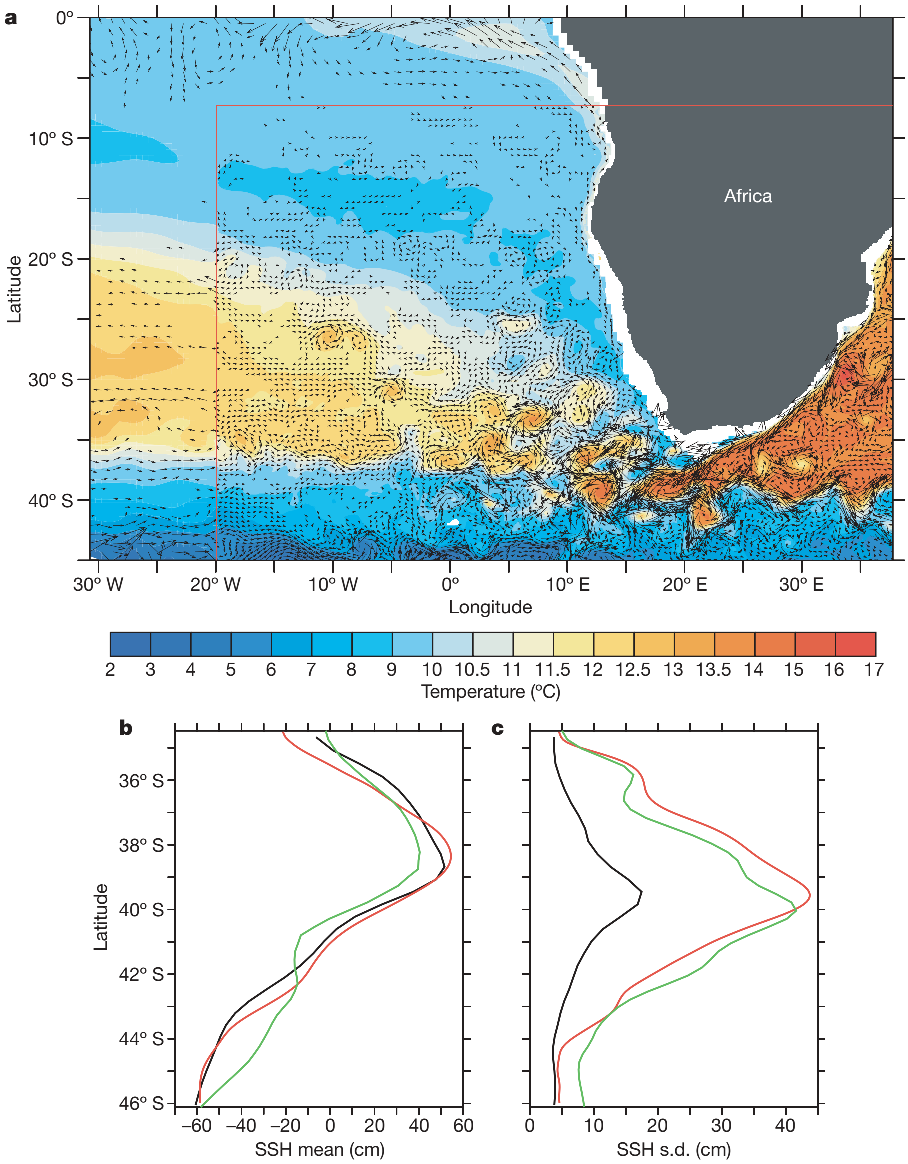

Figure 2 | Mid-depth circulation in the high-resolution Agulhas nest. **a**, Temperature (colour) and velocities (every fourth vector shown of a five-day average around 15 September 2004) at 450-m depth for model experiment AG01, the high-resolution (0.1°) Agulhas nest (the northwestern portion is delineated by the red lines) hosted in a global ocean model of 0.5° resolution. **b**, **c**, Mean (**b**) and standard deviation (**c**) of sea surface height (SSH) at longitude 20° E of the global coarse-resolution model (ORCA05, black), the high-resolution Agulhas nest (AG01, red) and satellite data (Aviso, green).

without the Agulhas nest) illustrates an effect on interannual to decadal timescales. There is a remarkable meridional coherence in the Agulhas-induced MOC signal: anomalies of more than ±1.5 Sv emerge near latitude 30° S and rapidly propagate towards the equator, with only slight damping. In the Northern Hemisphere the anomalies then gradually fade; at 20° N, amplitudes are below 0.5 Sv. The propagation from 30° S into the Northern Hemisphere is very rapid, occurring on the order of months, which is indicative of Kelvin wave processes as discussed in previous ocean model studies[20,21] and climate models[22]. The propagation is thus about 1–2 orders of magnitude faster than it would be if it were due to advective processes, such as the translation of Agulhas rings (which occurs at a few centimetres per second)[23]. This solution suggests that wave processes along the western boundary of the Atlantic Ocean have a prime role in the rapid communication of the signal, a mechanism (Fig. 4) that was theoretically described in idealized model studies[24].

Agulhas rings are the dominating vehicle of the inter-basin exchange into the Cape Basin off the west coast of South Africa. They can be reasonably traced by the depth of the 10 °C isotherm[25], where the anticyclonic rotation sense of a ring causes depressions in the isothermal surfaces. Time series of isopycnal depth along 30° S at full temporal resolution (Supplementary Fig. 4) indicate westward propagating signals of about 6 cm s^{-1}, in good agreement with observations of Agulhas rings[23]. The signals reveal a decadal modulation (Supplementary Fig. 5) that is also evident in the sea surface height, in good agreement with the observational record (Supplementary Fig. 6). The modulation has a similar temporal characteristic as the Agulhas-induced MOC signal, suggesting a projection of the zonally propagating, meridional velocity anomalies onto the zonally integrated MOC transport in this latitude range. Farther north, the MOC variability signal is mainly concentrated at the western boundary, which can be seen in a comparison of the MOC transport anomalies with the transport anomalies of the North Brazil current (Fig. 3a).

How significant are the Agulhas-induced MOC anomalies and what is their relative importance in comparison with decadal MOC signals originating from the subpolar North Atlantic? Although changes in the dense overflow at the Greenland–Scotland ridge

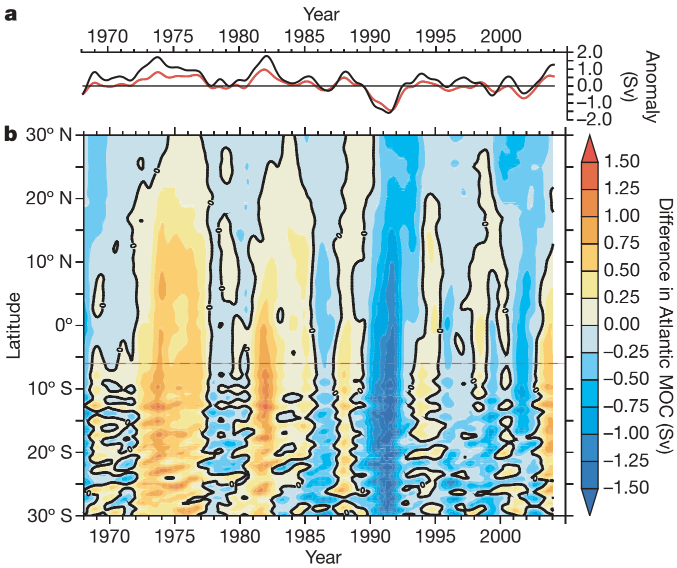

Figure 3 | Low-pass-filtered Agulhas-induced MOC anomalies. **a**, Comparison of the (low-pass-filtered) time series of the MOC anomalies (red) at 6° S (dashed red line in **b**) with the corresponding anomalies of the North Brazil current at this latitude (black). **b**, Hovmoeller diagram showing the difference in Atlantic MOC between model experiments with (AG01) and without (ORCA05) a high-resolution Agulhas nest. Integrated over the upper 1,000 m, this typically represents the total strength of the MOC (compare with Supplementary Fig. 2).

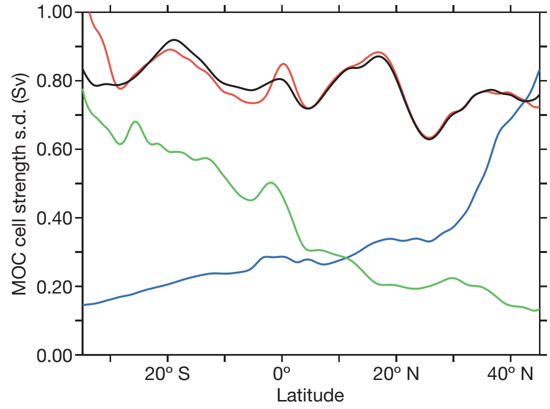

Figure 5 | Attribution of interannual MOC variability to different mechanisms. Standard deviation of the low-pass-filtered deep-water cell strength as a function of latitude, in the experiments without (ORCA05, black) and with (AG01, red) an Agulhas nest. The effect of the Agulhas-induced variability is isolated by the standard deviation of the MOC difference the two experiments (green). For comparison, the blue curve shows the individual effect of sub-arctic deep-water formation variability, obtained in a sensitivity experiment (HEAT[17]) in which ORCA05 was selectively driven by interannually varying heat-flux forcing and repeated-year wind and freshwater forcing.

appear to have had comparatively minor effects in past decades[6], modifications in the formation of Labrador Sea Water were identified in model studies as an important source of basin-scale MOC signals on decadal timescales[7], leading to mid-latitude North Atlantic MOC changes on the order of 1–2 Sv.

A quantitative assessment of the relative importance of the various MOC signals is provided in Fig. 5. In the experiments with (red) and without (black) the Agulhas nest, the total variability is broadly similar, owing to the dominance of local wind-induced variability on interannual timescales[17]. The individual effect of the mesoscale Agulhas dynamics (red), given by the difference of the two MOC time series, has a maximum amplitude in the South Atlantic, but reaches well into the tropical (North) Atlantic. For comparison, the figure also depicts the influence due to the variability in sub-arctic deep-water formation: in a previous study[17] its effect was isolated by a sensitivity experiment (HEAT) based on ORCA05 in which interannual forcing variations were retained in the heat fluxes and a repeated year was used for wind and freshwater fluxes. In that case, MOC variability is primarily induced in the sub-arctic North Atlantic; its strength decreases towards the Equator, becoming comparable to that of the Agulhas effect in the tropical Atlantic. The simulations thus suggest that the variability of inter-hemispheric transport (Fig. 1) arises from a combination of effects from the north as well as the south. It also suggests that both influencing factors need to be invoked to interpret MOC variations in the subtropical North Atlantic, as currently studied in multi-year measurement programs at 16° N (MOVE)[3] and 26° N (RAPID)[2,3].

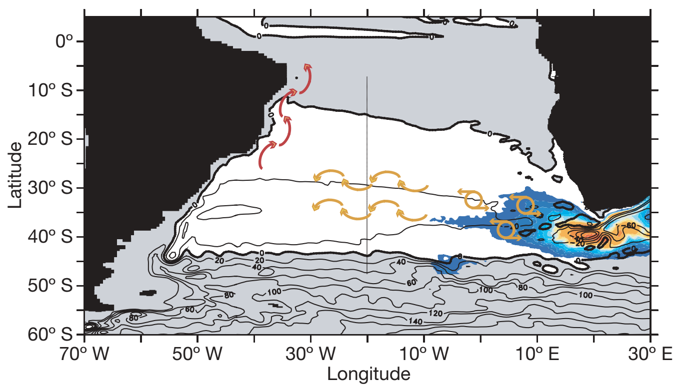

Figure 4 | Illustration of the wave processes conveying Agulhas-induced anomalies in the upper limb of the MOC. The contour lines depict the time-mean barotropic stream function (Sv), indicating the anticyclonic (white area) subtropical gyre in the South Atlantic; the colour information shows the time-mean eddy kinetic energy. The arrows give an illustration of the dynamic processes transporting eddies and Rossby waves originating in the Agulhas across the South Atlantic (yellow) and Kelvin waves along the continental slope of South America (red).

Using a two-way nesting scheme that selectively resolves mesoscale dynamics in the greater Agulhas region, the model simulations demonstrate that the Agulhas leakage acts as the source of decadal MOC variability: low-frequency undulations in thermocline depth induced in the leakage regime project onto a dynamical signal carried across the South Atlantic by Rossby waves and into the North Atlantic by wave processes along the American continental slope. This is reflected in a decadal MOC transport signal that gradually diminishes from south to north, but has an amplitude in the tropical Atlantic of comparable magnitude to the effect of sub-arctic deep-water formation processes discussed in previous studies. The effect of the Agulhas leakage dynamics on decadal timescales identified here adds to previous palaeoclimate studies[13] concluding that changes in inter-basin heat and fresh water fluxes between the Indian and Atlantic Ocean can strongly influence the MOC on centurial and longer timescales; it demonstrates the need to realistically capture the mesoscale dynamics of this regime in projections of climate change over the Atlantic Ocean.

METHODS SUMMARY

The model is based on the NEMO ocean/sea-ice model (v2.3)[26]. The global base model (ORCA05) has a nominal resolution of 0.5°, and therefore does not resolve the oceanic mesoscale. Its state-of-the-art set-up (including partial bottom cells and advanced advection schemes) has been used by the DRAKKAR consortium in a wide range of applications. This base model hosts a high-resolution, 0.1°-resolution regional model of the Agulhas region (20° W–70° E, 47° S–7° S, AG01[16]; Fig. 2). Using an adaptive mesh refinement[18], it not only receives its boundary conditions from the base model but is also able to update it. This 'two-way nesting' approach makes it possible to study the effect of the high-resolution dynamics in the nest on the global circulation, the main element of this study. The model system is driven by a consistent data set[27] of six-hourly to daily, interannually varying wind and thermohaline surface forcing fields over the period 1958–2004. For comparison we use an ORCA05-based sensitivity experiment of a previous study[17] (HEAT), in which only heat fluxes were allowed to vary interannually; wind stress and freshwater fluxes had no variations from year to year. In this case, MOC variations are reverberations of deep-water formation events in the subpolar North Atlantic. (We note that the sensitivity experiment differs slightly in its model set-up, in that it mainly uses an eddy parameterization[28] that is necessary for a realistic representation of the deep-water formation processes in the Southern Ocean.) Regarding the wave processes communicating the dynamical signal northward, we point out that NEMO is formulated on a C grid, on which Kelvin wave propagation is unaffected by horizontal resolution[29].

The model fields are compared with an altimeter product by Aviso. In this data set, GRACE (Gravity Recovery And Climate Experiment) satellite sea surface heights were subtracted, and a new mean dynamics topography (Rio05)[30] using *in situ* measurements from drifters and hydrography was then introduced. (The altimeter products were produced by Ssalto/Duacs and distributed by Aviso with support from CNES. Rio05 was produced by CLS Space Oceanography Division.)

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

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Author Contributions A.B. and C.W.B. designed the experiments. A.B. implemented and conducted the experiments and carried out the analysis. All authors discussed the results and jointly wrote the manuscript.

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