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Increased transport of ocean currents due to global warming and its relationship to atmospheric pressure systems

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Introduction

Global circulation models are able to simulate the atmospheric and oceanic conditions in response to future radiative forcing and are used to project changes in the Earth system under specific scenarios. In the sixth phase of the Coupled Model Intercomparison Project (CMIP6), organized by the WCRP (World Climate Research Programme), the climate scenarios used to construct the future projections correspond to the Shared Socio-economic Pathways (SSPs) (Eyring *et al.*, 2016; IPCC, 2021; O'Neill *et al.*, 2016). The SSPs are complex and combine elements from their predecessors: the SRES (Special Report on Emissions Scenarios) and the RCPs (Representative Concentration Pathways). There are five SSP scenarios which define the radiative forcing stabilization by 2100, in which the SSP2-4.5 is an update of RCP4.5 from the previous IPCC (Intergovernmental Panel on Climate Change) report and represents a condition in which an 2°C global warming, relative to the beginning of the century, is extremely likely to occur. Global warming affects the ocean circulation patterns and heat pathways which in a positive feedback also affect the global climate. This work aims to investigate the possible changes in ocean currents and the mechanics of these changes, under future climate conditions.

Methods

To quantify the changes in the main global ocean current systems, monthly results from six global climate models were used: ACCESS-ESM1.5, CAMS-CSM1-0, CAS-ESM2.0, CESM2-WACCM, GFDL-ESM4, and MIROC6. Projections for surface winds, sea level pressure, sea surface height and ocean currents were extracted based on the first ensemble member of each model for the SSP2-4.5 scenario (projections for 2015 to 2100). The water volume transported by some western and eastern boundary ocean currents was calculated considering the cross-sections shown in Fig. 1. The north/southward migration of their origin was estimated from the changes in the core of the ocean currents they are derived from (dashed lines in Fig. 1), following the approach used by Toste *et al.*, 2019.

The results for the last 10 years were compared to the first 10 years available for this experiment and the differences (anomalies) were interpreted as due to climate change. The significance of the changes is defined using paired Student's t-tests. Changes observed in the ocean variables were related to the changes observed in the atmospheric fields.

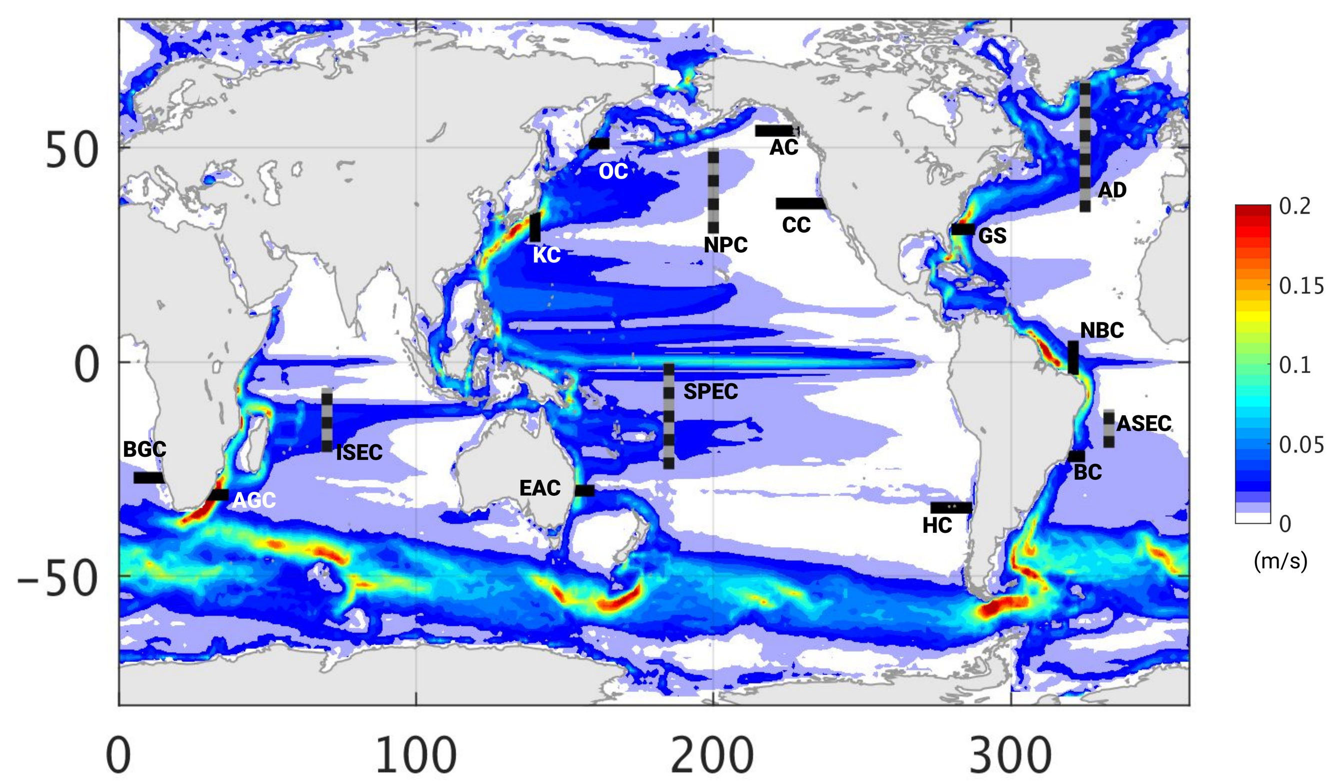

Fig. 1: Cross-current sections used to calculate the volume transport (black continuous lines) and the migration (black dotted lines) of ocean currents. The color shading represents the inter-model average speed, in meter per second, integrated in the upper 1000 m for the first 10 years of SSP2-4.5 experiment (2015-2025). Ocean currents abbreviations: BGC (Benguela), AGC (Agulhas), ISEC (Indian South Equatorial), EAC (Eastern Australia), KC (Kuroshio), OC (Oyashio), SPEC (South Pacific Equatorial), NPC (North Pacific), AC (Alaska), CC (California), HC (Humboldt), GS (Gulf Stream), NBC (North Brazil), BC (Brazil), AD (Atlantic Drift), and ASEC (Atlantic South Equatorial).

Results

- Oceanic changes

All the changes projected to the end of the century in the volume transport (VT) were consistent with changes in the current speed in the upper 1000 m (Fig. 2; Tables 1 and 2).

South Atlantic: BC and BGC VT are projected to increase (~19% and ~7%, respectively) while NBC's to decrease (~11%). These changes are in accordance with the northward migration of the southern branch of the SEC which favors the southward flow of BC, as also pointed by previous studies using CMIP5 models (Toste *et al.*, 2018; Pontes *et al.*, 2016).

North Atlantic: GS VT is projected to decrease at 31° N (~20%) and the position of the Atlantic Drift, which derives from GS flow, to shift 1.26° to the north.

Indian Ocean: AGC presents a consistent decrease in current speed along its path and its VT decreases by ~11% at 31°S, despite the northward migration of the Indian SEC, similar to that projected to the Atlantic.

South Pacific: The EAC and HC VT are projected to increase by ~3 and 19%, respectively, and the SPEC is projected to migrate 0.39° to the north.

North Pacific: Along with the northward migration of the NPEC, also verified by CMIP5 models (Toste *et al.*, 2019), the CC VT is expected to increase (~2%). Accordingly, KC VT is projected to increase and OC to decrease, however these changes are not statistically significant. With the NPEC migration, the AC VT would decrease with its shortening, however, this was not observed in the results and an increase of ~13% is projected.

Table 1: Volume transport, in Sverdrup, for each ocean current at the cross-current sections shown in Fig.1, for the beginning and end of the experiment. Significant changes are in bold and the percentage of models which agree in the sign of change are shown in the last column.

Ocean Current	VT Sv (2015-2025)	VT Sv (2089-2099)	Change (Sv)	Model agreement (%)
Brazil	3.39	4.05	**0.66**	83
North Brazil	35.75	31.80	**-3.95**	100
Benguela	7.72	8.29	**0.57**	67
Gulf Stream	53.09	42.41	**-10.68**	100
Agulhas	70.71	62.61	**-8.10**	100
Alaska	7.08	8.00	**0.92**	83
California	6.85	7.05	**0.20**	33
Kuroshio	43.03	43.14	0.11	50
Oyashio	23.36	23.08	-0.28	83
Eastern Australia	27.70	28.56	**0.86**	67
Humboldt	6.91	8.24	**1.33**	50

- Relationships with atmospheric changes

Changes observed in the VT of South Atlantic and South Pacific currents are in agreement with the displacement of ASEC and SPEC, respectively (Fig. 2; Table 2). The northward migration of these currents provides more steady flows in the analyzed sections since they are more distant from the currents' origins. These northward displacement follows a northwestward expansion of the subtropical highs, mainly in the South Atlantic (Fig. 3b).

For all the five currents evaluated, a northward migration was observed, and at the average latitude, a positive SLP anomaly was observed, except for the NPC.

In the western boundary of North Pacific, no significant changes were observed in ocean currents and it might be a response for multiple factors, as the migration of KC-OC confluence, as well as the intensification of west and south parts of the Aleutian Low (Fig. 3). Despite the significant NPC migration, models do not predict a reduction in AC VT as expected (e.g. Toste *et al.*, 2019) and the increase in CC is small. These results suggest the influence from intensified winds in the Aleutian Low and weakened winds in the eastern portion of the subtropical high (Fig. 3b).

In the Indian Ocean, despite the northward migration of the SEC, its speed is decreased and then the AGC is not enhanced (Fig. 2). The SEC flow is decreased since it is under influence of slower winds due to the shifted position of the subtropical high (Fig. 3b). Besides that, negative anomalies are observed in AGC region, different from what occur in the region of BC (Fig. 3a).

Table 2: Average position for the origin currents for the beginning and end of the experiment. Significant changes are in bold and the percentage of models which agree in the sign of change are shown in the last column.

Ocean Current	Latitude (2015-2025)	Latitude (2089-2099)	Change (deg.)	Model agreement (%)
Atlantic Drift	45.13 N	46.40 N	**1.26**	67
Atlantic sSEC	17.01 S	16.75 S	**0.26**	67
Indian sSEC	12.92 S	12.65 S	**0.27**	83
North Pacific Current	41.36 N	43.01 N	**1.65**	67
South Pacific Equatorial Current	14.30 S	13.91 S	**0.39**	83

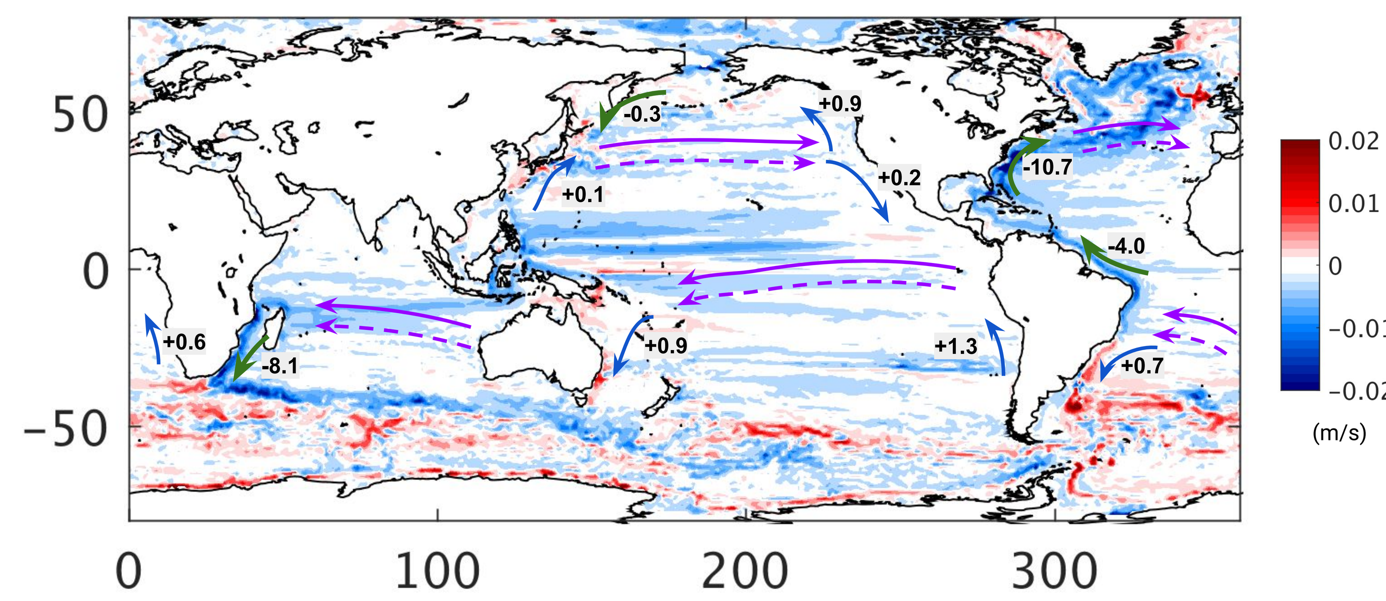

Fig. 2: Current speed anomalies (2089-2099 minus 2015-2025, color shading) for the upper 1000 m, in meter per second. Blue (green) arrows represent ocean current with enhanced (decreased) volume transport and the labels are the anomalies in Sverdrup. Purple dashed (continuous) arrows represent the positioning of the currents in the beginning (end) of the evaluated experiment.

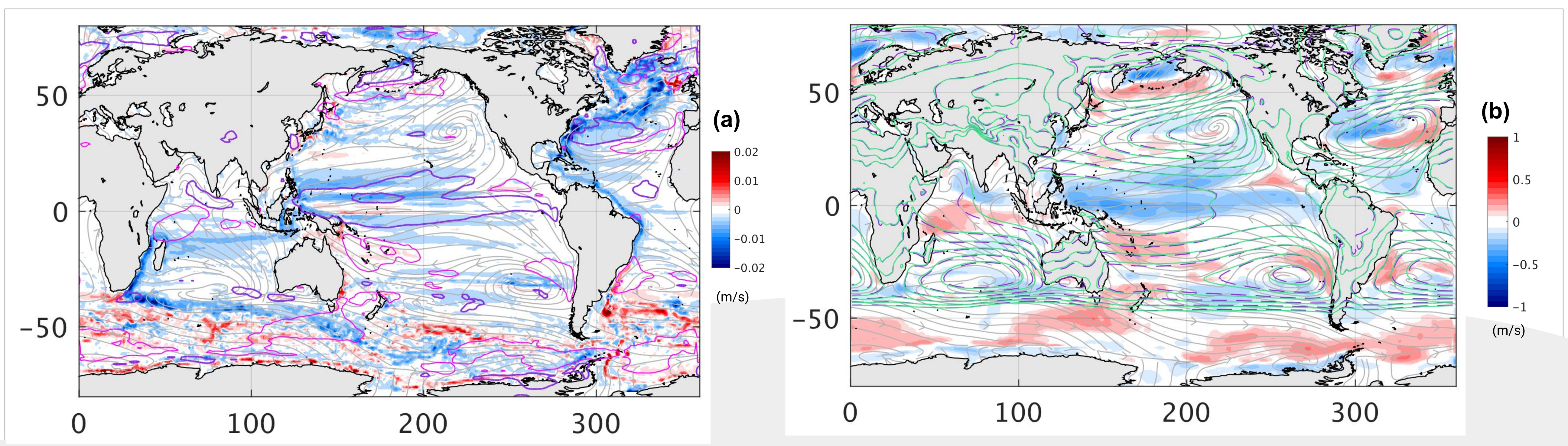

Fig. 3: (a) Current speed anomalies (2089-2099 minus 2015-2025, color shading) for the upper 1000 m, in meter per second, surface winds for 2015-2025 (gray streamlines), and the areas with positive (negative) anomalies in the surface wind speed represented by magenta (purple) lines. (b) Surface wind speed anomalies (2089-2099 minus 2015-2025, color shading), in meter per second, surface winds for 2015-2025 (gray streamlines), and sea level pressure isobars (from 1010 to 1020 hPa) for the first (purple dashed lines) and last (green lines) ten years of SSP2-4.5 experiment.

Final remarks

These preliminary results indicate the westward expansion of subtropical pressure highs which favors the north and southward flow of the subtropical gyres currents in the Southern hemisphere (BC, BGC, EAC, and HB), except for the Indian Ocean, where this migration leads to weakened currents due to the influence of weaker winds. On the other hand, this migration in the Northern hemisphere slow down the GS in the Atlantic, and in the North Pacific no significant changes and straightforward relationships were inferred from the results.

Further analysis are necessary to better understand the presented changes and also to better represent the ocean currents by each model, since they have different energetics, mainly due to different spatial resolutions, and then ocean features mismatch both in shape and positioning. Next steps include to consider more ensemble members/models and to consider individually each model to decide the boundaries defining each ocean current.

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