

Projected Atlantic overturning slow-down is to be compensated by a strengthened South Atlantic subtropical gyre

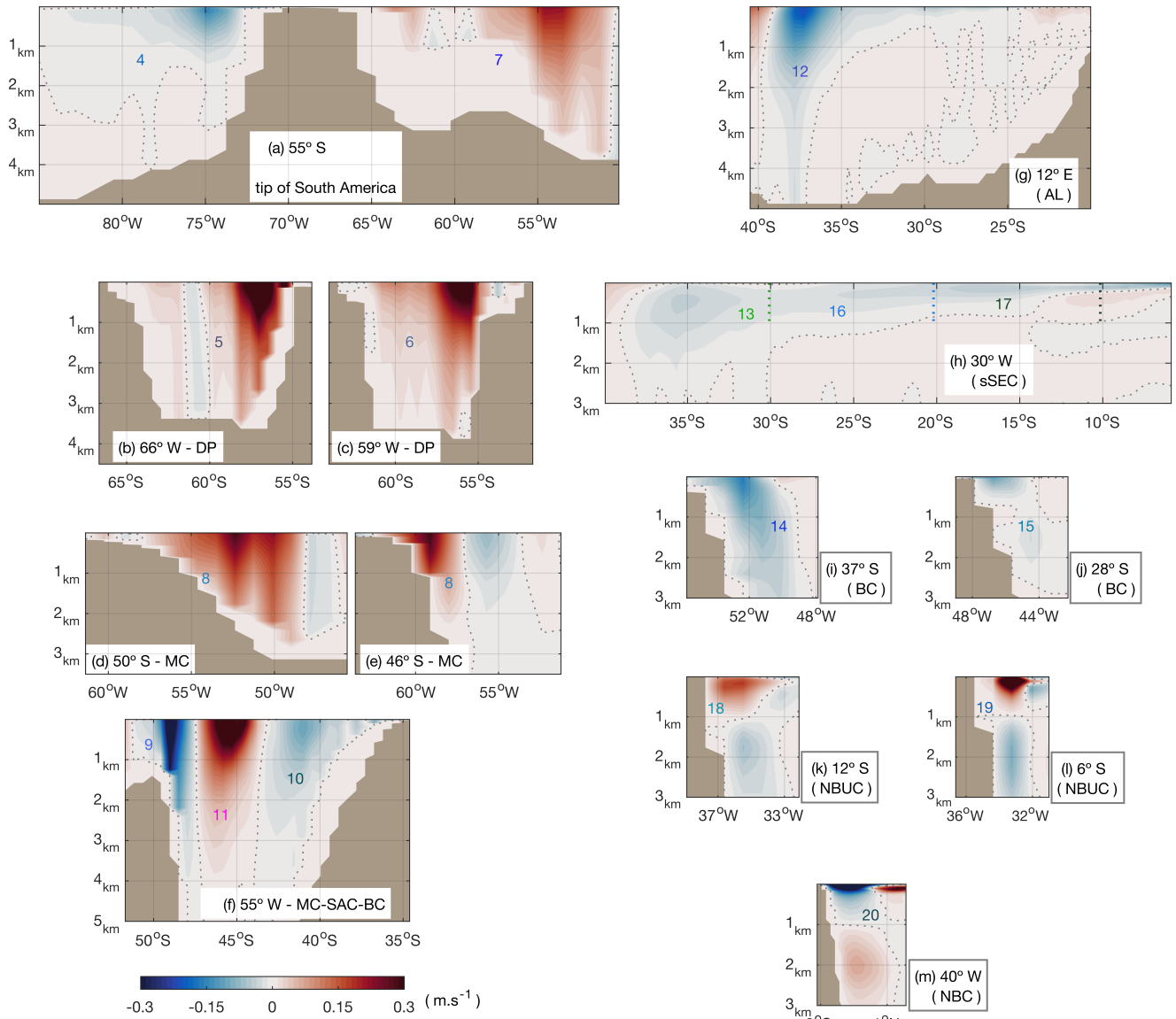
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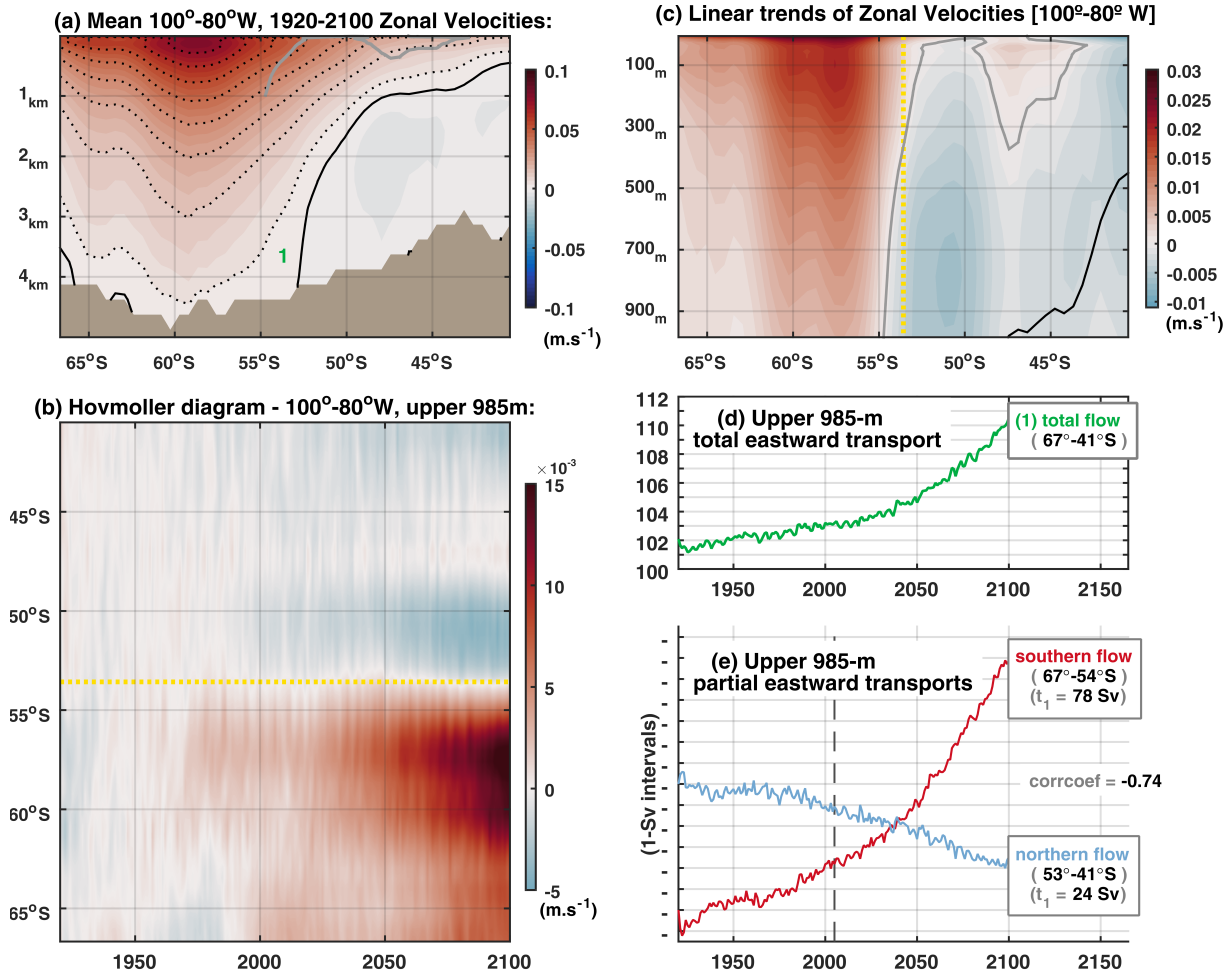
Supplementary Information

1. **Supplementary Figure 1** - Vertical profiles corresponding to boxes/transects and time series in article Figure 2
2. **Supplementary Figure 2** - Southern eastward flows prior to the Drake Passage (100° - 80° W) (Across box "1" in article Figure 2a)
3. **Supplementary Figure 3** - Southern eastward flows at the eastern South Atlantic sector (10° W- 25° E) (Across box "2" in article Figure 2a)
4. **Supplementary Figure 4** - Southern eastward flows entering the Indian Ocean sector (26° - 45° E) (Across box "3" in article Figure 2a)
5. **Supplementary Figure 5** - SASG structural changes (30° - 10° W)
6. **Supplementary Description of Figure 5**
7. **Supplementary Discussion on "SASG structural changes"**
8. **Supplementary Figure 6** - Wind pattern changes
9. **Supplementary Figure 7** - Sea surface height field - mean and trends (1920-2100)
10. **Supplementary Figure 8** - Climatological fields (1920-2100) and their corresponding 2080-2100 *minus* 1920-1970 difference

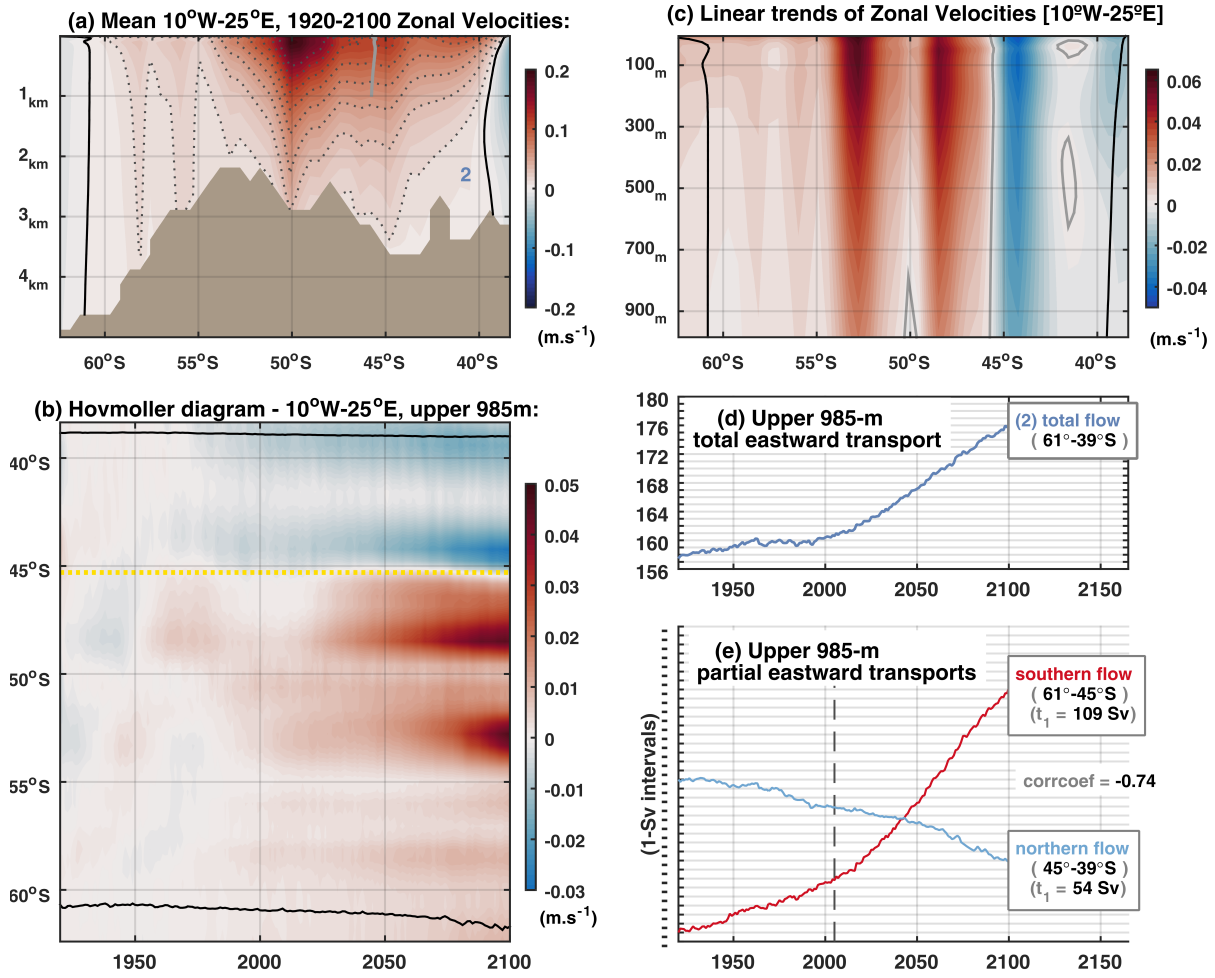
11. **Supplementary Discussion - Agreement between our results and those of previous studies**
12. **Supplementary Discussion - Implications of AMOC upper limb and SASG changes**
13. **Supplementary Table 1** - Volume transport values corresponding to the time series in article Figure 2
14. **Supplementary Table 2** - Magnitude of changes in the meridional position of the SASG boundaries corresponding to the time series in article Figures 5 and 6
15. **Supplementary References**



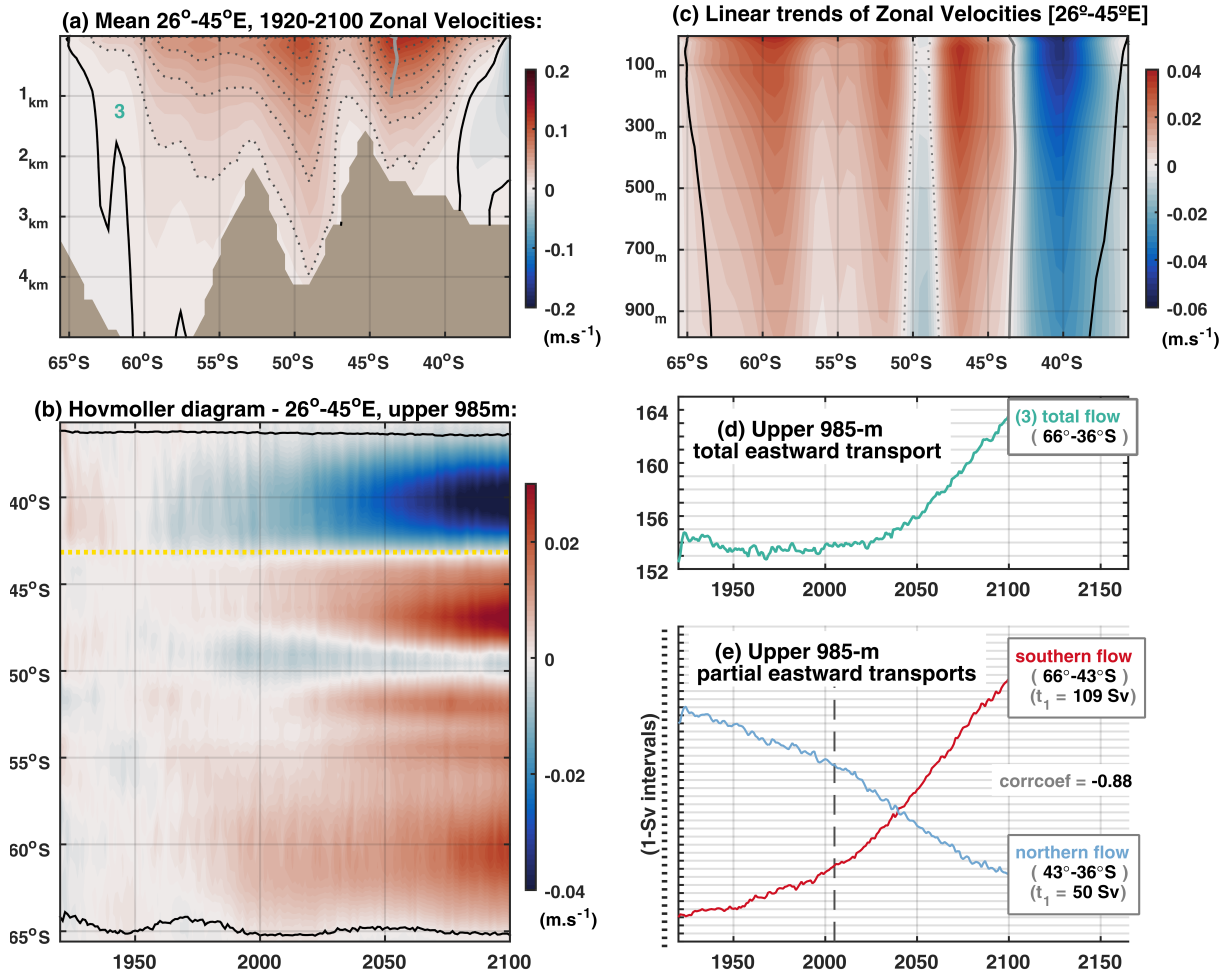
Supplementary Figure 1: | Vertical profiles corresponding to boxes/transects and volume transport time series in article Figure 2 |. 1920-2100 mean meridional (a, d, e, i, j, k, l) and zonal (b, c, f, g, m) velocities. Red represents positive (eastward/northward), while blue represents negative (westward/southward) velocities. Dotted gray contours indicate the zero zonal/meridional velocity line. The x- and y-axis ranges of all profiles are scaled, matching each other, in order to provide a perspective of relative flow width and depth. The volume transport time series in article Figure 2 are integrated in the upper 985-m layer (slightly above 1-km), where the strongest core of surface ocean currents are located – deeper layers are shown to provide a vertical perspective of their distribution. Eastward/northward (westward/southward) volume transports in article Figure 2 were derived by taking into account only positive/red (negative/blue) velocity values to avoid counterflow interference. DP = Drake Passage, MC = Malvinas Current, SAC = South Atlantic Current, BC = Brazil Current, AL = Agulhas Leakage, sSEC = southern branch of the South Equatorial Current, NBUC = North Brazil Undercurrent, NBC = North Brazil Current.



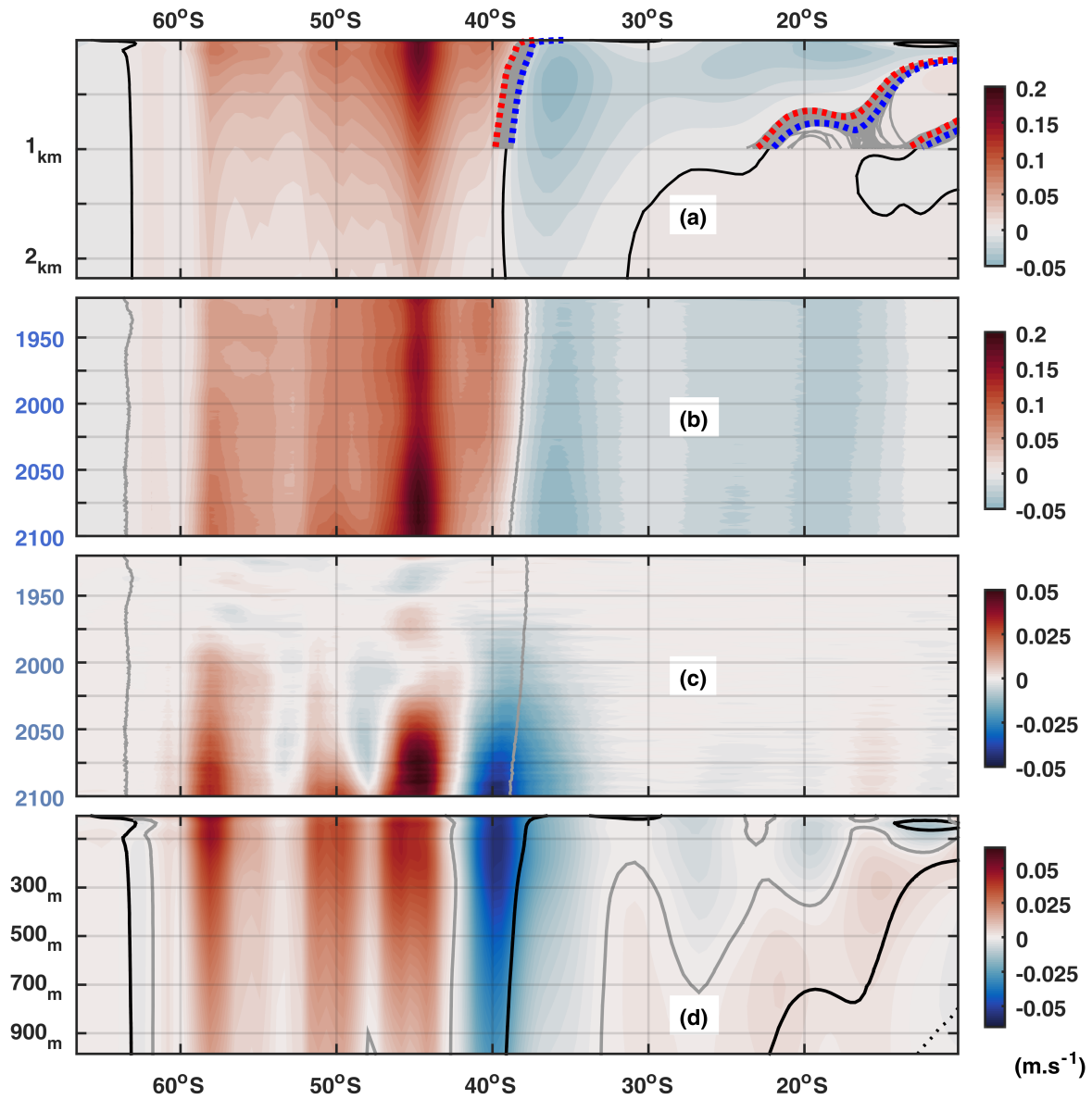
Supplementary Figure 2: | Southern eastward flows prior to the Drake Passage (100°-80°W) | Zonal velocities in the southern Pacific sector, averaged over 100°-80°W (box number 1 in article Figure 2a). **(a)** 1920-2100 mean vertical profile; red denotes positive (eastward) and blue denotes negative (westward) velocities. The black filled contour represents the zero zonal velocity line; and the black dotted contours indicate zonal velocity lines along contour intervals of 4×10^{-3} : 10^{-2} : 74×10^{-3} . The gray filled contour in the upper 1-km is reproduced from (c), for reference. **(b)** Hovmoller diagram (upper 985-m mean) of anomalous zonal velocities (1920-1970 base period); red (blue) indicates positive/eastward (negative/westward) anomalies. The yellow dotted line marks the mean latitude of transition between positive and negative anomalies (53.5°S), in correspondence to the yellow dotted line in (c), used as a reference to derive the southern and northern volume transports in (e). **(c)** 1920-2100 total trends of anomalous zonal velocities, corresponding to the upper 985-m layer in (a). The gray filled contour marks the transition from negative (blue) to positive (red) trends. The black filled contour corresponds to the upper 985-m portion of the black contour in (a), indicating where the mean flow shifts from eastward to westward velocities. **(d)** Time series of the total eastward volume transport associated with the upper 985-m of the zonal velocities in (a), along 67° - 41°S . **(e)** Time series of the southern and northern portions of the total eastward transport in (d). The value corresponding to their first time step (1920) is indicated, while the y-axis varies in 1-Sverdrup intervals ($1 \text{ Sv} = 10^6 \text{ m}^3 \cdot \text{s}^{-1}$). The gray dashed vertical line indicates the transition from the historical (1920-2005) to the RCP8.5 (2006-2100) period. The correlation coefficient between both detrended, standardized time series is indicated (-0.74).



Supplementary Figure 3: | Southern eastward flows throughout the eastern South Atlantic sector (10°W-25°E) | Zonal velocities in the southeastern Atlantic sector, averaged over 10°W-25°E (box number 2 in article Figure 2a). **(a)** 1920-2100 mean vertical profile; red denotes positive (eastward) and blue denotes negative (westward) velocities. The black filled contour represents the zero zonal velocity line; and the black dotted contours indicate zonal velocity lines along contour intervals of 14×10^{-3} : 2×10^{-2} : 154×10^{-3} . The gray filled contour in the upper 1-km is reproduced from (c), for reference. **(b)** Hovmoller diagram (upper 985-m mean) of anomalous zonal velocities (1920-1970 base period); red (blue) indicates positive/eastward (negative/westward) anomalies. The black contour represents the temporal evolution of the mean zero zonal velocity line corresponding to the upper 985-m average in (a). The yellow dotted line marks the mean latitude of transition between positive and negative anomalies (45.3°S), in correspondence to the full-depth gray contour in (c) along this latitude, used as a reference to derive the southern and northern volume transports in (e). **(c)** 1920-2100 total trends of anomalous zonal velocities, corresponding to the upper 985-m layer in (a). The gray filled contour marks the transition from negative (blue) to positive (red) trends. The black filled contour corresponds to the upper 985-m portion of the black contour in (a), indicating where the mean flow shifts from eastward to westward velocities. **(d)** Time series of the total eastward volume transport associated with the upper 985-m of the zonal velocities in (a), along $61^\circ\text{--}39^\circ\text{S}$. **(e)** Time series of the southern and northern portions of the total eastward transport in (d). The value corresponding to their first time step (1920) is indicated, while the y-axis varies in 1-Sverdrup intervals ($1 \text{ Sv} = 10^6 \text{ m}^3 \cdot \text{s}^{-1}$). The gray dashed vertical line indicates the transition from the historical (1920-2005) to the RCP8.5 (2006-2100) period. The correlation coefficient between both detrended, standardized time series is indicated (-0.74).



Supplementary Figure 4: | Southern eastward flows entering the Indian Ocean sector (26°-45°E) | Zonal velocities of the ocean currents leaving the Atlantic towards the Indian basin, averaged over 26°-45°E (box number 3 in article Figure 2a). **(a)** 1920-2100 mean vertical profile; red denotes positive (eastward) and blue denotes negative (westward) velocities. The black filled contour represents the zero zonal velocity line; and the black dotted contours indicate zonal velocity lines along contour intervals of 14×10^{-3} : 2×10^{-2} : 154×10^{-3} . The gray filled contour in the upper 1-km is reproduced from (c), for reference. **(b)** Hovmoller diagram (upper 985-m mean) of anomalous zonal velocities (1920-1970 base period); red (blue) indicates positive/eastward (negative/westward) anomalies. The black contour represents the temporal evolution of the mean zero zonal velocity line corresponding to the upper 985-m average in (a). The yellow dotted line marks the mean latitude of transition between positive and negative anomalies (43.2°S), in correspondence to the full-depth gray contour in (c) along this latitude, used as a reference to derive the southern and northern volume transports in (e). **(c)** 1920-2100 total trends of anomalous zonal velocities, corresponding to the upper 985-m layer in (a). The gray filled contour marks the transition from negative (blue) to positive (red) trends. The black filled contour corresponds to the upper 985-m portion of the black contour in (a), indicating where the mean flow shifts from eastward to westward velocities. **(d)** Time series of the total eastward volume transport associated with the upper 985-m of the zonal velocities in (a), along 66°-36°S. **(e)** Time series of the southern and northern portions of the total eastward transport in (d). The value corresponding to their first time step (1920) is indicated, while the y-axis varies in 1-Sverdrup intervals (1 Sv = $10^6 \text{ m}^3 \cdot \text{s}^{-1}$). The gray dashed vertical line indicates the transition from the historical (1920-2005) to the RCP8.5 (2006-2100) period. The correlation coefficient between both detrended, standardized time series is indicated (-0.88).



Supplementary Figure 5: | SASG structural changes (30°-10°W) | Climatological (1920-2100 mean) and anomalous (with respect to the 1920-1970 base period) zonal velocities (m.s^{-1}) centered at the South Atlantic subtropical gyre (SASG) (30°-10°W zonal average): (a) Climatological vertical profile (Latitude x Depth), depicting the westward flow of the consecutive sSEC branches at the northern limb of the subtropical gyre (blue) and the eastward SAC flow at the southern limb of the subtropical gyre merged with the ACC flow in the Southern Ocean (red). Black contours mark the climatological zero zonal velocity line, whose upper 985-m, 1920-2100 annual evolution is represented by gray contours (filling the whole range of their southward migration since 1920), delimited by the 1920-1970 (blue dotted contours) and 2080-2100 (red dotted contours) climatologies. (b, c) Hovmöller diagrams of the upper 985-m average of raw (b) and anomalous (c) zonal velocities; red (blue) denotes positive/eastward (negative/westward) raw velocity values (b) / anomalous velocity values (c); the gray thick line in (b) (also reproduced in (c), for reference) marks the temporal evolution of the zero zonal velocity line averaged over the upper 985-m; (d) 1920-2100 total trends of anomalous zonal velocities corresponding to the upper 985-m in (a). The black thick contour is reproduced from (a), for reference, corresponding to the upper 985-m mean zero zonal velocity line that separates west- from eastward mean flows. The gray filled contour separates positive from negative trends over 1920-2100. Red (blue) denotes positive (negative) trends, i.e., regions where eastward (westward) anomalies tend to increase.

6. Supplementary Description of Figure S5:

The sSEC system is entirely displaced southward (Figure S5a). The temporal evolution of raw (Figure S5b) and anomalous (Figure S5c) zonal velocities averaged over the upper 985-m evidences the strengthening of the sSEC at its southernmost portion, while the SAC actually weakens near the zero zonal velocity line setting its northern limit, and strengthens south of $\sim 42^\circ\text{S}$. Consistent anomalies start developing past $\sim 2000\text{s}$ (Figure S5c).

In Figure 5d, the 1920-2100 trends of the anomalous zonal velocities corresponding to the upper 985 m of Figure S5a reveal a more comprehensive perspective of changes in the sSEC structure along the meridional-depth plane: showing that projected anomalies in the sSEC system are split meridionally between two counterparts in a convoluted bowl-shaped way along depth – with a weakened (strengthened) northern (southern) counterpart, depicted by the red, eastward (blue, westward) anomalies.

This clarifies why the upper 985 m vertically integrated volume transports of the southern, central and northern sSEC (shown in Figure S1h) display increasing, nearly-zero and decreasing long-term trends, respectively (article Figure 2, time series 13, 16 and 17). These transports account only for the westward velocities corresponding to the sSEC system (blue shading in between black contours in Figure S5a); and while the southern sSEC range ($30^\circ\text{--}40^\circ\text{S}$) encompasses mostly negative (i.e., westward-strengthening) anomalies, the central sSEC range ($20^\circ\text{--}30^\circ\text{S}$) encompasses both negative and positive anomalies along depth in similar proportions – suggesting they cancel each other producing neither a westward strengthening nor weakening; and the northern sSEC range ($10^\circ\text{--}20^\circ\text{S}$) encompasses mostly positive (eastward, weakening) anomalies.

In summary, the westward transport along the northern boundary of the SASG (i.e., the sSEC) is slowing down along outer, northern portions while speeding up along inner, southern portions.

7. Supplementary Discussion on SASG structural changes:

(a) SASG northern boundary (sSEC system) at western domains:

Close to the South American coast (western domain), the three-dimensional SASG structure is dramatically reshaped: in short, its northern boundary (the sSEC) expands meridionally in a depth-dependent way – making its vertical distribution more inclined to the south at upper layers when compared to the mean climatological state. More specifically, the sSEC northernmost limit (represented by the sSEC bifurcation latitude) shifts northward at deeper layers (below $\sim 150\text{ m}$) – reflecting the increased (decreased) BC (NBUC) transport (article Figure 6); while the sSEC southernmost limit (the zero zonal velocity line separating the sSEC from the SAC) shifts southward entirely (with a bigger shift at the upper layers - article Figure 5) – reflecting a change in the mean direction of the southern sSEC flow, which strengthens and extends further towards the west. The reason for these tilted boundary displacements is that the SBL shift is more closely associated with density-driven flow compensations at deeper layers, linked to AMOC variations (in addition to the fact that wind anomalies seem rather weak near the SBL region); while the shifted direction of the southern sSEC flow is mostly driven by surface wind anomalies that can extend their influence downward through Ekman dynamics (see Figure S6b);

(b) SASG northern boundary (sSEC system) at central domains:

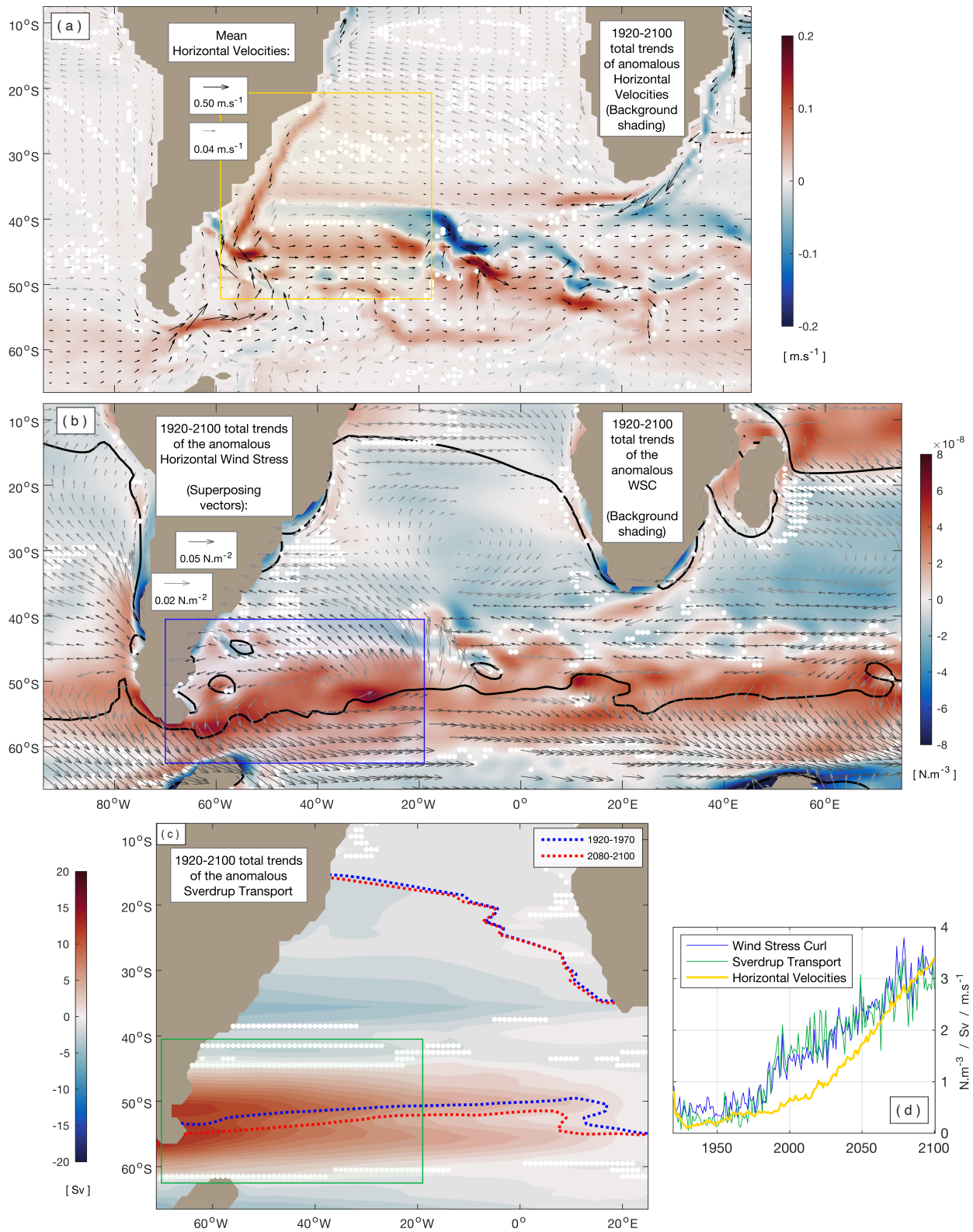
Far from the South American coast, between 30°-10°W (central domain), the SASG northern boundary shifts southward entirely (Figure S5a) – both at the north- and southernmost limits –, but the shift at the northern margin occurs along deeper layers, due to the fact that the sSEC system is shrinking to the north, along the outer portions of its bowl-shaped structure (Figure S5d), probably in response to the generalized weakening of the AMOC upper limb – in a larger degree than to wind-forced anomalies;

(c) Analyzing the shifts of the SASG northernmost edge from west to east:

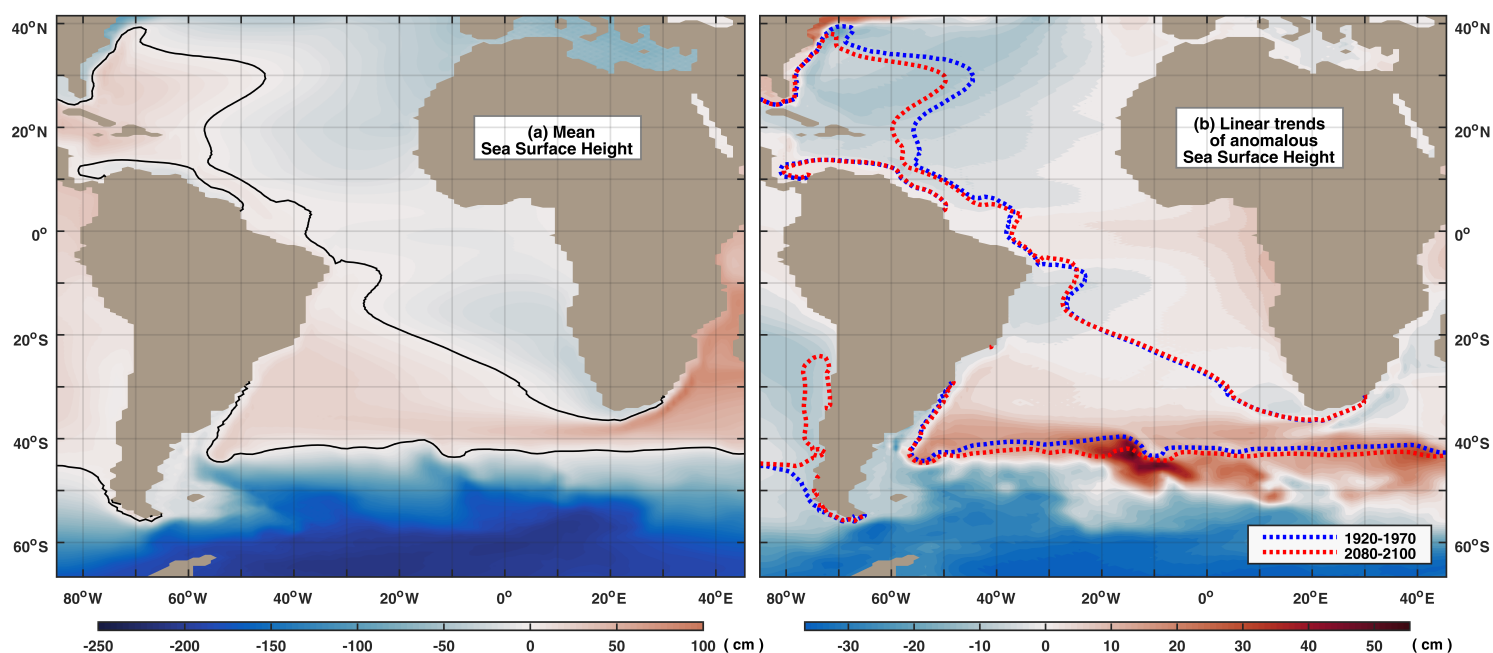
At the western domain, the typical bowl-shape of the subtropical gyre tends to flatten – decreasing its southward tilting with depth, since the SBL shifts northward in deeper layers (article Figure 6). Whereas at the central domain of the SASG, the southward tilting of the northern boundary is increased along depth (Figure S5a) – characterizing the generalized shrinking of the sSEC system (Figure S5d), as described above;

(d) SASG southernmost edge:

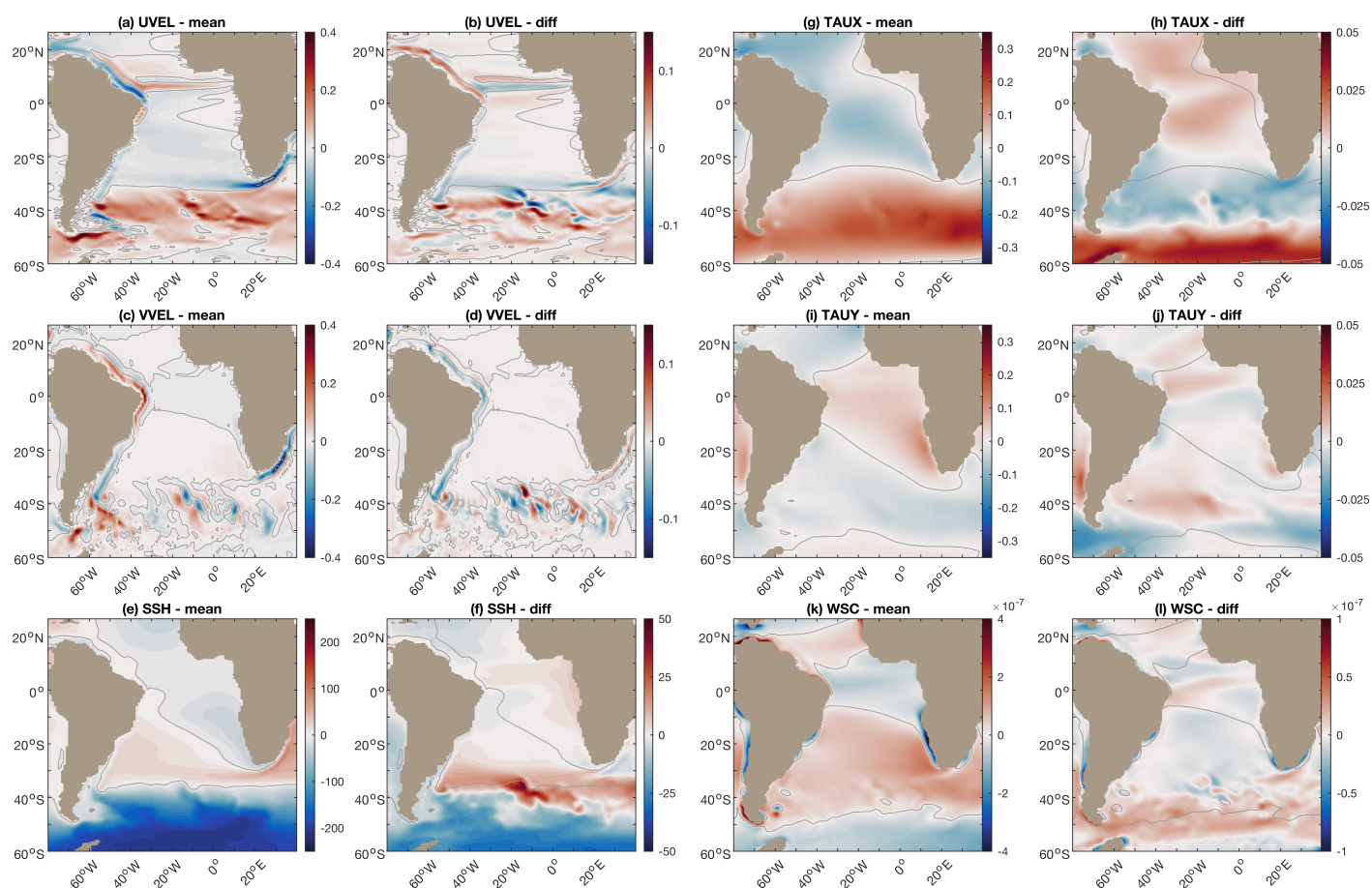
According to the zero SSH and zonally integrated WSC lines, the SASG southern boundary shifts poleward – following hemispheric-scale atmospheric trends (Figures S6c and S7).



Supplementary Figure 6: | Wind pattern changes | Trends along 1920-2100 with respect to the 1920-1970 base period. **(a)** Same as Figure 1 from the article, with focus on the South Atlantic, to aid visual interpretation. Superposing vectors denote the mean flow field while the background shading indicates the regions where ocean currents tend to strengthen (red) or weaken (blue). Please refer to article Figure 1 caption for further details. **(b)** Wind stress (superposing vectors) and wind stress curl (background shading) trends. Black (gray) vectors are plotted over regions where the horizontal wind stress magnitude is above (below) the 0.014 N.m^{-2} value, to aid visual presentation. The black contour represents the climatological zero wind stress curl line, which delimits the positive, anticyclonic wind stress curl at subtropical regions. **(c)** Sverdrup transport trends ($1 \text{ Sv} = 10^6 \text{ m}^3.\text{s}^{-1}$). The red (blue) dotted contour represents the mean 1920-1970 (2080-2100) zonally integrated zero wind stress curl line. Only statistically significant wind stress trend vectors are plotted, while points where wind stress curl trends (and also Sverdrup transport trends in **(c)**) are non-statistically significant are indicated by the white dots (the 95% confidence level was adopted). **(d)** Standardized time series of the mean positive anomalies of the absolute magnitude of horizontal velocities, of the wind stress curl and of the Sverdrup transport, averaged over the regions indicated by the yellow (a), blue (b) and green (c) boxes, respectively.



Supplementary Figure 7: | **Sea surface height field - mean and trends (1920-2100)** | **(a)** 1920-2100 mean sea surface height (SSH). Red (blue) represents positive (negative) SSH values and the black filled contour marks the zero SSH line. **(b)** 1920-2100 total trends of SSH anomalies (1920-1970 base period). Red (blue) background colors represent positive/increasing (negative/decreasing) trends, while the red (blue) dotted contour represents the mean 1920-1970 (2080-2100) zero SSH line.



Supplementary Figure 8: | Climatological fields over 1920-2100 (a, c, e, g, i, l) and their corresponding 2080-2100 *minus* 1920-1970 difference (b, d, f, h, j, m) | (a, b) Zonal velocities (UVEL, m.s⁻¹); (c, d) Zonal wind stress (TAUX, N.m⁻²); (e, f) Meridional velocities (VVEL, m.s⁻¹); (g, h) Meridional wind stress (TAUY, N.m⁻²); (i, j) Sea surface height (SSH, cm); (l, m) Wind stress curl (WSC, N.m⁻³). The respective climatological zero contours are reproduced over b, d, f, h, j and m, for reference.

11. Supplementary Discussion - Agreement between our results and those of previous studies:

The decreasing southward transport across box (4) in article Figure 2 is consistent with the recent spin-up of the South Pacific subtropical gyre (SPSG)^{1–4}, linked to an increase of the equatorward transport along its eastern boundary⁵. The reasoning is that less waters escape from the diffuse SPSG southeastern boundary to leak eastward towards the South American coast and join the flow through the DP. Based on mass conservation principles, a spun-up SPSG would increase the anticyclonic gyre transport, advecting more waters to the north at the eastern boundary, and therefore shedding less waters to the east at the southeastern base of the gyre, before closing the anticlockwise circulation loop. Despite the Pacific Ocean being out of our scope, this result also provides indirect evidence for the reported SHSG spin-up⁶.

Concerning our simulated change pattern over the AL-BeC-sSEC system (article Figures 1, 2, 4a), it should be noted that our results represent an average of the upper 985-m in the ocean (where SASG and AMOC upper limb pathways predominantly take place — see vertical profiles on Figure S1). Thus, even though the extension of the Agulhas leakage into the South Atlantic is mostly northwestward oriented at the surface layer^{7,8}, the westward (northward) component of its transport increases (decreases) with depth^{7,9}, following the subtropical gyre “bowl shape” at the northern boundary.

Accordingly, observational studies have reported a quasi-zonal path extending from the AL region towards the South Atlantic western boundary at intermediate depths^{10–13}. The CESM-LE ensemble mean simulates well the mean circulation field and the possibilities of AL-BeC-sSEC pathways across the South Atlantic basin (Figure 1, depicted by the superposing vectors), however, as background colors indicate the trends of the anomalous flow during 1920-2100, this suggests that external forcings are inducing a strengthening of this particular southern zonal route from the AL towards the South Atlantic western boundary into the future.

It is known that the AL amplitude and sensitivity to change might be compromised by inadequate resolution, and that to properly simulate the AL and its non-linear dynamics an effective resolution of at least 0.1° is needed¹⁴. Even though, a projected 21st century increase in the AL in response to Southern Hemisphere wind changes was also found with high-resolution ocean models that capture mesoscale processes of the Agulhas system^{15–17}, in agreement with our results. This suggests that mesoscale processes might be of secondary importance and that changes in basin-scale winds might explain a large component of the projected changes in the AL transport — which may be more reliable than projections for other variables that depend more critically on local processes¹⁸.

Our projected change pattern in the Agulhas system (weakened AC and strengthened AL transport) also resembles one recently found with CMIP5/CMIP6 simulations (see their Figure 1¹⁸) — where a projected decrease in the AC is shown, whereas the AC westward extension towards the SA intensifies. These authors state

that “the westward flowing AC extension south of Africa intensifies in all (28 CMIP5 and 25 CMIP6) models”. They also support a projected strengthening of the poleward BC and weakening of the cross-equatorial NBUC-NBC transport.

Also in accordance with our results, it has been shown that a simulated wind-driven increase in the AL happens along with a strengthening of the SASG, which leads to a favored recirculatory route at the SBL, resulting in less AL waters feeding into the NBC as part of the AMOC upper limb^{19,20}. In line with that, a projected intensification of the AL linked via interior pathways to an even greater increase in the BC strength (40%) was found with CMIP5 simulations²¹, along with a decrease in the northern SA basin interior and the downstream northward NBC transport.

Regarding the ACC-MC system and the Brazil-Malvinas confluence, our results point to an intensification of southern flows associated with the ACC transport from the Pacific across the Atlantic and into the Indian basin (Figures S2-S4), which seems to be associated with atmospheric induced trends, in agreement with some previous studies²²⁻²⁴. However, the anthropogenically-forced ACC response is inconsistent across future projections. Because the steeping of isopycnal surfaces induced by strengthened westerlies might either increase the ACC transport through Ekman pumping effects in some models (as described in Section 2.4 of the article) or lead to enhanced (parameterized) eddy-induced transports that act to then reduce the isopycnal slopes in others. The latter process, when acting in combination with a narrowing of the ACC (mainly caused by large poleward shifts of the subtropical gyres), can lead to a reduction in the ACC transport²⁵ – which in turn might lead to a decreased MC transport and a southward shift of the BMC²⁶.

Since our simulation results demonstrate a strengthened ACC and MC (article Figures 1, 2), we could not find a consistent southward shift of the Brazil-Malvinas Confluence (BMC)^{8,21,26,27} through the horizontal velocity fields, only the zero zonally integrated wind stress curl line depicts a southward shift of the gyre’s southern boundary at the BMC region (Figure S6c). Therefore we hypothesize that the strengthened MC might be hampering a southward shift of the BMC influenced by the wind anomalies in the CESM-LE.

In general, our results are in fair agreement with several other simulation and observational results recently reported in the literature. Cyclonic WSC anomalies over the Indian Ocean (Figure Sb) and a projected spin-down of its subtropical gyre coupled to a weakened AC transport are also shown under the RCP8.5 scenario in a warming climate²⁸. Based on observational data, a significant southward migration of the SASG southern boundary along 1993-2018 is found²⁹, though the authors did not find trends in gyre size or strength. In turn, a generalized strengthening of subtropical gyres in all three SH oceans (i.e. the SHSG) has been reported since 1993, using observational data and results from an ocean state estimate⁶. There is observational and model support for a strengthening and poleward movement of global WBCs in attribution to a positive SAM trend³⁰ – being the only exception the GS, which weakens along with the AMOC. Reanalysis data show that among all three southern subtropical oceans, the impact of SH climate trends over 1978-2002 was larger in the SA, with a 40% increase in the BC transport^{1,31}.

The CESM-LE shows to reproduce main climate trends according to the literature (e.g. the Southern Hemisphere atmospheric trends) and to predict a weakening of the AMOC as according to a set of CMIP5/CMIP6 model simulations³².

A wide range of processes of climate variability and change have been explored using the CESM1 Large Ensemble in previous studies^{33–37}, in good agreement with observations. The Atlantic climate and ocean state in CESM1 and in the Community Climate System Model, version 4 (CCSM4, which contains the same ocean component as CESM1) has also been discussed and compared against observations^{38–40}.

An extensive evaluation of the CESM1 ocean component (the Parallel Ocean Program version 2, POP2³⁸) over the South Atlantic and Southern Ocean⁴¹ shows that the simulated ocean variability over the Southern Hemisphere is dominated by the Southern Annular Mode (consistent with observations) and that the model represents well the frontal zones associated with the Antarctic Circumpolar Current, with their locations being “surprisingly well simulated”. However, the ACC transport and the Agulhas leakage are high relative to observations, and the correct location of the Brazil-Malvinas confluence is displaced southward. Since mesoscale features are not explicitly resolved in the model, the representation of some processes that result in water mass formation and interbasin exchanges might be compromised. Most relevant to our work is the fact that the model’s relative high viscosity (for compensating its inability to resolve mesoscale processes) produces boundary currents that are too viscous and lack the inertia necessary for retroflexion and ring shedding, as in the case of the Agulhas leakage. This overestimates the volume of water exchanged between the Indian and Atlantic Oceans. Still, these authors declare that the amount of Agulhas leakage that reaches the tropical Atlantic is reasonably close to what studies with higher-resolution models have found and that Agulhas leakage variability and trends are reasonably well captured.

12. Supplementary Discussion - Implications of AMOC upper limb and SASG changes:

Changes in the northward ocean heat transport accomplished by the AMOC upper limb^{42–44} might affect Atlantic multidecadal variability and many important climate phenomena, including Atlantic hurricane activity, U.S. drought frequency, European temperature/precipitation as well as Sahel/Indian monsoon and northeast Brazil rainfall^{45–50}. It also influences Arctic sea-ice extent^{51,52}, besides the oceanic uptake of heat and carbon^{53–58}.

In turn, wind-driven SASG changes might affect the rate and location of subtropical downwelling driven by the convergence of surface currents, influencing the vertical structure of the AMOC and also the rate of heat and carbon uptake, once subduction of water masses in the subtropics helps transfer heat downward and provides a pathway for the transport of anthropogenic CO₂ to greater depths^{59,60}. Since subtropical gyres are responsible for redistributing heat between the equator and high latitudes, anomalous heat transports along boundary currents might affect air temperatures over land and also increase the occurrence of marine heatwaves^{61,62}. Anomalous moist transport by the subtropical ocean may also influence drought/excess precipitation events over adjacent continental areas. Variations in the strength of the SASG are associated with variations in the strength of the South Atlantic Subtropical High (SASH) over the ocean surface^{63–65}, which induces phase shifts in the South Atlantic Subtropical Dipole (SASD) – the dominant mode of coupled ocean-atmosphere variability in the SA⁶⁶. The SASD is linked to sea surface temperature variations and heat flux anomalies that can influence South American and southern African climate variability, causing rainfall and temperature changes^{67,68}.

The wind-driven poleward expansion trend of the SASG and the SHSG also leads to a greater southward influx of warm water in the oceans, contributing to an increased rate of warming^{1,2}. From the 20th into the 21st century, the southern mid-latitudes have recorded the greatest heat content increase compared to all other latitudes, with the maximum zonally integrated warming occurring at 40°S^{69,70}.

Overall, changes in the transport of SASG boundary currents might affect the redistribution of heat⁷¹, dissolved gases and biogeochemical tracers^{72,73}, pollutants⁷⁴, plastic debris^{75,76}, nutrients⁷¹ and alter species dispersal (such as in the case of eggs and larvae)⁷⁷ – affecting surface primary productivity⁷⁸, altering the distribution of marine species^{79,80} and impacting regional fisheries in meaningful ways^{81,82}. As intensified WBCs transport more heat poleward⁸³, "tropicalisation" of marine communities is induced – meaning that warm-water species shift their distribution towards the poles in response to warming. This is already causing profound shifts in dominant foundation species and associated ecological communities⁸⁴.

In summary, projected changes in the AMOC upper limb and the SASG might translate into a series of climatic and ecosystemic impacts, posing threats that have the potential to trigger large socioeconomic implications^{85,86}.

Supplementary Table 1: | Volume transport values corresponding to the time series in article Figure 2 and the time series in Figures S2d, S3d and S4d | Mean transport averaged over 1920-1970; change in transport corresponding to the total period of 1920-2100; change in transport corresponding to the RCP8.5 period (2006-2100) and percentual change in transport (" % " = representing the amount of increase/decrease with respect to the 1920-1970 mean value). With exception of the 2006-2100 period from time series (16), all the presented trends (as "changes") are statistically significant at the 99% confidence level. All transport values are accompanied by the respective standard deviation.

Time series	1920-1970 mean	1920-2100 change	2006-2100 change	%
1 - ~Pacific ACC	101.9 ± 0.4 Sv	+ 7.5 ± 2.2 Sv	+ 7.3 ± 2.1 Sv	+ 7 %
2 - SA SAC/ACC	158.9 ± 0.7 Sv	+ 18 ± 5.2 Sv	+ 16.2 ± 4.8 Sv	+ 10 %
3 - ~Indian ACC	153.7 ± 0.6 Sv	+ 8.1 ± 2.4 Sv	+ 10.4 ± 3 Sv	+ 7 %
4 - Pacific 55°W	33.3 ± 0.4 Sv	- 7.2 ± 2.1 Sv	- 5.6 ± 1.6 Sv	- 18 %
5 - DP at 66°W	107.1 ± 0.8 Sv	+ 5.7 ± 1.6 Sv	+ 6.9 ± 2 Sv	+ 6 %
6 - DP at 59°W	103.9 ± 0.8 Sv	+ 4.8 ± 1.4 Sv	+ 6.5 ± 1.9 Sv	+ 6 %
7 - DP at 55°S	96.4 ± 1.8 Sv	+ 5.4 ± 1.6 Sv	+ 8.8 ± 2.6 Sv	+ 9 %
8 - MC system	113.5 ± 1.7 Sv	+ 10.6 ± 3.1 Sv	+ 15 ± 4.4 Sv	+ 13 %
9 - MC at 55°W	51.7 ± 1.1 Sv	+ 3 ± 0.9 Sv	+ 6.3 ± 1.8 Sv	+ 12 %
10 - BC at 55°W	24.3 ± 0.5 Sv	+ 18.4 ± 5.4 Sv	+ 16.3 ± 4.8 Sv	+ 54 %
11 - SAC at 55°W	84.1 ± 1.5 Sv	+ 24.6 ± 7.2 Sv	+ 25.2 ± 7.4 Sv	+ 28 %
12 - AL at 12°E	54.8 ± 0.4 Sv	+ 8.1 ± 2.4 Sv	+ 5.1 ± 1.5 Sv	+ 9 %
13 - southern sSEC	20.7 ± 0.7 Sv	+ 10.2 ± 3 Sv	+ 7.8 ± 2.3 Sv	+ 32 %
14 - BC at 37°S	33.7 ± 0.6 Sv	+ 14.5 ± 4.2 Sv	+ 14.5 ± 4.2 Sv	+ 39 %
15 - BC at 28°S	7.2 ± 0.4 Sv	+ 5.9 ± 1.7 Sv	+ 7.3 ± 2.1 Sv	+ 91 %
16 - central sSEC	18.1 ± 0.5 Sv	- 0.4 ± 0.1 Sv	+ 0.04 ± 0.01 Sv	+ 0.2 %
17 - northern sSEC	15.7 ± 0.3 Sv	- 2.4 ± 0.7 Sv	- 1.6 ± 0.5 Sv	- 11 %
18 - NBUC at 12°S	29.9 ± 0.6 Sv	- 9.1 ± 2.6 Sv	- 9 ± 2.6 Sv	- 33 %
19 - NBUC at 6°S	34.8 ± 0.7 Sv	- 11 ± 3.2 Sv	- 10.3 ± 3 Sv	- 32 %
20 - NBC at 40°W	32.1 ± 0.6 Sv	- 9.4 ± 2.8 Sv	- 9.3 ± 2.7 Sv	- 31 %
21a - nAMOC at 34°S	48.5 ± 0.5 Sv	- 1.2 ± 0.4 Sv	+ 0.4 ± 0.1 Sv	+ 0.9 %
21b - AMOC at 34°S	23.4 ± 0.6 Sv	- 9.1 ± 2.6 Sv	- 8.6 ± 2.5 Sv	- 41 %
22a - nAMOC at 24.5°S	30.7 ± 0.6 Sv	- 6.7 ± 2 Sv	- 6.1 ± 1.8 Sv	- 21 %
22b - AMOC at 24.5°S	19.3 ± 0.5 Sv	- 8.7 ± 2.5 Sv	- 8.3 ± 2.4 Sv	- 49 %
23a - nAMOC at 6.5°S	38.6 ± 0.7 Sv	- 11.7 ± 3.4 Sv	- 10.8 ± 3.2 Sv	- 31 %
23b - AMOC at 6.5°S	18.6 ± 0.5 Sv	- 8.8 ± 2.6 Sv	- 8.2 ± 2.4 Sv	- 50 %
24a - nAMOC at 26.5°S	57.2 ± 0.9 Sv	- 15.6 ± 4.5 Sv	- 12.7 ± 3.7 Sv	- 24 %
24b - AMOC at 26.5°S	25.5 ± 0.6 Sv	- 11.9 ± 3.5 Sv	- 10 ± 2.9 Sv	- 46 %

Supplementary Table 2: | Magnitude of changes in the meridional position of the SASG boundaries corresponding to the time series in article Figures 5 and 6 | Mean position averaged over 1920-1970; change in position corresponding to the total period of 1920-2100 (total trend) and change in position corresponding to the RCP8.5 period (2006-2100). Negative (positive) values express southward (northward) migrations. All long-term trends (expressed by "changes") shown are statistically significant at the 99% confidence level. All values are accompanied by the respective standard deviation. ZZVL = zero zonal velocity line, SBL = sSEC bifurcation latitude.

Time series	1920-1970 mean	1920-2100 change	2006-2100 change
(ZZVL-40°W)	36.1° ± 0.2°s	- 2.2° ± 0.6°s	- 1.5° ± 0.4°s
(ZZVL-30°W)	36.4° ± 0.1°s	- 2.3° ± 0.7°s	- 1.8° ± 0.5°s
(ZZVL-20°W)	37.4° ± 0.04°s	- 1.2° ± 0.4°s	- 0.8° ± 0.2°s
(ZZVL-5°W)	38.8° ± 0.03°s	- 0.3° ± 0.09°s	- 0.1° ± 0.04°s
(SBL-25 m)	18° ± 0.2°s	+ 0.3° ± 0.1°s	+ 0.6° ± 0.2°s
(SBL-50 m)	19° ± 0.1°s	+ 0.2° ± 0.07°s	+ 0.4° ± 0.1°s
(SBL-100 m)	19.8° ± 0.2°s	+ 0.4° ± 0.1°s	+ 0.5° ± 0.2°s
(SBL-250 m)	23.5° ± 0.1°s	+ 0.8° ± 0.2°s	+ 1.1° ± 0.3°s
(SBL-500 m)	26.4° ± 0.4°s	+ 2° ± 0.6°s	+ 2.5° ± 0.7°s
(SBL-500 m)	28.1° ± 0.2°s	+ 2.5° ± 0.7°s	+ 3.2° ± 0.9°s

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