

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30

Supplementary Information *for*
Limited influence of the Agulhas leakage on the Atlantic Meridional
Overturning Circulation in present climate

Ruize Zhang^{1,2}, Shantong Sun^{2*}, Zhaohui Chen^{1,2*}, and Lixin Wu^{1,2}

¹Frontier Science Center for Deep Ocean Multisphere and Earth System
(FDOMES)/Academy of Future Oceans and Physical Oceanography Laboratory,
Ocean University of China, Qingdao, China

²Laoshan Laboratory, Qingdao, China

*** Correspondence can be addressed to Shantong Sun (stsun@qnlm.ac) and**
Zhaohui Chen (chenzhaohui@ouc.edu.cn)

Supplementary Note 1: Experiment setup

In this study, we conduct a series of ocean-only sensitivity experiments based on the Parallel Ocean Program version 2 (POP2). To investigate the impact of Agulhas leakage increases on the AMOC, we modify the surface zonal wind stress in the Agulhas leakage region to the south of Africa (10°E-40°E, 35°S-40°S) (Supplementary Figure 2). This regional change in surface wind is confined in the Agulhas leakage region, avoiding significant modifications to the Southern Ocean upwelling, which returns North Atlantic Deep Water back to the sea surface. For the reference run (“Ref”), the Agulhas leakage is 5.3 Sv, which is small enough to conduct a series of experiments. Branched from 601 model years in Ref, we conduct a total of 10 perturbation experiments (see Supplementary Table 1), in which we increase the Agulhas leakage up to 40 Sv.

To investigate the impact of Agulhas leakage increases on the AMOC recovery from a collapsed state, we conduct another suite of experiments, initialized from a “hosing” experiment in which the AMOC collapses. The “hosing” experiment (“Hosing”) was designed to generate a collapsed AMOC by applying 0.06 Sv freshwater perturbations in the subpolar North Atlantic (50-60°N, -60°W-0°), initialized from Ref at year 601. Initialized from Hosing at Year 200, when the AMOC has collapsed, we conduct another experiment that runs in parallel with Hosing but with increased Agulhas leakage to 26 Sv (“Hos26”).

Supplementary Note 2: Model assessment

To ensure robustness of the results, we conduct an assessment of the experiment. Due to the sensitivity of the AMOC response to the thermohaline background, here we evaluate the vertical salinity distribution in the southern boundary of the Atlantic Ocean, which determine the AMOC stability. Compared with other coupled climate model, the salinity bias of the Atlantic southern boundary in our experiment is much smaller, especially in the upper 500 meters (Supplementary Figure 14a&b). The better simulation of salinity background results in negative freshwater transport by the overturning circulation F_{ov} (Supplementary Figure 14c), consistent to the observation.

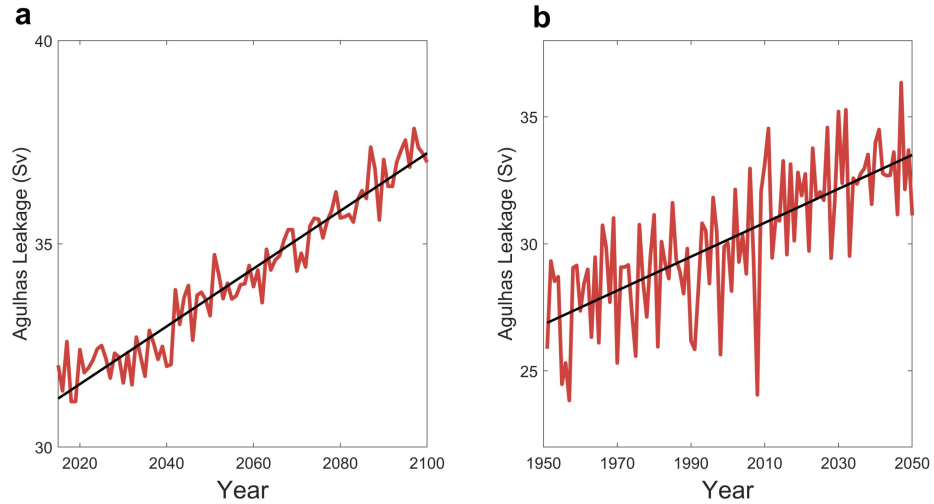
We also evaluate the salinity and temperature difference between the Agulhas Current region and the Southeast Atlantic Ocean, which determines the efficiency of salt exchange between Indian ocean and Atlantic Ocean. The salinity difference is controlled by the strength of Agulhas leakage. In the Ref and AL26, the salinity in the Agulhas Current region is significantly higher than that in the Southeast Atlantic Ocean over the upper 1300 meters, consistent with the observation (Supplementary Figure 9). In other coupled model and the default POP2, due to the excessive Agulhas leakage, the salinity differences are not well represented.

Besides, we also compare the temperature changes with the results in high-resolution CESM to highlight the robustness of Atlantic subsurface warming. We show a composite of temperature and salinity evolutions of Agulhas Rings in the

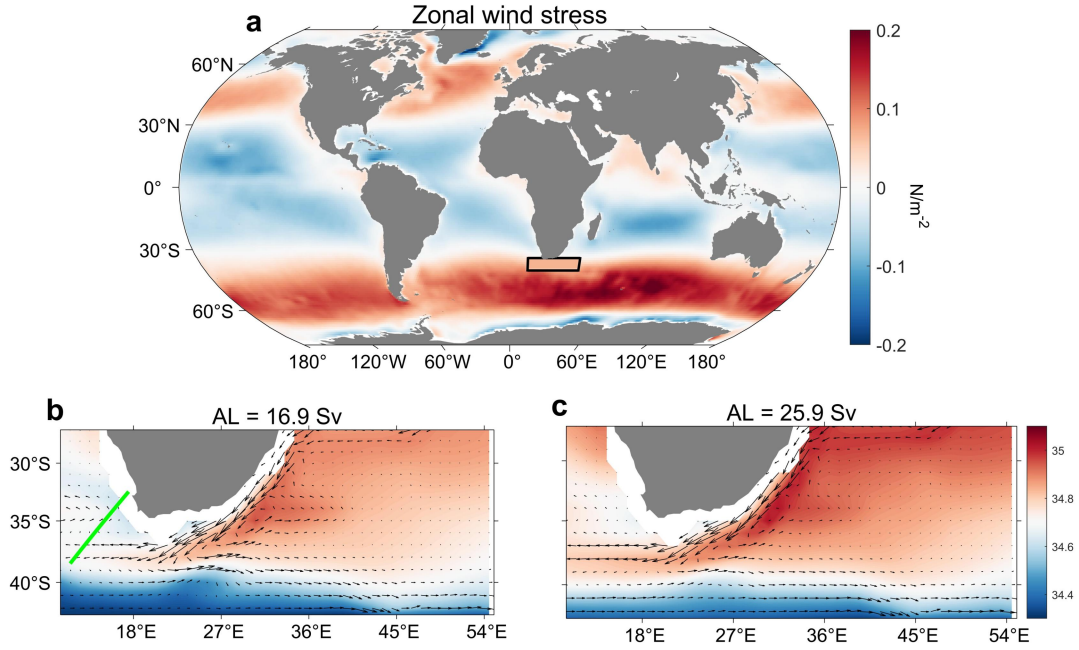
high-resolution CESM (Supplementary Figure 12). We identify 412 Agulhas Rings during 150 model years of the pre-industrial simulation. As the rings travels toward north-westward in Fig. S14, surface warming rapidly decreases, but the subsurface warming persists during the course, consistent with our low-resolution simulations.

Supplementary Table 1 Configuration of the perturbation experiments

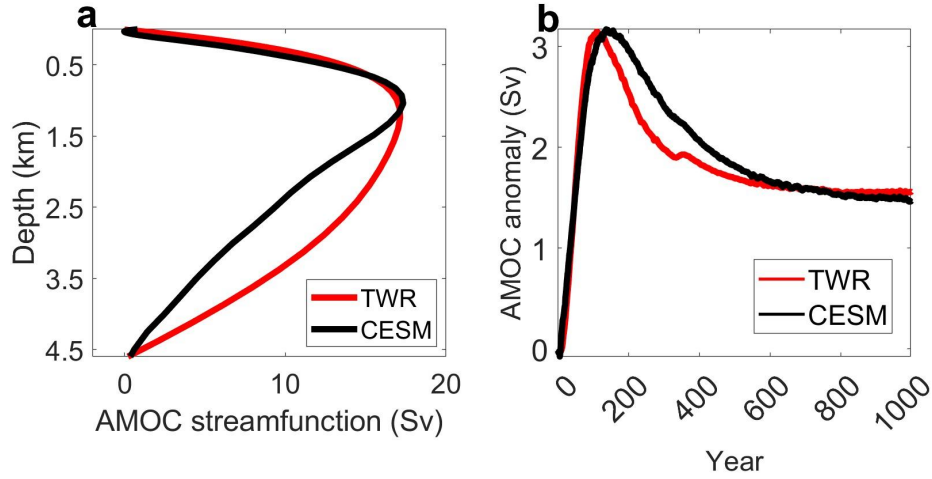
AL_Lagrangian	AL_Eulerian	Local wind stress (Pa)	Model years
5.3 SV (REF)	7.5 SV	0.25	1-1600
7.1 SV	11.1 SV	0.22	601-1600
8.7 SV	13.9 SV	0.20	601-1600
11.9 SV	18.4 SV	0.17	601-1600
16.9 SV (AL17)	21.7 SV	0.15	601-1600
19.9 SV	24.2 SV	0.13	601-1600
25.9 SV (AL26)	28.3 SV	0.10	601-1600
32.5 SV	32.0 SV	0.09	601-1600
34.3 SV	36.0 SV	0.07	601-1600
38.8 SV	39.6 SV	0.01	601-1600
39.2 SV	40.4 SV	0.002	601-1600



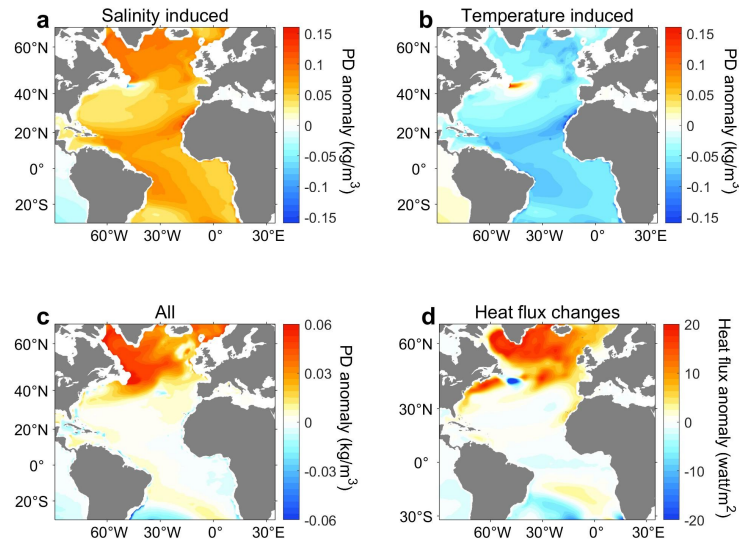
Supplementary Figure 1| Agulhas leakage increases projected in a warming climate. (a) Multi-model ensemble mean of the Agulhas leakage under the high-emission scenario during the 21st century in CMIP6 (red line) and its linear trend (black line). The multi-model mean of Agulhas leakage increase by 7.1 Sv during the 21st century with a standard deviation of 4.7 Sv. (b), Same as (a), but for a high-resolution climate model in HighResMIP, which resolve the mesoscale processes involved in the Agulhas leakage. The multi-model mean of Agulhas leakage increase by 6.7 Sv from 1950 to 2050 and the standard deviation is 5.6 Sv.



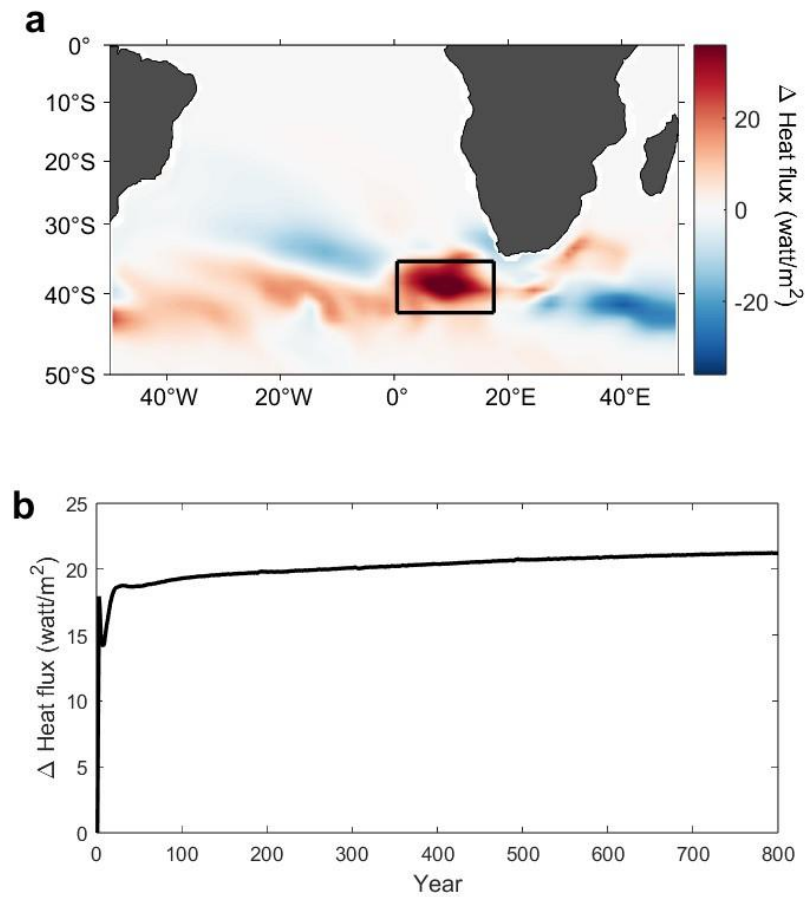
Supplementary Figure 2| Surface wind stress and circulation in the Agulhas Current region. (a) Annual-mean zonal wind stress used in the ocean model from COREv2. The black box south of the African continent denote the region (10°E - 40°E , 35°S - 40°S), where we change the zonal wind stress to modify the strength of Agulhas leakage. (b) Annual-mean salinity (color scale) and horizontal velocity (black arrows) at 500 m depth in the Southwest Indian Ocean in sensitivity experiment in which the Agulhas leakage is 16.9 Sv (“AL17”). The green line denotes the section used to calculate the volume transport of Agulhas leakage. (c) Same as (b), but for the sensitivity experiment in which the Agulhas leakage is increased to 25.9 Sv (“AL26”).



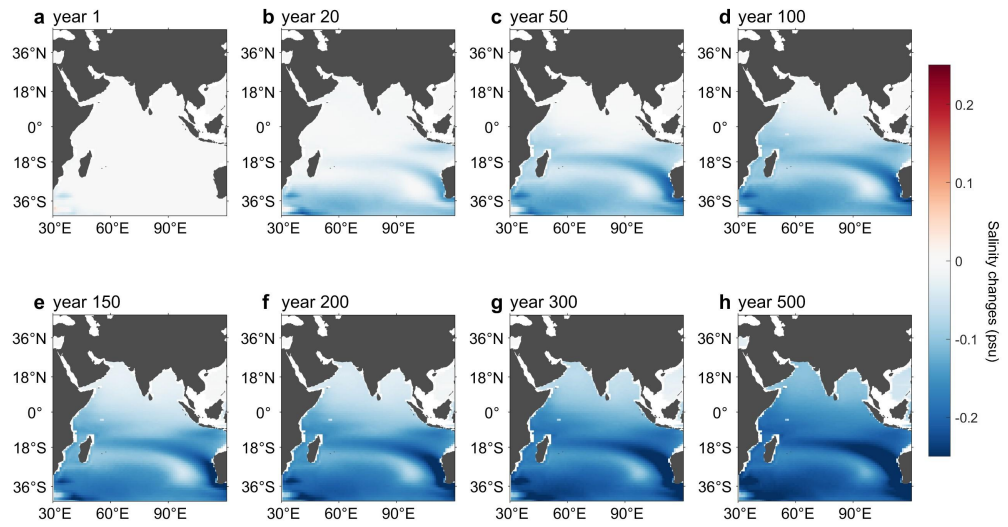
Supplementary Figure 3| Comparing the thermal wind relation with CESM. (a) the AMOC streamfunction reconstructed by the thermal wind relation (red line) in comparison with the AMOC streamfunction reported by CESM (black line). (b) Transient evolution of the AMOC strength reported by CESM (black line) and the AMOC reconstructed from the thermal wind relation (red line).



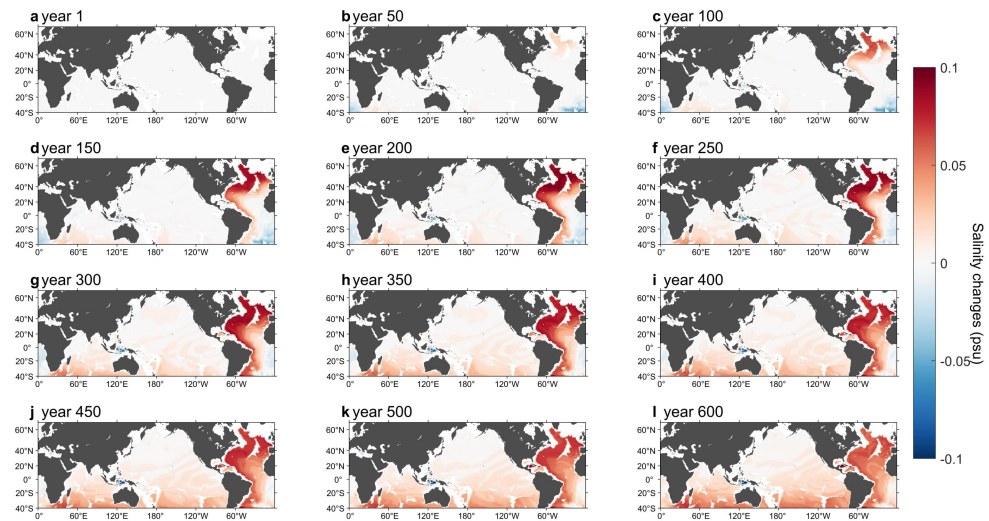
Supplementary Figure 4| Upper Ocean density changes in the Atlantic Ocean. (a) Potential density changes due to salinity changes averaged over the upper 2000 meters after strengthening the Agulhas leakage. (b) Same as (a), but for the potential changes due to the temperature changes. (c) Potential density changes averaged over the upper 2000 meters after strengthening the Agulhas leakage. (d) Sea surface heat flux changes (positive for more ocean loss heat) in the Atlantic Ocean after strengthening the Agulhas leakage.



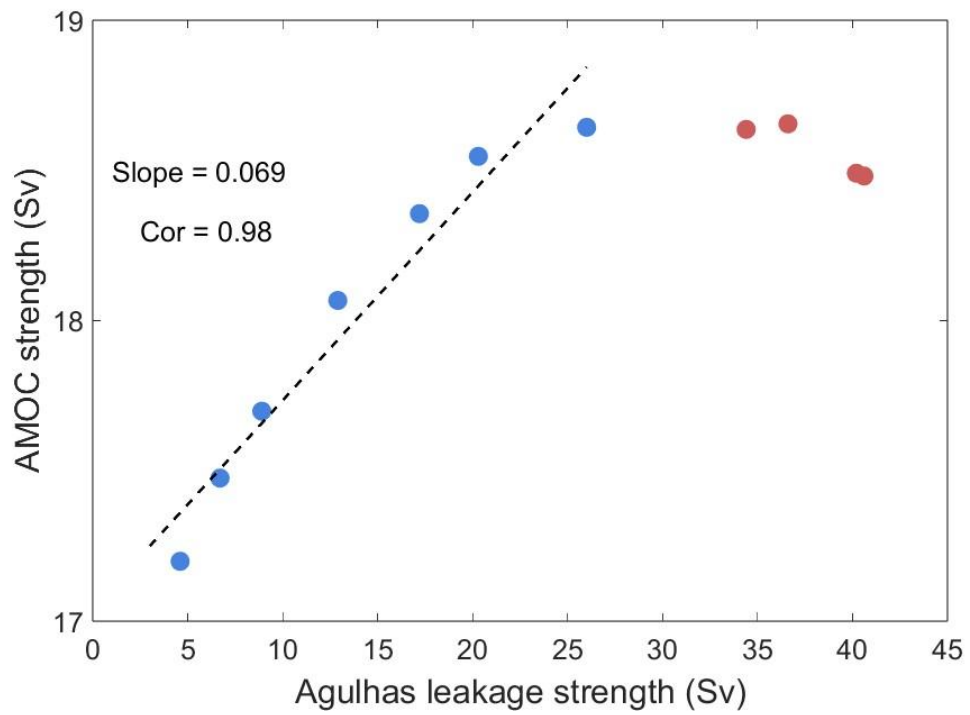
Supplementary Figure 5| (a) Sea surface heat flux changes (positive value indicates more ocean loss heat) after strengthening the Agulhas leakage. The value is calculated as difference of sea surface heat flux between the experiments with Agulhas leakage of 25.9 Sv (AL26) and Agulhas leakage of 16.9 Sv (AL17). **(b)** Evolution of sea surface heat flux averaged over the black box in **a** (0°-17 °E, 35 °S-45 °S).



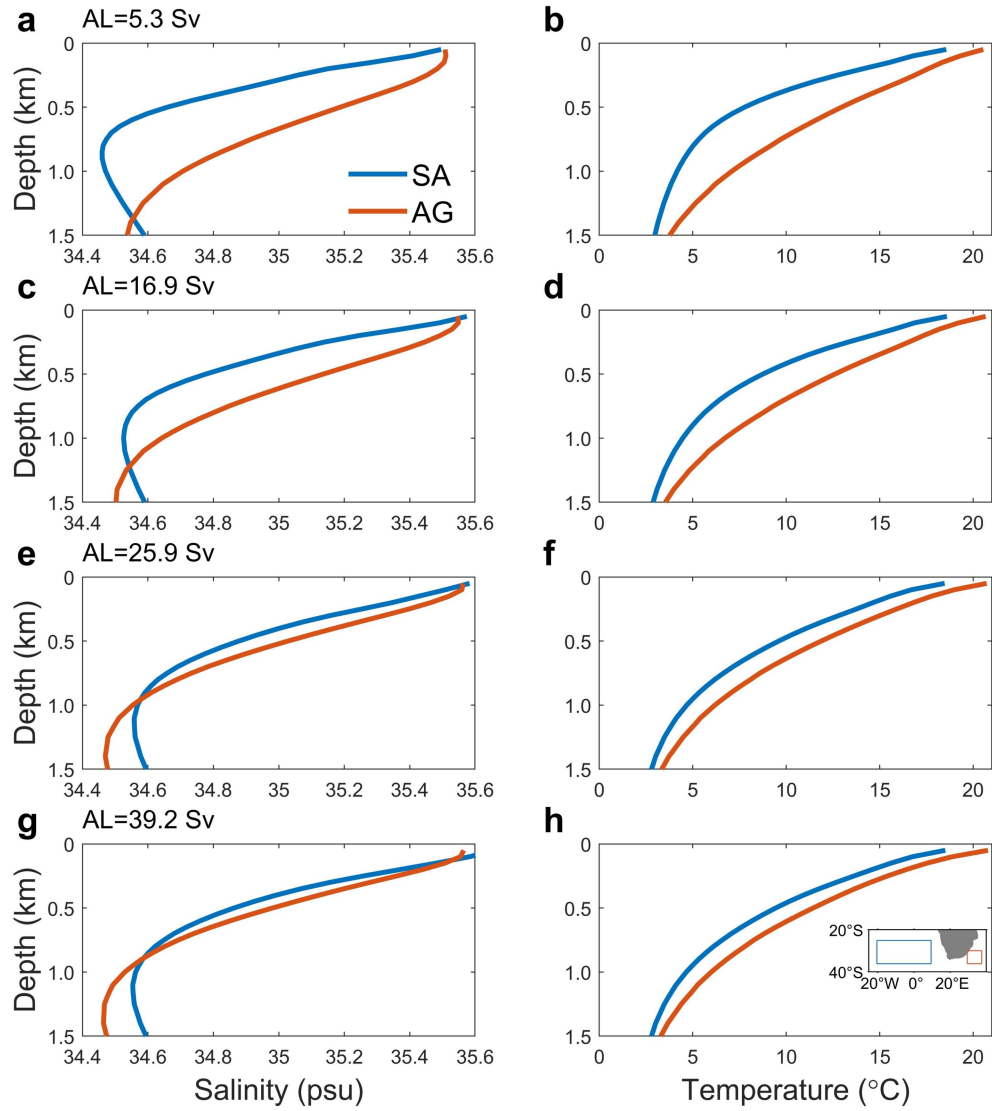
Supplementary Figure 6| Subsurface (500 m) salinity decrease in the Indian Ocean after increasing the Agulhas leakage. The subtitles denote the years after increasing the volume transport of Agulhas leakage.



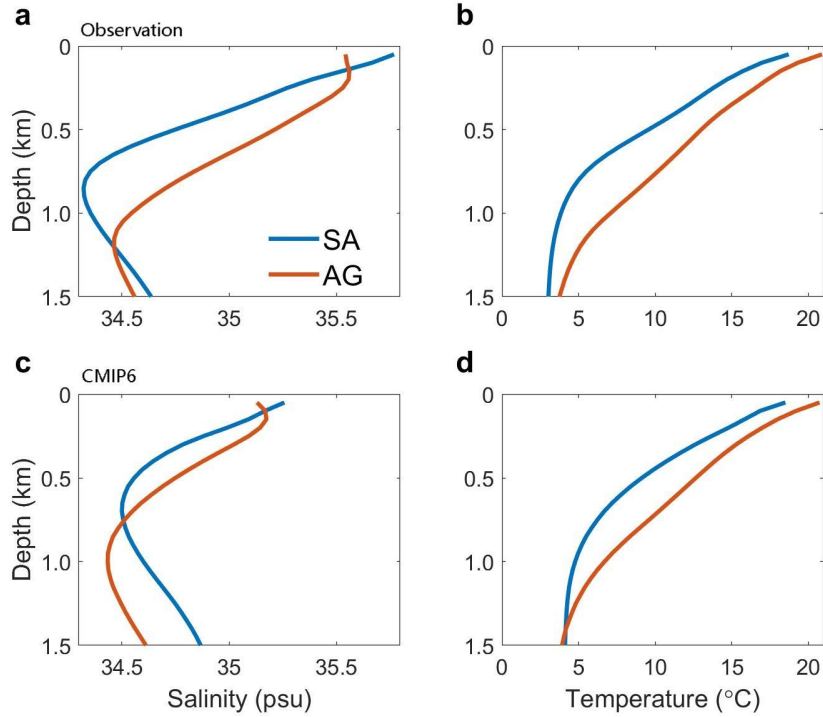
Supplementary Figure 7| Deep-ocean (3000 m) salinity increase after increasing the Agulhas leakage. The subtitles denote the years after increasing the Agulhas leakage.



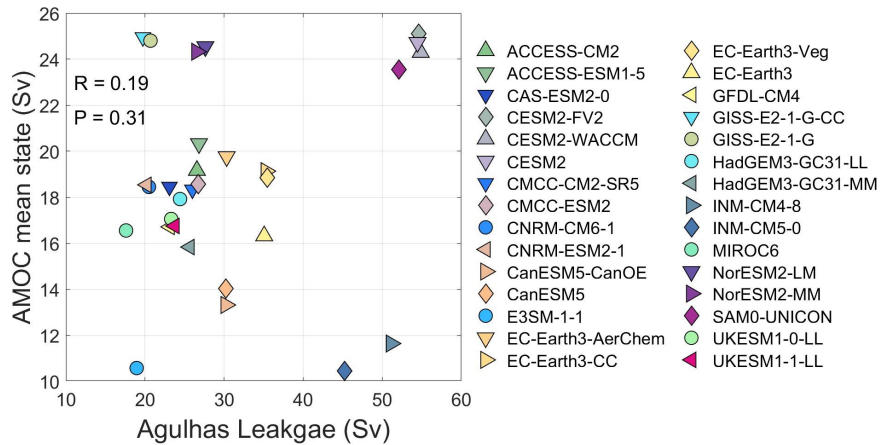
Supplementary Figure 8| AMOC changes as a function of the Agulhas leakage estimated after 1000 years. The black dashed line represents a linear regression for Agulhas leakage below 30 Sv.



Supplementary Figure 9| Thermohaline contrast between the Agulhas water and Southeast Atlantic Ocean in the ocean-only experiments. (a) Vertical salinity profile in the Agulhas Current regions (orange line), averaged over (30.5°S-36.5°S, 29.5°E-37.5°E) and the Southeast Atlantic Ocean (blue line), averaged over (25.5°S-36.5°S, 20.5°W-9.5°E) in Ref. (b) Same as (a), but for temperature. (c-h) Same as (a, b) but for the sensitivity experiment with the Agulhas leakage increased to (c,d) 17.2 Sv, (e,f) 26.5 Sv, and (g,h) 40.2 Sv.

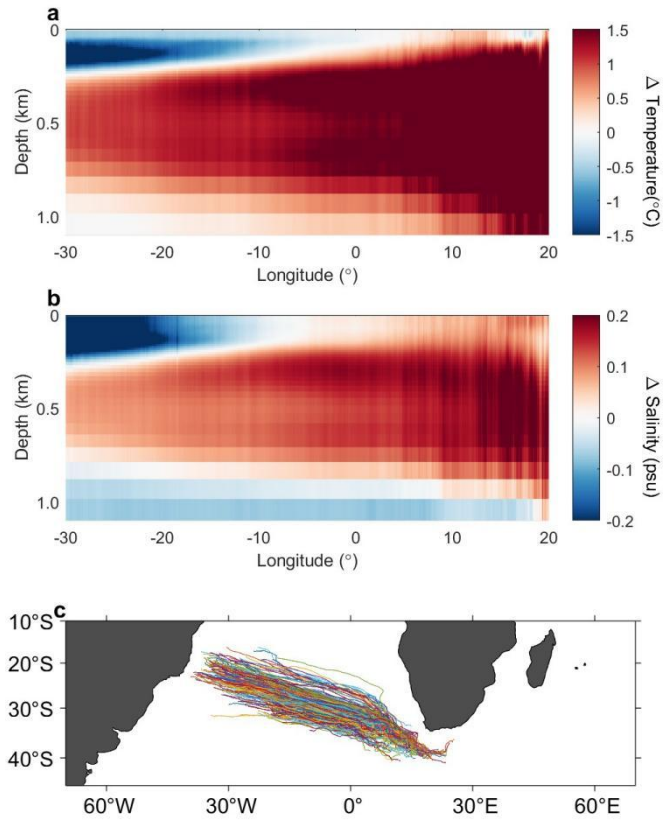


Supplementary Figure 10| Thermohaline contrast between the Agulhas water and the Southeast Atlantic Ocean in observations and CMIP6 multi-model ensemble mean. Vertical profiles of (a) salinity and (b) temperature in the Agulhas Current regions (orange line), averaged over (30.5°S-36.5°S, 29.5°E-37.5°E) and the Southeast Atlantic Ocean (blue line), averaged over (25.5°S-36.5°S, 20.5°W-9.5°E) in observations. (c,d) same as (a,b) but for the CMIP6 multi-model ensemble mean.

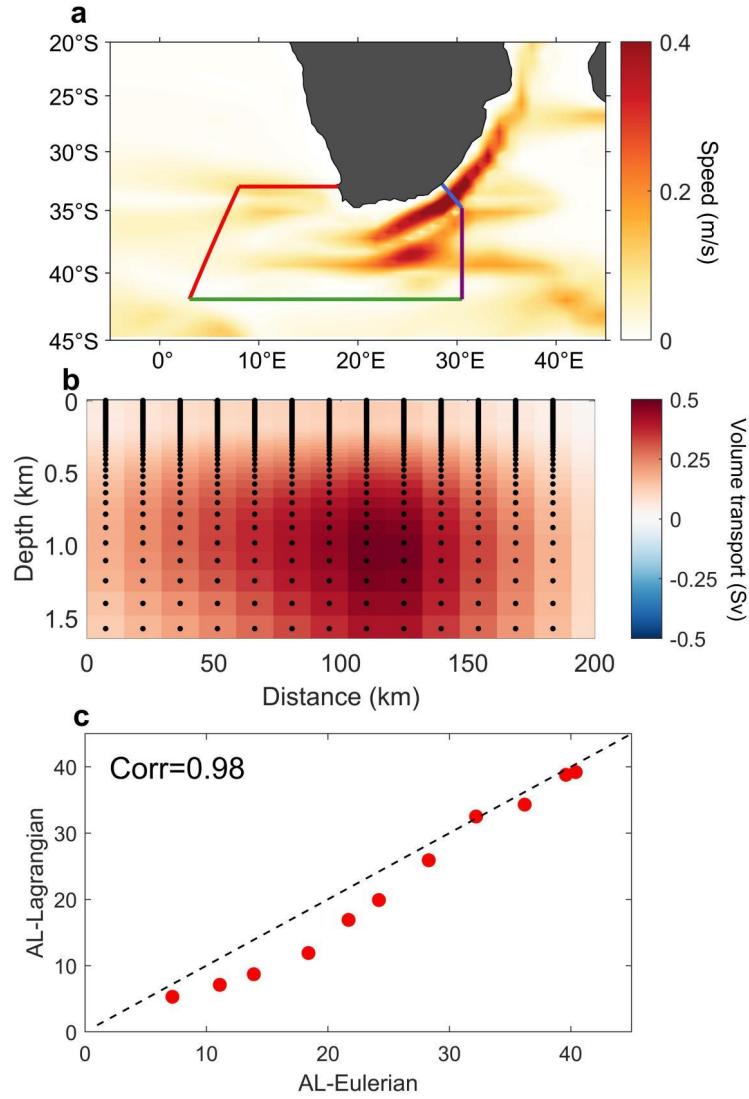


Supplementary Figure 11| Inter-model relationship between the AMOC and the Agulhas leakage among CMIP6 climate models. The linear correlation coefficient R and P value are calculated.

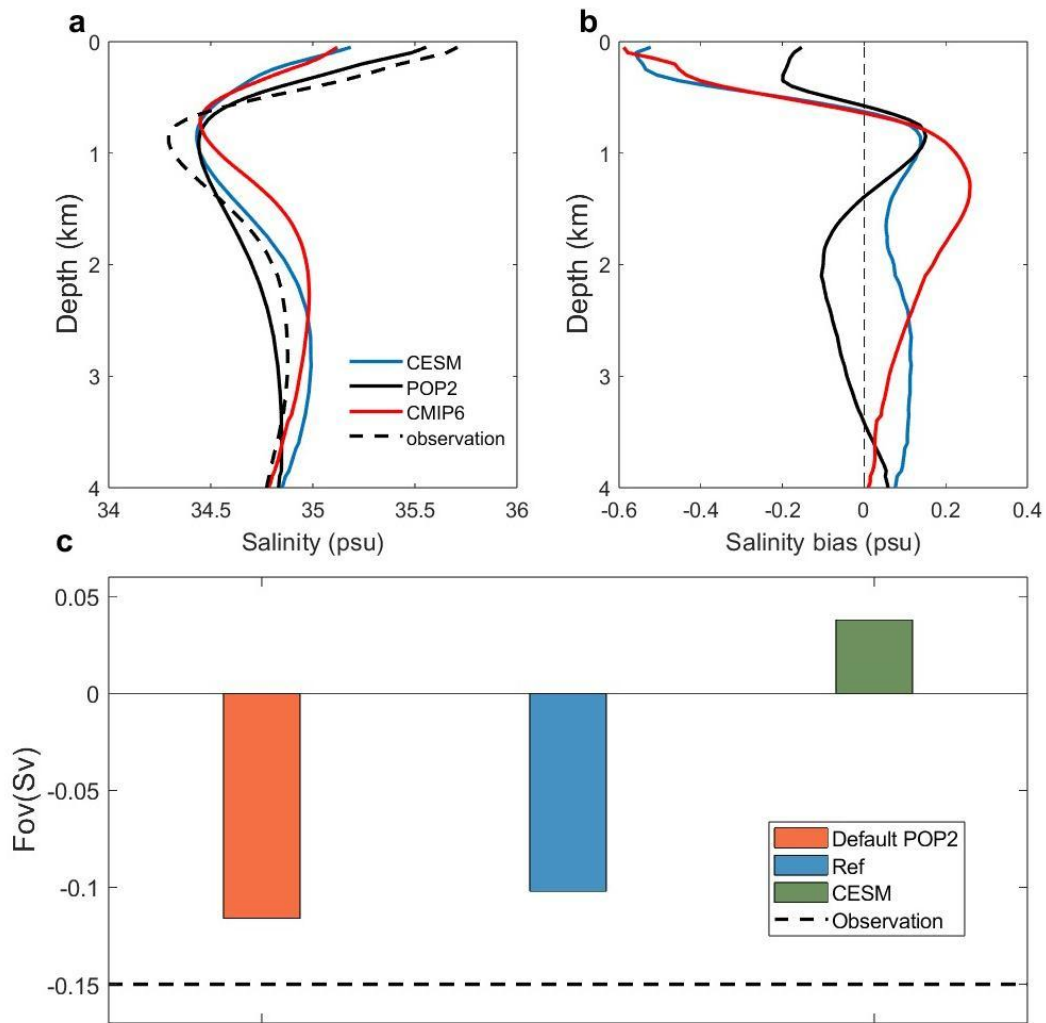
177
178



179
180 **Supplementary Figure 12** | Thermohaline evolution of the Agulhas Ring in the
181 high-resolution CESM. (a) Temperature anomaly evolution of the Agulhas Rings
182 during their journey westward. (b) Same as (a) but for the salinity anomaly. (c) the
183 tracks of Agulhas Rings used to composite the evolution of thermohaline anomaly.
184



Supplementary Figure 13 | Comparison of the Agulhas leakage estimated by the Lagrangian method with the Agulhas leakage estimated by the Eulerian method. **(a)** Sections for estimating Agulhas leakage. The background shading denotes climatological speed averaged over the upper 500 meters. The blue line is the ACT section, where we release the particle. The red lines denote the good hope line used to estimate the Agulhas leakage. The purple line and green line are used to calculate the particles leaving this domain from eastern and southern boundaries, respectively. **(b)** The background shading denotes the volume transport of Agulhas Current in each grid cell. The black dots denote the virtual particles being tracked. **(c)** Comparison of the Agulhas leakage estimated by the Lagrangian method (y-axis) with estimates using the Eulerian method (x-axis). The dashed black line denotes $y=x$.



Supplementary Figure 14| (a) Vertical salinity distribution averaged over the southern boundary (34°S) of Atlantic Ocean. (b) Vertical salinity biases distribution averaged over the southern boundary (34°S) of Atlantic Ocean. (c) Comparison of freshwater transport by the overturning circulation F_{ov} between ocean-only POP2 simulation and fully-coupled CSM simulation.