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Changes in the South Atlantic Subtropical Gyre circulation from the 20th into the 21st century

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Whatever discipline you are in...

Do what only you can do best.

Make good art.

~ Neil Gaiman

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Acho que quando decidimos entrar num questionamento profundo sobre o que realmente importa, chegamos à conclusão de que o propósito mais puro e nobre é sempre *agregar valor*, de alguma forma. Então quando entendemos isso, paramos de ter tanto medo.

Este trabalho é novamente só um começo, de eu tentando ser um pouquinho melhor na minha busca por algo significativo. Estou e estarei em constante fase de aperfeiçoamento, e acredito que devemos sempre ser humildes para reconhecer e admitir que nada sabemos perto do universo de conhecimento que nos espera. O importante mesmo é despertar para a curiosidade. Eu sempre sonhei em ‘ser cientista’ e hoje posso dizer que o meu objetivo é conseguir comunicar ciência para o mundo, de alguma forma, através da minha pesquisa. Acho também que se cada um buscar deixar sua marca em algo específico, por menor que seja, mas que seja verdadeiro e significativo, o mundo vai ser um lugar melhor.

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“ De acordo com *Seneca*, a palavra grega *eutimia* é uma sobre a qual deveríamos pensar com mais frequência. É o senso do nosso caminho, como segui-lo sem ser distraído. É sobre ser quem você é, e ser o melhor possível nisso. Sem sucumbir à todas as coisas que possivelmente te distanciam disso. É sobre ir para onde você determinou que ia. Sobre realizar o melhor que *você* é capaz, e realizar o que *você* escolheu. (Ser a melhor versão de você mesmo.)

Por outro lado, *eutimia* significa perfeita tranquilidade ou serenidade de espírito, sereno contentamento. É hora de sentar e pensar sobre o que é realmente importante para você. E então dar um passo atrás para abandonar todo o resto. Sem isso, o sucesso não será prazeroso, ou sequer tão completo como poderia ser. Ou pior, não irá durar.

Quando você não sabe do *quanto* você precisa, o padrão facilmente se torna ‘mais’.

Então, sem pensar, energia crítica é desviada em função disso. Quando se combina insegurança com ambição, se adquire uma inabilidade em dizer *não* às coisas.

O ego nos faz querer tudo e, eventualmente, estamos dizendo *sim* demais. Por razões que nem sequer compreendemos. Mas você precisa saber. Você precisa saber o que você *não quer* e o *que* as suas escolhas vão impedir. Porque as estratégias são em geral mutualmente exclusivas; a vida requer trocas, mas o ego não permite.

Por que você faz o que faz?

Essa é a pergunta que você precisa responder.

Encare ela até não poder mais. Só então você vai entender o que importa e o que não. E só então você pode dizer não; você pode optar por abandonar competições estúpidas que não fazem sentido ou nem mesmo existem.

Quanto mais você tem e faz, mais difícil será manter fidelidade ao seu propósito, mas o mais criticamente você precisará. Todos caem no mito de que, *se ao menos tivessem ‘aquilo’* — geralmente o que outra pessoa tem — seriam felizes. Talvez seja preciso “se queimar” algumas vezes para perceber o vazio dessa ilusão.

Todos nós ocasionalmente nos vemos em meio a um projeto ou obrigação e não conseguimos entender porque estamos lá. Será preciso coragem e fé para se auto-impedir.

Descubra por que você está atrás do que está atrás. Ignore aqueles que confundem seu caminho. Deixe que eles cobicem o que você tem, e não o contrário. Porque *isso* é independência.”

¹ Também como uma forma de agradecimento à toda a minha família e amigos, que frequentemente me perguntam sobre o que eu estou estudando, elaborei um simples *Resumo Informal* para esses leitores de fora da área de Oceanografia Física que estão folhando o meu trabalho. Está apresentado como *Apêndice I*, ao final do documento.

Abstract

Through analysis of large-scale ocean gyre dynamics from simulation results of the ocean component of the Community Earth System Model version 1 – the Parallel Ocean Program version 2 (CESM1-POP2) – this study builds upon existing research suggesting recent changes in the circulation of global subtropical gyres with respect to the South Atlantic Ocean. Results all point to an increase in the total counterclockwise circulation and a southward displacement of the subtropical gyre system. The northern boundary of the South Atlantic Subtropical Gyre (SASG) is represented by the bifurcation of the southern branch of the South Equatorial Current (sSEC) into the North Brazil Undercurrent/Current (NBUC/NBC) to the north and the Brazil Current (BC) to the south. The sSEC Bifurcation Latitude (SBL) dictates the partition between waters flowing poleward and those flowing equatorward. Although a northward migration of the SBL would be expected with the gyre spin up and associated poleward transport increase, the SBL migrates southwards at a rate of $0.051^{\circ}/\text{yr}$, in conjunction to a substantial increase in the equatorward advection of waters within the sSEC-SBL-NBUC system, which is included in the upper-branch of the Atlantic Meridional Overturning Circulation.

Keywords: South Atlantic Ocean. Subtropical gyre circulation. sSEC Bifurcation Latitude. Southward migration.

Resumo

Através de análises da dinâmica de grande-escala do giro oceânico, proveniente dos resultados de simulação da componente oceânica do *Community Earth System Model* versão 1 – o *Parallel Ocean Program* versão 2 (CESM1-POP2) – este estudo se baseia em estudos prévios sugerindo mudanças recentes na circulação dos giros subtropicais globais, com respeito ao oceano Atlântico Sul. Os resultados apontam para uma intensificação da circulação anti-horária e um deslocamento para sul de todo o sistema do giro subtropical. A borda norte do Giro Subtropical do Atlântico Sul (GSAS) é representada pela bifurcação do ramo sul da Corrente Sul Equatorial (CSEs) em Subcorrente/Corrente Norte do Brasil (SCNB/CNB) para norte e Corrente do Brasil (CB) para sul. A Latitude da Bifurcação da CSEs (LBC) determina a partição entre as águas fluindo em direção ao pólo e aquelas fluindo em direção ao equador. Embora seja esperada uma migração para norte da LBC com a aceleração da circulação do giro e consequente aumento do transporte em direção ao pólo, a LBC migra para sul a uma taxa de $0.051^\circ/\text{ano}$. Esta migração ocorre em conjunto à um aumento substancial na advecção de águas em direção ao equador com o sistema CSEs-LBC-SCNB, o qual está incluso no ramo superior da Circulação de Revolvimento Meridional do Atlântico.

Palavras-chave: Oceano Atlântico Sul. Circulação de giro subtropical. Latitude da Bifurcação da CSEs. Migração para sul.

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List of Abbreviations

ACC	Antarctic Circumpolar Current
AMOC	Atlantic Meridional Overturning Circulation
BC	Brazil Current
BeC	Benguela Current
BMC	Brazil-Malvinas Confluence
BSF	Barotropic Stream Function
BSF0	Zero BSF Line
BSF0s	BSF0 at southern edge
CESM	Community Earth System Model
CFSR	Climate Forecast System Reanalysis
ECMWF	European Center for Medium-Range Weather Forecasts
ENSO	El Niño - Southern Oscillation
GFDL	Geophysical Fluid Dynamics Laboratory
GODAS	Global Ocean Data Assimilation Systemgulf
MC	Malvinas Current
MOC	Meridional Overturning Circulation
NAO	North Atlantic Oscillation
NBC	North Brazil Current
NBUC	North Brazil Undercurrent
NCEP	National Centers for Environmental Prediction
NEC	North Equatorial Current
NP	Northernmost Position
NPO	North Pacific Ocean
ORAS4	Ocean Reanalysis System 4
PDO	Pacific Decadal Oscillation
POP	Parallel Ocean Program
SAO	South Atlantic Ocean
SAC	South Atlantic Current

SASG South Atlantic Subtropical Gyre

SBL sSEC Bifurcation Latitude

sSBL sSEC Bifurcation Latitude at the surface

SEC South Equatorial Current

cSEC central branch of the South Equatorial Current

eSEC equatorial branch of the South Equatorial Current

nSEC northern branch of the South Equatorial Current

sSEC southern branch of the South Equatorial Current

SECC South Equatorial Countercurrent

SEUC South Equatorial Undercurrent

SH Southern Hemisphere

SIO South Indian Ocean

SODA216 Simple Ocean Data Assimilation version 2.1.6

SP Southernmost Position

SPO South Pacific Ocean

SSH Sea Surface Height

SSH0 Zero SSH Line

SSH0s SSH0 at southern edge

SST Sea Surface Temperature

SVT Sverdrup Transport

SVT0 Zero SVT Line

SVT0n SVT0 at northern edge

WBC Western Boundary Current

WSC Wind Stress Curl

WSC0 Zero WSC Line

1 Introduction

1.1 Subtropical gyres and climate variability

Anticyclonic subtropical gyres dominate the circulation at midlatitudes in each of the five ocean basins, providing a major pathway for water in the subtropics to be transported to the equator and high latitudes, which is believed to play a key role in modulating the world's climate system. Subtropical gyres circulation is, therefore, closely related to global climate variability.

The South Atlantic Ocean (SAO), for instance, is characterized by substantial variability from intraseasonal to interdecadal and longer time scales, which have significant impacts on neighbouring South America and southern Africa, as well as further afield (Wainer and Venegas, 2002). Although the mechanisms associated with this variability remain poorly understood, modulations of the South Atlantic anticyclone and the subtropical gyre seem to play a central role (International CLIVAR Project Office, 2007; Lübbecke et al., 2014; Cabos et al., 2016).

Furthermore, interactions between physical and biological processes within the subtropical gyres are also critical in determining the magnitude and variability of the carbon exported from the surface to the deep ocean. Ecosystem indicators which are present in subtropical gyres respond to climate variability (Karl et al., 2001; Andreas Oschlies, 2001), since physical-biological coupling between climate cycles (such as the El Nino-Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), the North Atlantic Oscillation (NAO) and so on) and ecosystem dynamics is a consequence of altered nutrient flux pathways that result from changes in the stratification and circulation of the subtropical gyres (McClain et al., 2002).

Over the past century, there has been direct and indirect evidence supporting changes having occurred in the subtropical gyres (Hu et al., 2015). These changes include an intensification (Li et al., 2012, 2013) and poleward expansion (Saenko et al., 2005; Zhang et al., 2013) of these oceanic gyres in both hemispheres, featuring a southward shift of the position of zero wind stress curl in the mid-latitudes of the Southern Hemisphere (SH) and a spin-up of the Southern Ocean super-gyre (Alory et al., 2007; Beal et al., 2011; Biastoch et al., 2009; Cai et al., 2005; Cai, 2006; Roemmich et al., 2007; Roemmich, 2007; Saenko et al., 2005) associated with changes in ozone and CO₂ forcing (Cai and Cowan, 2007; Arblaster et al., 2011; Polvani et al., 2011) which project onto the Southern Annular Mode (SAM). The SAM is the dominant mode of the SH extratropical circulation (e.g., Thompson and Solomon, 2002; Marshall, 2003).

Moreover, in conjunction with a systematic change in winds over both hemispheres, it is found an accelerated surface ocean warming along the path of global subtropical western boundary currents (WBCs) in association with a synchronous poleward shift of their mid-latitude extensions and/or an intensification in their strength (Wu et al., 2012).

The aforementioned studies are rather focused on other individual ocean basins or take a more global perspective. Relative to the South Atlantic Subtropical Gyre (hereafter, SASG) circulation, however, little is known about its basin-scale climate variability and long-term changes.

Except for the numerical coupled model analysis from Wainer et al. (2004), who suggested an increased barotropic transport associated with the intensification of the SASG and the ACC under a global warming scenario; and for the recent study by Pontes et al. (2016), based on 19 models from the Coupled Model Intercomparison Project phase 5, which show projections of changes in large-scale features of the SAO circulation under increasing greenhouse gases; previous studies have mainly addressed features located further south, especially the Brazil-Malvinas Confluence (BMC), which is documented to be drifting southwards (Goni et al., 2011; Lumpkin and Garzoli, 2011; Combes and Matano, 2014; Pontes et al., 2016).

It is particularly important, though, to better investigate the SAO circulation variability as a whole, considering it takes place in the only basin which is in direct contact with all the other major oceans and therefore in a rather unique position to influence their inter-basin exchanges (International CLIVAR Project Office, 2007).

The pattern of gyre-scale flow in the SAO is strongly influenced by these interocean connections, which play an important role in the thermohaline circulation (Reid, 1994). These interocean exchanges permit the thermohaline regimes of neighboring oceans to interact on a variety of timescales. In this process, external forcings may induce variability in the South Atlantic boundary currents, which may, in turn, impact the whole of the SASG. Studies of the gyre-scale circulation and of low-frequency variability in the boundary current regimes may, therefore, provide insight to variations of the thermohaline circulation (Witter and Gordon, 1999).

1.2 The South Atlantic Subtropical Gyre and the sSEC Bifurcation

Transfer of heat and salt of the northward return limb of the Atlantic Meridional Overturning Circulation (AMOC) takes place in the upper Atlantic Ocean where the Agulhas Leakage plays a significant role according to recent studies (e.g., Donners and Drijfhout, 2004; Gordon et al., 1992; Gordon, 1985, 1986; Holfort and Siedler, 2001; Rodrigues et al., 2010; Weijer et al., 2001; Weijer and Ruijter, 2002). Therefore, the SAO circulation is remarkable in at least two major ways: this intermittent supply of heat and salt received from the South Indian Ocean (e.g., Beal et al., 2011; Richardson, 2007; de Ruijter et al., 1999) and the anomalous net northward heat transport occurring in the low and midlatitudes (e.g., Vellinga and Wu, 2004). With the SAO being the critical crossroad for the meridional circulation, the underlying cause-response relations between its wind-driven features and the overturning components are undeniable.

The SASG encompasses a system of wind driven surface currents (e.g., Peterson and Stramma, 1991; Stramma and England, 1999) (Figure 1). It is comprised by the southward western boundary Brazil Current (BC), flowing along the South American coast until it meets the north-eastward extension of the ACC into the Atlantic, the MC, characterizing the BMC (Garzoli, 1993; Gordon, 1985, 1989). From there on, an eastward meandering flow is formed, originating the South Atlantic Current (SAC) (Stramma and Peterson, 1990), which is the southern limb of the

subtropical gyre. The SAC partially feeds the eastern boundary Benguela Current (BeC), recirculating within the subtropical gyre. The BeC then heads northwestward turning into the southern branch of the South Equatorial Current (sSEC), which is the one that forms the northern edge of the subtropical gyre (Stramma, 1991; Goni et al., 2011). The broad, westward flowing sSEC carries these subtropical waters towards the Brazilian shelf region, where it bifurcates around 15°S, closing the subtropical gyre by flowing into the southward BC (Reid, 1994; Rodrigues et al., 2007; Stramma et al., 1990).

The bifurcation of the sSEC also gives rise to an equatorward low-latitude WBC - the North Brazil Undercurrent (NBUC), besides the subtropical BC. As the sSEC splits into two branches, the sSEC Bifurcation Latitude (hereafter, SBL) becomes an important indicator of the partition of the sSEC mass, heat and salt between its northward and southward components. The SBL is indicative of how much subtropical water bends equatorward to flow into the tropical/equatorial region via the NBUC and how much turns poleward recirculating in the subtropical gyre via the BC; given that as the sSEC bifurcation moves southward (northward) the NBUC transport increases (decreases) and the BC transport decreases (increases) (Rodrigues et al., 2007 — hereinafter referred to as R2007).

Many studies have been developed for the long-term variation of equatorial currents' bifurcation in other ocean basins, which suggest that there has been a synchronous southward shift of the Pacific North and South Equatorial Current (NEC and SEC) bifurcations over the past 60 years (Chen and Wu, 2012 and Zhai et al., 2014, respectively; summarized in Fig. 4 from Hu et al., 2015). As for the SAO, however, previous studies have only described the sSEC bifurcation mean position (Boebel et al., 1999; Harper, 2000; Malanotte-Rizzoli et al., 2000; Stramma and England, 1999; Wienders et al., 2000) or even investigated its seasonal variability and mechanisms involved (R2007).

The sSEC bifurcation in the SAO can have important consequences for climate variability. Besides setting the northern limit of the SASG, it involves other two important scenarios regarding the large-scale SAO circulation: the sSEC-SBL-NBUC system is the main conduit for upper-ocean return flow of the Meridional Overturning Circulation (MOC) (Talley, 2003; Ganachaud, 2003; Lumpkin and Speer, 2003) and for the subtropical–tropical mass exchange (McCreary and Lu, 1994; Malanotte-Rizzoli et al., 2000; Zhang et al., 2003).

It is worth mentioning that, in the Atlantic Ocean, nearly 2/3 of the water encountered in the equatorial thermocline comes from the South Atlantic and not from the North Atlantic (Metcalf and Stalcup, 1967; Wilson et al., 1994; Schott et al., 1995; Harper, 2000; Zhang et al., 2003). The presence of the northward upper limb of the MOC in the SAO increases the flow of the equatorward western boundary current (the NBUC), diminishing the poleward BC transport.

The path along the warm route of the AMOC depicts a northward advection through the BeC-sSEC-NBUC-NBC crossing the equator and joining the Gulf Stream in the northern hemisphere, followed by complex pathways from the subtropics to the subpolar gyre and Nordic Seas. The participation of the sSEC bifurcation in this scenario illustrates an external forcing mechanism

Figure 1 | Schematic representation of upper South Atlantic circulation. | Shown are the major wind-driven currents (black arrows) and mean Wind Stress Curl (N.m^{-3} , background colors). Abbreviations are used for the South Atlantic Subtropical Gyre (SASG), Brazil Current (BC), South Atlantic Current (SAC), Benguela Current (BeC), southern branch of the South Equatorial Current (sSEC), sSEC Bifurcation Latitude (SBL), North Brazil Undercurrent (NBUC), Equatorial Undercurrent (EUC), Antarctic Circumpolar Current (ACC) and Malvinas Current (MC). Adapted from Pontes et al. (2016) [Figure 1 from their Supplementary Information].

that can influence the SBL, which is also controlled by subsurface, thermohaline induced fluxes apart from the wind-forcing.

For this reason, besides investigating the SASG structure, this work attempts to elucidate the relative behaviour of its northern boundary, represented by the SBL, amidst ongoing

global climate changes.

This work is organized as follows: Section 2 briefly describes the models and methods used. Section 3.1 presents a validation of the model results with reanalysis product data together with a characterization of the sSEC bifurcation. Section 3.2 addresses the main goal of this study, so that, initially, the long-term change of the SBL is assessed, then a general description of its annual cycle is provided. Section 3.3 and 3.4 show the results concerning the SASG basin-wide dynamics and the transport of the SAO currents, respectively, in which Section 3.4.3 relates the change in the SBL with the change in the transport of currents. Section 3.5 describes observed recent changes relative to a longer record, comprised by the Last Millennium (850-2005). And Section 4 provides a summary of the main conclusions.

1.3 Scientific Hypothesis

It has been suggested that mid-latitude gyres in all of the oceans have been affected by variability in the atmospheric forcing (Section 1.1 and references therein). The present study investigates this hypothesis for the SAO, by examining its basin-wide dynamics.

Furthermore, the long-term change of the SASG northern boundary, represented by the sSEC bifurcation, is addressed. Because it is included in the AMOC upper branch return flow, variations in the SBL may be attributable both to variations in the wind driven subtropical circulation and to altered thermohaline induced fluxes.

Therefore, in order to obtain a comprehensive picture of the possible changes in the upper SAO circulation, exploring only its gyre scale dynamics might not be sufficient. The SBL must be investigated apart, which includes considering both its subtropical southward component (the BC) and the low-latitude northward NBUC.

Our hypothesis is that the SASG circulation is undergoing substantial changes along with worldwide subtropical gyres. The relative behaviour of the SBL amongst this scenario is still unknown. Our primary goal consists in elucidating this question.

1.4 Objectives

1.4.1 Central Objective

The central objective of this study is to answer two principal questions:

1) Is the SASG circulation changing, as inferred by the literature that signals in other ocean basins are likely to have a global expression (Roemmich et al., 2007) and/or manifest as a intensifying, southward shifting Southern Ocean super-gyre circulation (Cai, 2006)?

2) Does the SBL manifest a long-term trend and, if so, what is the mechanism primarily controlling it?

1.4.2 Explicit Objectives

The explicit objectives are:

► Using simulation results from the ocean component of the *Community Earth System Model* (CESM) for the 1948-2015 period:

1) To first assess the SBL time series, derived from meridional velocity data, in order to identify significant linear trends;

2) To assess the SASG dynamics through signals in WSC, SSH, BSF and SST fields in order to detect variations in its counter-clockwise circulation strength and/or position plus spatial distribution along the basin;

3) To investigate the long-term change of the transport of the currents involved in the process of the sSEC bifurcation and how they relate to the previous results obtained.

► And using simulation results from the *Last Millennium Ensemble* experiment of the CESM for the 850-2005 period:

4) To provide a wider temporal perspective of the observed changes.

2 Methods

2.1 Data

This study examines the simulation results of the ocean component of the Community Earth System Model, version 1 (CESM1.0): the Parallel Ocean Program version 2 (POP2), which is hereafter referred to as CESM-OCN. The CESM-OCN data set is used to investigate changes which have occurred along the late 20th century into the beginning of the 21st century.

Simulation results from the *Last Millennium Ensemble* experiment of the CESM (hereafter, CESM-LME), are also analyzed in order to provide a perspective from a longer record of climate variability, which represents an opportunity to understand how the climate system varied under "natural" conditions, before anthropogenic forcing became significant.

To validate the model results, a set of five ocean reanalysis products is used to compare the mean circulation fields and to access the accuracy in reproducing the main feature addressed by this study — the sSEC bifurcation.

More details concerning each data set mentioned above is provided in the following subsections.

2.1.1 The *Community Earth System Model*

The Community Earth System Model (CESM) (Hurrell et al., 2013) is a coupled global climate model that provides state-of-the-art computer simulations of the Earth's past, present, and future climate states. It is composed of four separate models simultaneously simulating the earth's atmosphere, ocean, land surface and sea-ice, and one central coupler component.

The coupled components include an atmospheric model (e.g., the Community Atmosphere Model, version 5 - Neale et al., 2010), a land-surface model (e.g., the Community Land Model, version 4 - Lawrence et al., 2009), an ocean model (the Parallel Ocean Program, version 2 - Smith et al., 2010), and a sea ice model (e.g., the Community Ice CodE - Hunke et al., 2015).

The central coupler coordinates the models and passes information between them. During the course of a CESM run, the model components integrate forward in time, periodically stopping to exchange information with the coupler. The coupler meanwhile receives fields from the component models, computes, maps, and merges this information, then sends the fields back to the component models. The coupler brokers this sequence of communication interchanges and manages the overall time progression of the coupled system.

In this study, CESM-OCN refers exclusively to the CESM ocean component; while CESM-LME refers to simulation results from the *Last Millennium Ensemble*, which employs version 1 of CESM with the configuration of individual model components given as the above examples.

2.1.2 CESM-OCN

The CESM ocean component is a level-coordinate ocean general circulation model that solves the three-dimensional primitive equations for ocean dynamics. The version used is based on the POP version 2.1 of the Los Alamos National Laboratory. The ocean model has a 1° horizontal resolution and 60 vertical levels. For the details of the numerical methods and discretization used, the reader is referred to "The POP Reference Manual" (Smith et al., 2010).

2.1.3 CESM-LME

The CESM Paleoclimate Working Group at NCAR conducted a series of Last Millennium community experiments, referred to as the *Last Millennium Ensemble* (LME). The experiment includes a set of simulations forced with the transient evolution of solar intensity, volcanic emissions, greenhouse gases, aerosols, land use conditions, and orbital parameters, both together and individually; for the period 850-2005. It employs version 1.1 of CESM with the CAM version 5 [CESM1(CAM5); Hurrell et al., 2013]. The CESM-LME uses 2-degree resolution in the atmosphere and land components and 1-degree resolution in the ocean and sea ice components. Please refer to the overview paper of the Last Millennium Ensemble Project (Otto-Bliesner et al., 2016) for more details.

To investigate the long-term change in the SBL and in the SASG dynamics, the present study examines the ensemble average of 10 simulations with the full-set of external forcings.

2.1.4 Ocean Reanalysis Products

In order to validate the CESM data-set, we used five ocean reanalysis products for comparison: the European Center for Medium-Range Weather Forecasts (ECMWF) ocean analysis/reanalysis system 4 (ORAS4), the Geophysical Fluid Dynamics Laboratory (GFDL), the Simple Ocean Data Assimilation version 2.1.6 (SODA216), the Global Ocean Data Assimilation System (GODAS) and the Climate Forecast System Reanalysis (CFSR) from the National Centers for Environmental Prediction (NCEP) (Table 1).

Table 1: Time period, horizontal resolution and number of vertical layers above 1000 m of the 5 ocean reanalysis products.

Product	Period	Horiz. Resolution	Vertical Layers - 1000 m
ORAS4	1960-2010	$1^\circ \times 1^\circ$	26
GFDL	1961-2010	$1^\circ \times -$	34
SODA216	1960-2008	$0.5^\circ \times 0.5^\circ$	22
GODAS	1980-2010	$1^\circ \times 1/3^\circ$	31
CFSR	1980-2010	$0.5^\circ \times 0.5^\circ$	31

* The latitudinal resolution of the GFDL reanalysis varies between approximately 0.33° near the equator to 1° near 30°S .

2.2 Variables and indices

This study covers a domain ranging from 55°S to the equator, between South America and Africa (70°W-20°E). The analysis are based on the data-sets of zonal and meridional total velocities (UVEL, VVEL), zonal and meridional wind stress (TAUX, TAUY), Sea Surface Height (SSH), Barotropic Stream Function (BSF) and Sea Surface Temperature (SST).

The Wind Stress Curl (WSC) field, was derived from TAUX and TAUY data; and finally, the Sverdrup Transport (hereafter, SVT) field was derived by zonally integrating the WSC field from the eastern to the western basin (e.g., Stewart, 2008).

2.2.1 SBL definition

The SBL index was obtained by first zonally averaging the meridional velocities within a 4° longitude band off the South American coast and finding, at each time step, the latitude of transition from negative (southward) to positive (northward) velocities, i.e., the zero meridional velocity, in each level of interest of the linearly interpolated vertical profile (at 25 m intervals).

Since the focus of this study is the surface layer, which is in direct contact with the major forcings of upper ocean circulation, only the SBL time series at 25 m and at 100 m are displayed. We construct monthly time series for these individual upper levels, instead of averaging the bifurcation latitude over a whole vertical layer. The poleward shift with depth of the sSEC bifurcation in the SAO is more pronounced than that of the bifurcations from the North Pacific, South Pacific and South Indian oceans (hereafter, NPO, SPO and SIO). Our results show that the SBL poleward tilting for the top 400 m is at least of 10°S (Section 3.1), while (Chen et al., 2014) find a corresponding shift of only 1.5°S for the SBL off Madagascar, in the SIO. Likewise, R2007 find a shift of approximately 14° of latitude in the top 1000 m, in contrast to the shift of the NBL in the NPO, which does not exceed 8° of latitude (compare Fig. 3 in R2007 with Fig. 11 in Qu and Lukas, 2003); consequently, the SBL varies a great deal within vertical layers.

As argued by Chen and Wu (2012) with regard to the Pacific NBL, the bifurcation latitude defined by meridional velocity is not sensitive to different averaging longitudes. A band of 4° longitude was adopted in order to favour WBCs representation in conjunction with the sSEC bifurcation vertical profile in Section 3.1. A 2° longitude band, for instance (as used by R2007) yielded virtually the same results.

2.2.2 SASG dynamical indices

Changes in the SASG dynamics were inferred from variations in WSC, SSH, BSF and SST fields (Figure 2). However, alternative approaches were applied to the WSC, SSH and BSF fields, whose spatial distributions are given through enclosed contours within the South Atlantic basin, rather than meridionally varying ones, as is the case of the SST field.

The SVT field was used as an auxiliary tool, when suitable, in order to consistently

capture the relevant changes in WSC field, once the zonal integration removes small scale zonal variability, retaining the large-scale signal in which we are truly interested in. The SVT field is shown as background colors in Figure 9, at Section 3.3.

Thus, the aforementioned fields were analyzed in terms of their intensity (magnitude) and spatial fluctuations. More specifically, we aimed to keep track of the temporal evolution **1)** of their varying strength *inside* the dynamical rims given by the zero contours (Figure 2); plus, **2)** of the varying position of the gyre boundaries given by the zero contours.

Figure 2 | Large-scale SAO dynamical fields. | Climatological (a) WSC, (b) SSH, (c) BSF and (d) SST. Contours are every (a) $2.5 \times 10^{-8} \text{ N.m}^{-3}$, (b) 5 cm, (c) 5 Sv and (d) 1°C . Zero contours which delimitate positive (negative) WSC/SSH (BSF) fields are indicated by black solid lines. Also highlighted by black dashed lines are the (a) $5 \times 10^{-8} \text{ N.m}^{-3}$, (b) 15 cm, (c) -10 Sv and (d) 10°C , 15°C , 20°C , 25°C contours; used as parameters to perform index calculations.

Intensity indices:

The indices to monitor the varying intensity of the large-scale WSC, SSH and BSF fields within **a)** the zero contour, plus **b)** the isocontours of $>(5 \times 10^{-8} \text{ N.m}^{-3})$, $>(15 \text{ cm})$ and $<(-10 \text{ Sv})$, indicated in Figure 2a, 2b and 2c, respectively, were calculated as follows:

► $VAR_{avg}(t)$ = time series of mean WSC/SSH/BSF within the zero contour² inside the South Atlantic domain (as in Fig. 2);

► $Area(t)$ = time series of the corresponding area within the zero contour of each field — which can vary, by contraction or expansion depending on the evolving dynamics.

²One should note that, consequently, only positive (negative) values of WSC and SSH (BSF) were considered for these calculations.

► $VARavg/Area(t)$ = resulting time series of the mean value of the respective variable within the contour, divided by the corresponding area surrounded by the contour.

The same calculation was conducted for the $>(5 \times 10^{-8} \text{ N.m}^{-3})$, $>(15 \text{ cm})$ and $<(-10 \text{ Sv})$ contours (in the case of the WSC, SSH and BSF fields, respectively), which are all placed inside the zero contour of each dynamical field.

With regard to accuracy, the $VARavg/Area(t)$ index consists of a more reliable measure of the varying strength of enclosed WSC, SSH and BSF which modulates the gyre circulation. It considers the variables' magnitude (mean value within the contour) relative to its corresponding area in each time step. The anomalies (with respect to the annual cycle) are presented in Figure 11 from Section 3.3.

Displacement indices:

The meridional displacement of the dynamical fields was also monitored. Time series of their boundaries were derived exclusively in regions where there were considerably high meridional gradients on both northern and southern limits of the zero contour. In view of that, indices of the latitudinal position of the zero contour were generated for:

(a) the SVT, at the northern boundary and at the first grid point off the South American coast (i.e., the zero zonally integrated WSC line);

(b) the SSH, at the southern boundary and both at a western (40° - 20° W) and an eastern (10° W- 10° E) portion of the basin; and

(c) the BSF, at the southern boundary and both at a western (50° - 20° W) and an eastern (10° E) portion of the basin, as well (the variability at 10° W and 0° is highly restricted by the meridional gradient south of the zero line).

These time series are presented in Figure 15. Hereinafter, the zero contours in general are referred to as WSC0, SVT0, SSH0 and BSF0.

Core indices:

Time series of the maximum zonally averaged WSC/SSH/|BSF| and of the corresponding latitude of the maximum were also derived — in order to represent a measure of the *dynamical central cores* of the gyre.

The maximum WSC was estimated for the whole basin extent (70° W- 20° E), while the zonal bands used to derive maximum SSH and BSF are indicated in Figure 2b and 2c, respectively. These time series are presented in Figure 13 from Section 3.3.

2.3 Volume transports

The total transport of the ocean currents (the sSEC at 30°W, the BC at 28.5°S and the NBUC at 6.5°S) was derived by horizontally and vertically integrating the zonal (sSEC) and meridional (BC, NBUC) velocities³, following Equation 1, where dx and dz are the horizontal and vertical dimensions of the model cell. For the NBUC and the BC, the zonal length of the section was based on the climatological width of the currents. In the case of the westward flowing sSEC, which is broader, the latitude band of 6°-22° S was adopted, following R2007.

$$T_{sv}(x, t) = \int \int_{-H}^0 v(x, t) dz dx \quad (1)$$

The barotropic transports time series were derived from the two-dimensional BSF field (at the same locations as total transports plus additional locations specified in Section 3.4.2).

2.3.1 MOC

The time series of the MOC streamfunction were computed for the latitudes of 6.5°S and 26.5°N. The MOC represents the large-scale motion of the oceans, including thermohaline induced fluxes as well as wind-driven circulation, and can be defined as vertically and zonally integrated meridional velocity in an east-west section across an ocean basin, at a given latitude (e.g., Cunningham and Marsh, 2010):

$$\Psi_{MOC}(y, z, t) = \int_{x_e, y}^{x_w, y} \int_{-H}^z v(x, y, z, t) dz dx \quad (2)$$

where $\mathbf{v}(\mathbf{x}, \mathbf{y}, \mathbf{z}, \mathbf{t})$ is the meridional velocity at longitude $\mathbf{x}$, depth $\mathbf{z}$, time $\mathbf{t}$ and latitude $\mathbf{y}$; $-\mathbf{H}$ and $\mathbf{z}$ are the vertical limits of integration (from a given depth to the surface) and $\mathbf{x}_e, \mathbf{y}$ and $\mathbf{x}_w, \mathbf{y}$ are the eastern and western boundaries at a given latitude.

At 6.5°S, the MOC was calculated so that it could be compared with the western boundary NBUC transport, at the same latitude; and the latitude of 26.5°N is chosen for being the location where there is a continuous observing system since 2004 (the RAPID-MOC - McCarthy et al., 2015), which measures the main flux components that represent the AMOC strength (e.g., Rayner et al., 2011). For both latitudes, the MOC streamfunction is vertically integrated above 1000-m.

³Only positive (negative) velocities were used for the NBUC (BC, sSEC) transport calculation.

2.4 Low-pass filtering

In order to reduce random noise while retaining a sharp step response of the time series (extracting, therefore, the low-frequency component), a *multiple-pass moving average filter* was applied, which involves passing the input signal through a moving average filter twice or more times (e.g., Smith, 1997).

The moving average filter (or *running-mean*) is the most common filter in Digital Signal Processing, used to smooth data by replacing each data point with the average of the neighbouring data points defined within the span.

When not mentioned, all the time series were smoothed 3 times using a 15-month moving average. This procedure compared to the use of regular annual means, for instance, does not change our results. In a few exceptions, a length of 35-month was used instead.

2.5 Linear trends, Significance Testing and Correlations

The long-term trends were estimated by least squares fit and their statistical significance were estimated with the Mann-Kendall test (Kendall, 1975; Mann, 1945). This is a non-parametric method less affected by outliers sometimes contained in data (e.g., Tokinaga and Xie, 2011). If the Student's *t*-test is applied for the same data, our conclusions do not change.

To quantify the linear relations between time series, the Pearson's correlation coefficient was used (see Rodgers and Nicewander, 1988, for detailed information). To determine if the correlations are significant a *t*-test was applied, at the 95% confidence level. All the correlations mentioned in this study are statistically significant.

3 Results

3.1 Validation and Characterization

To investigate how well the models simulate the sSEC bifurcation and the scenario in which it is inserted, their results were compared to those of the ocean reanalysis products described in Section 2.1.4. The comparisons are made based on the periods covered by the reanalysis products, displayed in Table 1; on the full 1948-2015 period for CESM-OCN and on the interval of 1960-2010 for CESM-LME.

The meridional velocity averaged within a 4° longitude band off the South American coast is compared (Figure 3). As described in Section 2.2.1, the SBL is defined as the point where the zonally averaged meridional velocity is zero, denoted by the thick-black contours. All data sets seem to depict well the depth dependence of the bifurcation latitude, although slightly different configurations of the sSEC bifurcation vertical profile can be noted between them.

Figure 3 | sSEC bifurcation vertical profile from the reanalysis products and model results. | Mean meridional velocity (m.s⁻¹) averaged over the western boundary layer (<4° from the coast) from ocean reanalysis products (a-e) and from model results (f-g). Positive (negative) values indicate northward (southward) flow associated with the NBUC (BC), and the contour of zero velocity represents the bifurcation of the sSEC.

From hydrographic observations and numerical model results, R2007 characterized the sSEC bifurcation vertical structure at the western boundary, providing a description of its annual mean depth dependence. The authors showed that the bifurcation occurs at about 10°–14°S in the top 100 m and shifts poleward with increasing depth, reaching 27°S at 1000 m (Figure 4).

Figure 4 | sSEC bifurcation vertical profile, extracted from Rodrigues et al. (2007). | Annual mean **(a)** geostrophic meridional velocity from observations and **(b)** total meridional velocity from model results. The velocities (m.s^{-1}) are averaged within a 2° longitude band off the South American coast.

Among the reanalysis products that were examined, the structure that more closely resembles the contour from R2007 hydrographic observations is the one reproduced by ORAS4. A previous investigation which evaluated the products' performance in terms of the mean circulation field for different levels in comparison to the available observations of R2007 (not shown), also suggested that ORAS4 better captures the dynamics of the SBL.

ORAS4 also captures reasonably well the Pacific SBL interannual variation, as shown by Yamagami and Tozuka (2015). The authors compare the SBL derived from ORAS4 with the

one calculated from the surface meridional velocity obtained from AVISO derived data ⁴.

The mean SBL for individual levels up to 600 m is listed in Table 2. Despite some small differences, all data-sets reproduce the poleward tilting of the sSEC bifurcation with increasing depth. The total shift up to 600 m of the R2007 observations and of ORAS4, CESM-OCN and CESM-LME are within the range of 9°-13.1°.

Table 2: SBL values obtained by R2007 from hydrographic observations; derived from ocean reanalysis products and obtained from the CESM-models results.

Level	surface	100 m	200 m	400 m	600 m	Total shift
Obs.*	14°S	14°S	18.6°S	21°S	23.6°S	9.6°
ORAS4	13°S	19.6°S	21.3°S	23.3°S	24.7°S	11.7°
GFDL	18.3°S	20.1°S	21.2°S	25.5°S	27.1°S	8.8°
SODA216	13°S	18.1°S	22.1°S	25.1°S	27.6°S	14.6°
GODAS	7.2°S	16.9°S	19°S	22.2°S	24.1°S	16.9°
CFSR	8.4°S	14.4°S	16.5°S	20.5°S	22.6°S	14.2°
CESM-OCN	14.7°S	19°S	23.3°S	25.7°S	27.8°S	13.1°
CESM-LME	17.8°S	20.3°S	22.3°S	24.9°S	26.8°S	9°

* Hydrographic observations from R2007: geostrophic velocities determined from dynamic heights relative to 1000 dbar, calculated with an annual mean climatology of temperature and salinity constructed from observations [quality-controlled CTD and bottle data obtained from HydroBase (Curry 1996)]. The authors' calculations do not include the Ekman current, which would affect the bifurcation latitude near the surface. They clarify that adding the Ekman currents to the geostrophic currents (calculated from observations) moves the bifurcation latitude northward by about 1° (i.e., the bifurcation occurs at 13°S at the surface).

Considering the large scale climatology, a good correspondence between the SBL and the zero zonally integrated WSC line is expected. That is because, according to Sverdrup balance (Pedlosky, 1996), the sSEC should bifurcate along this line — at the latitude where no western boundary current compensates the total interior transport. Figure 5 demonstrates this relation between the bifurcation latitude in the upper ocean and the large scale basin-integrated WSC, showing the mean horizontal flow field, vertically integrated over the top 50 m as vectors. The ORAS4 product, CESM-OCN and CESM-LME reasonably attain to the Sverdrup relation, as can be seen in Figure 5a, f, g.

⁴It has been remarked by the authors that, since ORAS4 assimilates observed sea level anomalies, it is not completely independent of the AVISO derived data.

Figure 5 | Depth-integrated flow over the upper 50 m (blue vectors). | Derived from ocean reanalysis products: **(a)** ORAS4, **(b)** GFDL, **(c)** SODA216, **(d)** GODAS, **(e)** CFSR; and from model results: **(f)** CESM-OCN and **(g)** CESM-LME. The dark dots indicate the mean position of the SBL, and the red lines indicate the zero contour of the wind stress curl integrated from east to west.

Therefore, the simulation results from CESM-OCN and CESM-LME are similar to the results derived from ORAS4 and to R2007 hydrographic observations, proving that the models simulate well the sSEC bifurcation and the region of study.

These results also agree with the available literature. From hydrographic data, Stramma and England (1999) showed that the bifurcation latitude is 16°S in the nearsurface layer (top 100 m), 20°S in the South Atlantic Central Water (SACW) layer (100–500 m), and 26°S in the intermediate layer (500–1200 m). Using isobaric RAFOS floats, Boebel et al. (1999) showed that the Return Current [analog to the SEC, but within the Antarctic Intermediate Water (AAIW) layer] reaches the South American coast at about 28°S (called by the authors the Santos Bifurcation). Using data from the World Ocean Circulation Experiment (WOCE) hydrographic section A17 taken during the austral summer of 1994, Wienders et al. (2000) estimated the transport of the SEC and its bifurcation latitude for several isopycnal layers: the SEC bifurcation latitude is 14°S at the surface, 24°S in the 26.7–26.9 layer (400–500 m), and nearly constant around 26°–28°S in the

AAIW and Upper Circumpolar Water (UCPW: 600–1200 m). These results should be interpreted with caution because they are based on a single hydrographic section taken 6°–10° from the western boundary. In the simulations by Harper (2000), the bifurcation point in the near-surface layer at the western boundary of the South Atlantic occurs at 18°S; and in those by Malanotte-Rizzoli et al. (2000), at 17°S. From the results of two high-resolution ocean global circulation models OGCMs (Hybrid Coordinate Ocean Model – HYCOM and Ocean Circulation and Climate Advanced Modeling Project – OCCAM), Pereira et al. (2014) found that the latitude of bifurcation of the zonal flows reaching the coast (analog to the SEC), is 13°–15°S for the Tropical Water, 22°S for the Central Water, 28°–30°S for the Antarctic Intermediate Water. Cirano et al. (2006), using data from the global circulation model Ocean Circulation and Climate Advanced Modelling Project (OCCAM), found that the bifurcation occurs between 9°–15°S in the TW (0–116 m), migrating to 25°S in the SACW (116–657 m) and between 25°–30°S in the AAIW (657–1234 m).

3.2 Long-term change of the SBL

Having validated the main features associated with the sSEC bifurcation, it is possible to explore the temporal evolution of the SBL.

To better establish a linkage between changes in the SBL and changes in surface dynamical fields (i.e., WSC, SSH, SST), we focus on the SBL right below the surface, at 25 m depth (hereinafter referred to as sSBL). The smoothed time series reveals well-defined low-frequency variability (Figure 6a).

Still, an apparent feature depicted in Figure 6a, c is the long-term trend of the sSBL. From 1948 to 2015, the mean position of the sSBL has shifted southward from 11.5°S to 15°S, at a rate of $0.051^{\circ}\text{S yr}^{-1}$. Yet, if one considers the period from 1970 on, whereupon the southward migration is more clearly defined, the corresponding values are of 11°S to 16°S, at a rate of $-0.108^{\circ}\text{ yr}^{-1}$. This southward shift is further supported by the linear trend derived from ORAS4 reanalysis data (green dots), which is of $-0.019^{\circ}\text{ yr}^{-1}$. All trends shown are statistically significant at the 95% confidence level. Periods between solid (1965–1980) and dotted (2000–2015) vertical lines in Fig. 6a were used to average the SBL vertical profile in Fig. 6b – elucidating the poleward displacement at the surface and also giving a spatial perspective of the change with increasing depth. It is observed that below approximately 100 m, the scenario reverts to a slight northward migration along the SBL vertical extent, characterizing a decrease in its poleward shift with depth and thus a smaller depth-dependence of the subtropical gyre circulation.

The sSBL monthly anomalies are shown in Figure 6c, with the aforementioned 1970–2015 abrupt linear trend highlighted in yellow.

Figure 6d gives a clear notion of the difference between the mean annual cycle of the periods marked in between solid/dotted vertical lines in Fig. 6a. Besides a southward displacement of the position of each climatological month, a subtle change in their distribution is also observed: the month of northernmost position switches from November to December.

Figure 6 | Long-term change of the SBL. | (a) Low-pass-filtered (15-month multi-running mean) SBL time series. The blue (green) dots indicate the linear trend for the CESM-OCN (ORAS4) during 1948-2015 (1960-2010). Both linear trends are subtracted by 5° for clarity. Solid (dashed) vertical lines indicate the period of northerly (southerly) sSBL used to average the sSEC bifurcation vertical profile in 6b and annual cycle in 6d. (b) Vertical profile of the sSEC bifurcation (i.e., contour of zero meridional velocity averaged within a 4° longitude band off the South American coast) averaged during years of northerly sSBL (1965-1980 – solid line) and southerly sSBL (2000-2015 – dashed line), according to the time series in 6a. Blue (light blue) asterisks indicate the level used to derive the sSBL time series in 6a (the SBL time series at 100 m in Fig. 7). (c) sSBL monthly anomalies (i.e., annual cycle was removed). Yellow solid line indicates the linear trend for 1970-2015. (d) Climatological sSBL for years of northerly (solid line) and southerly (dashed line) bifurcation position, also according to the time series in 6a. For clarity, the monthly values are plotted for a 2-year time period.

The SBL at 100 m undergoes considerable multidecadal oscillations (Figure 7). Its overall linear trend (not shown) also yields a southward migration ($-0.022^\circ \text{ yr}^{-1}$) albeit smaller than at the surface (recall Fig. 6b). Considering the period after the 80's, the long-term total shift is of -1.94° (or $-0.054^\circ \text{ yr}^{-1}$, dashed light blue line below the time series — statistically significant at the 95% confidence level).

Figure 7 | Time series of the SBL anomalies at 100 m. | Monthly means (light gray) overlaid by low-passed, 15-month multi-running means (light blue). The light blue dots indicate the linear trend for the period of 1980-2015, which is subtracted by 5° for clarity. The position used to derive the time series (100 m depth) is indicated by the light blue asterisk in Figure 6b.

The modulation of the low-frequency change (i.e., long-term change of the mean position of the SBL) on high-frequency variability (i.e., seasonal variability of the SBL) is shown in Figure 8. This figure provides a more detailed view of the SBL annual cycle and its associated long-term variability; by first characterizing the sSEC bifurcation climatological annual march from its northernmost to southernmost position (hereinafter, NP and SP) along its vertical profile extent (Fig. 8a) and the detailed surface climatology (Fig. 8b). Since ORAS4 seemed to perform better among the six reanalysis products described in Section 2.1.4, its annual cycle is displayed in 8b as well, for reference; plus, the annual cycle derived from the CFSR reanalysis product is shown as a parameter to compare differences between model-reanalysis and reanalysis-reanalysis, showing that the discrepancies between CESM-OCN and ORAS4 climatological sSBL are still within an acceptable range.

The climatological sSBL moves to its SP in July (May) and to its NP in December (November) for CESM-OCN and CFSR (for ORAS4), as shown in Fig. 8b. These seasonal variations are in close agreement with the numerical model results from R2007, in which the SBL northernmost (southernmost) position occurs in November (July) in the top 400 m (which corresponds roughly to the ventilated thermocline and accounts for most of the seasonal variability in the bifurcation latitude, according to the authors).

In Fig. 8c, each annual value of the seasonal amplitude of the sSBL (brown line, hereinafter Ab) represents the difference in latitude from the month of NP to the month of SP of the sSBL in that year, i.e., the distance between the annual values of the red and blue time series in Fig. 8d – where the sSBL time series was deconstructed into time series of NP and SP in each year. The corresponding month of the respective extreme bifurcation position in 8d can be seen as another time series in 8e, showing that, although climatological months of NP and SP are December and July, respectively, these extremes are revealed to occur in different periods over the years, mainly when it comes to the SPs – where fluctuations reach up to 5 months (blue line

Figure 8 | SBL Seasonal Variability. | (a) Full-depth (0-600 m) sSEC Bifurcation annual march, denoting the vertical profile for months of northernmost position (NP) and southernmost position (SP), as well as months in between. (b) Climatological sSBL derived from CESM-OCN (solid black, 1948-2015 base period), ORAS4 (dashed gray, 1960-2010 base period) and CFSR (dashed orange, 1960-2010 base period), where red (blue) asterisk indicates the NP (SP) for CESM-OCN. (c) Time series of the monthly sSBL (blue) and seasonal amplitude (brown). (d) SBL time series only for months of NP (red) and SP (blue) in each year. (e) Respective months of NP (red) and SP (blue) in each year. Straight lines represent the climatological months of NP and SP (December and July, respectively). (f) Difference in the sSEC bifurcation vertical profile between 1965-1980 and 2000-2015 (as in Fig. 6b), except that averaged only for the months of sSBL NP. (g) Same as 8f, but for the months of sSBL SP.

in Fig. 8e).

As to the mean seasonal south-north migration (the Ab), the bifurcation latitude varies by 10.7° at the surface. While, according to R2007, it shifts by 7° in the top 100 m and by about 3° from 100 m to 400 m. In Fig. 8c, where the SBL time series and its corresponding Ab are displayed, there is a noticeable feature in addition to the southward shift of the mean position: Ab increases mainly after the 70's, by about 3.51° , and then falls from 2005 on. The factors controlling

Table 3: Magnitude of the seasonal amplitude of worldwide bifurcations, in comparison to the SBL in the SAO.

Reference	Vertical Level/Layer	Ab
SAO SBL - This study	surface / top 400 m	10.7° / 4.2°
SAO SBL - R2007	top 100 m	7°
SIO SBL - Chen et al. (2014)	surface	1.5°
NPO NBL - Different studies*	top 400 m	1°-2.5°
SPO SBL - Chen and Wu (2015)	surface / top 410 m	3.6° / 2.9°

* Different studies = summarized results from studies mentioned in Fig. 1 from Chen and Wu (2011); Qu and Lukas (2003), Wang and Hu (2006) and Qiu and Chen (2010); plus the proceeding results from Chen and Wu (2012).

the long-term change of the Ab are beyond the scope of this work; nevertheless, R2007 suggest that the seasonal variability of the SBL in the upper thermocline is related primarily to variations in wind forcing by combined effect of local Ekman pumping and remotely forced Rossby waves.

The seasonal cycle of the SBL off the South American coast is generally analogous to that in the NPO, SPO and SIO, all of which shift synchronously back and forth seasonally and arrive at their southernmost positions in austral late autumn and early winter.

Other studies have also investigated the seasonal variation of equatorial current bifurcations in the other ocean-basins: the SEC bifurcation in the SIO and the NEC and SEC bifurcations in the NPO and SPO (e.g., Chen et al., 2014; Qiu and Lukas, 1996; Kim et al., 2004; Chen and Wu, 2011, 2012, 2015, respectively), suggesting that, in the upper thermocline, they likely share the same governing dynamics, influenced by baroclinic adjustment — except maybe for the SIO, which has also the combined effect of the Madagascar island changing the western boundary topography.

The magnitude of the SBL's Ab in the SAO here described and also according to R2007 is substantially bigger than that of its other oceans' counterparts (Table 3).

The difference between the climatological vertical profile averaged in years of northerly and southerly bifurcation position (as shown in Fig. 6b) is further decomposed into the months of NP (Fig. 8f) and SP (Fig. 8g) of the annual cycle in those years.

Therefore, through Figure 8d, it is clear that the linear trend in the sSBL (shown in Fig. 6a) is led mostly by months of SP, whereas the time series of NPs presents more steadily fluctuations, with no apparent long-term changes. And this is confirmed by Figures 8f and 8g, which show that at the surface, the difference in the vertical profile is bigger for months of SP. Relative to the change in the mean position of the Pacific NBL and SBL the southward migration of the SBL in the SAO stands out, with a displacement rate twice as big (Table 4).

Table 4: Comparison of the southward shift of the SAO SBL in this study with Pacific NBL and SBL, from Chen and Wu (2012) and Zhai et al. (2014), respectively.

Bifurcation	Level/Layer	Period	Shift	Rate
SAO SBL	surface	1948-2015	from 11.5° to 15°S	-0.051° yr ⁻¹
NPO NBL	upper 381 m	1950-2008	from 15.5° to 13.9°N	-0.028° yr ⁻¹
SPO SBL	upper 200 m	1950-2010	from 14.5° to 15.7°S	-0.020° yr ⁻¹

* See Figure 4 from Hu et al. (2015) for instance, where both Pacific NBL and SBL time series from these studies are displayed.

Analogous to what was pointed out by Chen and Wu (2012) when discussing the long-term trend of the Pacific NBL, this type of southward shift in the SBL is associated with a poleward stretching of the boundary between the tropical gyre and the subtropical gyre in the upper western Atlantic Ocean, implying a substantial impact on the origin of the low-latitude WBCs near the South American coast.

Therefore, the relation between the bifurcation latitude in the upper ocean and the transport of the generated WBCs will be further explored in Section 3.4.3.

3.3 Long-term change of SASG dynamics

After reporting changes in the SBL, it is desirable to investigate how these observed changes relate to changes in the basin-wide gyre circulation - through analysis of the SASG dynamical fields: **WSC/SVT**, **SSH**, **BSF** and **SST**.

The wind stress is a driving agent of ocean currents, but it is the horizontal gradient rather than the absolute strength that mostly matters – the large-scale **WSC**, which is, in general, the major forcing mechanism of the upper ocean (Goni and Wainer, 2001; Cai, 2006). Nevertheless, changes in the local basin-scale wind-driven circulation can be plausibly inferred from changes in the **SVT** field (e.g., Saenko et al., 2005) — which yields a relation for wind-forced flow transport dominated by the Earth's rotation. Variations in the **SSH**, in turn, can provide important insights into large-scale ocean circulation, since physical processes highly impact global mean sea level. As to the **BSF** field, it gives exclusive information about the barotropic, "depth averaged" component of the flow, which varies solely due to horizontal variations in surface height without compensation in the ocean interior. And, finally, the **SST** field strongly affects ocean-atmosphere coupling and, therefore, also responds to the mean ocean circulation.

Worldwide examples:

One topic of great importance for the dynamical understanding of ocean circulation is recognizing the existing linkages among the processes involved. Several studies have explored the relation between the large-scale forcings: by investigating low-frequency circulation changes

in the SPO through wind-forced SSH anomalies (Qiu and Chen, 2006) or even using SSH anomalies in the NPO as a proxy for the NEC bifurcation (Qiu and Chen, 2010). The latter study further relates the bifurcation of the NEC, on interannual and longer time scales, to the Niño-3.4 index, which is derived from SST data. Chen and Wu (2012) also explore ENSO-related NBL variability, in conjunction with the influence of large-scale WSC and Sverdrup dynamics. While Qiu and Chen (2012) assess multidecadal sea level and gyre circulation variability in the northwestern tropical Pacific ocean, revealing that the thermosteric sea level rise is dynamically associated with changes in the NEC transport. These are, in turn, largely attributable to upper-ocean water mass redistribution modulated by the surface wind forcing field. In the North Atlantic Ocean, the linkage between SSH and upper-ocean gyre circulation, for instance, has been explored by Wang et al. (2015); while the relationship between SST and circulation has been investigated by Delworth and Mann (2000). In the SAO, Goni et al. (2011) report observed low frequency variability in the southern limb of the subtropical gyre from satellite-derived SSH and SST observations and Pontes et al. (2016) relate projected changes in upper ocean transport to variations in the WSC field and associated poleward shift of the gyre's southern boundary.

Although the present study does not establish a specific mechanism for linking the different components of gyre circulation, it intends to reinforce the notion that potential changes in the SAO may simultaneously manifest in various of the hydrographic as well as atmospheric fields involved in the processes of ocean circulation.

In order to elucidate how these changes in the basin-scale SASG dynamics are explored in this study, Figure 9 provides a comprehensive framework of the dynamical fields integration through two complementary panels. The top panel shows superimposed zero contours for the WSC, SSH and BSF, with the WSC as background colors; while the lower panel displays superimposed contours of SVT0, WSC0 and BSF0, with the SVT as background colors, that is, the zonally integrated WSC, by the Sverdrup relation. The gray (top) and white (bottom) bars refer to where climatological maximum SSH and $|BSF|$ fields are located, respectively; and therefore, to the width taken into account to derive the latitude time series in Figure 13. As to the maximum WSC, its latitudinal position represents an average of the full domain. The SST field is considered separately, once its spatial distribution is given through linearly increasing values along the meridional extent of the basin, instead of through enclosed contours (see Section 2.2.2 for detailed explanation).

Figure 9 | Schematic of the South Atlantic basin-scale controlling dynamics. | **(Top)** Background colors show the mean WSC field (contour interval: 0.5 N.m^{-3}), where positive values within the gyre are bounded by thin black dotted lines (WSC0 contour). Thick gray dashed lines demarcate the contour of SSH0, while gray zonal labels indicate the widths used to derive the time series of the position of maximum zonally averaged SSH (35° - 25° W, center) and of the SSH0 at a western (40° - 20° W) and an eastern portion of the basin (10° W- 10° E). Thick white dashed lines demarcate the contour of BSF0. **(Bottom)** Same as top panel but with mean SVT field as background colors (contour interval: 5 Sv), where positive values within the gyre are bounded by the thick solid black line. The black dot centered at 36° W shows the location used to derive the SVT0 time series at the northern boundary. White labels denote the widths and location used to derive the time series of the position of maximum zonally averaged $|\text{BSF}|$ (45° - 25° W, center) and of the BSF0 at a western (50° - 20° W) and an eastern portion of the basin (10° E).

The large-scale zero contours reveal the path of the gyre-wide circulation and the connection between the Atlantic and the Indian oceans – part of a southern midlatitude inter-basin “super-gyre” (e.g., Cai et al., 2005; Speich et al., 2007).

Among the analyzed fields, one could say that the *all-embracing* one is the WSC. At the northern boundary, from the inside, it is noticeable how the BSF0 follows the WSC0 line, in a way that in the resulting zonal integration of the WSC, the SVT0 accurately coincides with the BSF0 at the entire upper limb. The SSH emerges as the innermost field, narrowly confined inside all other zero contours, except for its northwestern rim, which veers northward towards the equator (top panel of Fig. 9).

The basin-averaged differences before and after the 80’s (solid versus dashed lines in Fig. 10) are more pronounced relative to the wind field, expressed by the changes in TAUX, WSC and SVT. Nevertheless, albeit comparatively modest, increasing trends can be seen in all fields.

More specifically, the easterly zonal wind stress (TAUX) north of 30°S intensifies, while the westerlies’ magnitude substantially increases south of 40°S, which favours the intensification and poleward displacement of the positive curl, especially at this same region. However, despite this overall intensification of the positive WSC south of 20°S, it seems to slightly weaken between 13°-20°S (Fig. 10a). The variation of the zonal mean SVT naturally reflects those of the WSC, revealing an increased northward basin interior transport implied by the positive WSC intensification, together with the analogous poleward displacement of the system (Fig. 10b). Zonally averaged SSH, in this case regarding the western portion of the basin, rises in the constraints of the zero contour, as well as south of 40°S, where sea level assumes negative values. This is also a suggestion of a southward displacement (Fig. 10c). Accordingly, the difference in basin-wide zonally averaged BSF shows increased barotropic transport within the gyre (negative values north of 43°S) with corresponding decreased barotropic transport south of the BSF0 line, where the SAC and ACC transports take place. However, this decrease can also be viewed in terms of a general poleward migration (Fig. 10d). When it comes to the surface temperature, the warming seems to be more restricted to the region closer to the equator (Fig. 10e).

In Figure 10f, the latitude of transition from negative to positive meridional velocities represents the mean SBL for the top 200 m. As northwards (positive) velocities are clearly increasing, dashed lines (1980-2015) cross the zero VVEL line in southerly positions, compared to the solid lines (1948-1979). This is consistent with the southward displacement of the SBL, described in Section 3.2.

Figure 10 | Transition of South Atlantic zonally averaged fields. | (a) Wind Stress Curl (black curve) and Zonal Wind Stress (TAUX, gray curve); (b) Sverdrup Transport; (c) Sea Surface Height, from the western boundary up to 10°W (recall Fig. 2b); (d) Barotropic Stream Function; (e) Sea Surface Temperature; and (f) Meridional Velocity, from the South American coast (i.e., the western boundary) up to 4° longitude eastwards. The velocities are also vertically averaged within the top 200 m layer. Solid (dashed) lines represent the period ranging 1948-1979 (1980-2015). The WSC, TAUX, SVT, BSF and SST are zonally averaged along the entire basin.

When addressing the "core structure" of the gyre, the anomalies of positive (negative) WSC and SSH (BSF) within the zero and the further confined contours of $5 \times 10^{-8} \text{ N.m}^{-3}$ and 15 cm (-10 Sv) all show a substantial increase (Figure 11), displaying statistically significant positive linear trends after the 80's (Table 5).

Figure 11 | Low frequency SASG variability. | Low-passed anomalies of mean (a) WSC, (c) SSH and (e) BSF horizontally averaged inside their zero contour within the SASG (gray); of the corresponding area enclosed by the respective zero contour (light blue) and resulting time series of mean WSC/SSH/BSF per area (i.e., the gray divided by the blue line – in thick black lines). (b) (d) (f) Same as (a)/(c)/(e) but averaged inside the (b) $5 \times 10^{-8} \text{ N.m}^{-3}$ WSC line, (d) 15 cm SSH line, and (f) -10 Sv BSF line (recall Figure 2 from Section 2.2.2 for reference, where these specific contours are shown).

Table 5: Total period mean value and increase corresponding to the 1980-2015 period of the time series of mean WSC, SSH and BSF within contours (displayed as gray lines in Figure 11). The mean values refer to the corresponding raw time series (since the anomalies in Fig. 11 are with respect to their annual cycles).

Time series	Mean value	1980-2015 increase
a) WSC > 0	$7.6 \times 10^{-8} \text{ N.m}^{-3}$	$1.5 \times 10^{-8} \text{ N.m}^{-3}$
b) WSC > $5 \times 10^{-8} \text{ N.m}^{-3}$	$10.6 \times 10^{-8} \text{ N.m}^{-3}$	$1.6 \times 10^{-8} \text{ N.m}^{-3}$
c) SSH > 0	10.7 cm	0.8 cm
d) SSH > 15 cm	18.1 cm	0.3 cm
e) BSF < 0	-15.3 Sv	-3.3 Sv
f) BSF < -10 Sv	-25.2 Sv	-3.7 Sv

* All linear trends corresponding to the 1980-2015 period are statistically significant at the 95% confidence level.

The black solid time series in Fig. 11 represent: the mean fields within the indicated contours (in gray lines), taking into account the respective areas enclosed by these contours as well (in light blue lines), at each time step. WSC and BSF (SSH) strength hold an indirect (direct) relation with their filling areas (with correlation coefficients reaching up to -0.66 for the WSC in Fig. 11a, +0.83 for the SSH in Fig. 11d and -0.82 for the BSF in Fig. 11e). However, the resulting time series "Mean intensity *per Area*" is not substantially affected by this and does not change our conclusions that the WSC, SSH and BSF strength are indeed increasing. For this same reason, the 1980-2015 linear trend values presented in Table 5 are relative to the gray time series in Fig. 11 (instead of the black ones), as this highlights the idea of how much of each field is really strengthening.

Figure 11 is summarized by Figure 12, which expresses reasonably well the transition from the late 20th into the early 21st century: with increasing values of WSC, SSH and BSF within the SASG domain, obtained from within the respective zero contours which delimitate the governing dynamics of the subtropical gyre circulation (i.e., positive WSC, positive SSH and negative BSF).

Figure 12 | Highlights of the 21st century intensification of SASG circulation. | Climatological mean (a) WSC, (b) SSH and (c) BSF fields with their respective zero contours indicated for reference. (d) Low-passed (35-month multi-running mean), normalized (by standard deviation) anomalies of mean WSC (dark blue), SSH (green) and BSF (lilac) per area, within the zero contours (same time series as in Figure 11a, c, e; save for the differentiated statistical treatment).

Time series of the maximum WSC, SSH and |BSF| and of their respective latitudes are displayed in Figure 13. The maximum values show an overall increase, especially after the 80's, whilst their respective latitudes concurrently migrate southwards. The maximum SSH (13c)

seems to linearly increase from 1948 to 2015, whereas maximum WSC (13a) and |BSF| (13e) do not increase continuously — in addition to the total period linear trend, they both decrease from 1948-1979 after which they show an increasing trend, from 1980 to 2015. All the linear trends in Figure 13 are detailed in Table 6.

Figure 13 | Intensity and latitude of maximum zonally averaged fields. | Low-passed time series of (a) maximum WSC and (b) respective latitude of maximum WSC, averaged over 70°W-20°E; (c) maximum SSH and (d) respective latitude of maximum SSH, averaged over 35°-25°W; (e) maximum |BSF| and (f) respective latitude of maximum |BSF|, averaged over 45°-25°W. The zonal bands used for averaging the SSH and BSF are displayed as gray and white labels in Fig. 9. Total linear trends (1948-2015, red solid lines) are subtracted by: (a) $2 \times 10^{-8} \text{ N.m}^{-3}$, (b) 2° , (c) 3.5 cm, (d) 4.5° , (e) 6 Sv and (f) 1° , for clarity. Dashed red lines denote linear trends for separate periods: (a, e) 1948-1979 / 1980-2015; (d) 1975-2015. All the linear trends displayed (both total and separated periods) are statistically significant at the 95% confidence level.

Table 6: Linear trends from the time series in Fig. 13. The separate period ranging 1948-1979 (1975/1980-2015) is marked in brown (red), for reference.

Time series	Period	Linear trend
a) Max. WSC	1948-2015	$+1.23 \times 10^{-8} \text{ N.m}^{-3}$
a) Max. WSC	1948-1979	$-1.19 \times 10^{-8} \text{ N.m}^{-3}$
a) Max. WSC	1980-2015	$+2.92 \times 10^{-8} \text{ N.m}^{-3}$
b) Lat. of Max. WSC	1948-2015	-1.21°
c) Max. SSH	1948-2015	$+2.97 \text{ cm}$
d) Lat. of Max. SSH	1948-2015	$+0.44^\circ$
d) Lat. of Max. SSH	1975-2015	-1.14°
e) Max. BSF	1948-2015	$+4.21 \text{ Sv}$
e) Max. BSF	1948-1979	-4.47 Sv
e) Max. BSF	1980-2015	$+9.39 \text{ Sv}$
f) Lat. of Max. BSF	1948-2015	-0.66°

The latitude of the maximum WSC and |BSF| (13b and 13f) appear to continuously migrate southward. The latitude of maximum SSH (13d) shifts to the south from 1975-2015, still, the linear trend for the entire period is positive. This positive trend of the maximum SSH position can be understood in terms of the formation of a new local of maximum, centered at approximately 28°S , 35°W (Figure 14b). This suggests that in addition to the southward migration of the SSH contours, increasing values are taking place in the gyre's core, which are causing the latitude of the maximum zonally averaged SSH to remain in a northerly position.

Figure 14 | Featuring the SASG poleward displacement and core intensification. | Climatological contours for the periods: 1948-1979 (solid lines) and 1980-2015 (dashed lines). Shown are the: **(a)** SVT, **(b)** SSH, **(c)** BSF and **(d)** SST fields.

A robust, recurring change pattern displayed in Figure 14 is the SASG poleward displacement (depicted by the southward shift of isopleths), combined with a core intensification, manifested through the enlargement of the regions of higher values in the center of each dynamical field (not considering the SST field).

To better explore the poleward displacement of the SASG system, time series of the dynamical boundaries were derived in regions of high gradients. Defined by the zero contours, they are: the northern edge of the positive SVT field (SVT0n), the southern edge of positive SSH field in two portions along the basin (SSH0s; 40°-20°W and 10°W-10°E) and the southern edge of negative BSF field in two portions along the basin as well (BSF0; 50°-20°W and 10°E). The spatial pattern of the SST field was monitored by time series of the isotherms of 25°C (at 30°W) and 20°C, 15°C and 10°C (both at 30°W and 0° longitude) (Figure 15).

Figure 15 | Monitoring the position of SASG dynamical boundaries. | Low-pass-filtered time series of the latitude of zero contour indices derived from regions of high gradient: **(a)** Latitude of the SVT0 at the northern edge (SVT0n) in the 1st grid point off the South American coast, i.e., the position of zero zonally integrated WSC line; **(b)** Latitude of the SSH0 at the southern edge (SSH0s) in two portions along the basin: a western band ranging 40°-20°W (solid line) and an eastern one, 10°W-10°E (dashed line); **(c)** Latitude of the BSF0 at the southern edge (BSF0s) in two portions along the basin as well: a western band ranging 50°-20°W (solid line) and an eastern section at 10°E (dashed line). **(d)** Latitude of SST contours in two portions along the basin – the 25°C isotherm at 30°W (red solid line) and the 20°C, 15°C and 10°C (in light red, light blue and blue solid lines, respectively) isotherms at 30°W and 0° longitude (in solid and dashed lines, respectively).

The SVT0n, SSH0s and BSF0s indices in Figure 15 all reflect a southward migration, which is more prominent especially after the 70's (except for the BSF0 at the western portion — 50°-20°W — whose 1948-2015 total linear trend is bigger). The overall linear trends are statistically significant at the 95% confidence level. Table 7 lists the southward shifts corresponding to them.

The SVT0n index migrates southward from 11.21°S to 13.13°S, at a rate of 0.028°S yr⁻¹, considering the total period. Therefore, from 1970-2015, the rate increases to -0.059°S yr⁻¹, reaching the latitude of 14.23°S. This rate of southward migration is comparable to that of the SBL during the same period (of 0.108°S yr⁻¹, shown in Section 3.2). As mentioned in Section 3.1, on longer time scales it is expected that the SBL coincides with the SVT0, being subject to the governing Sverdrup dynamics. Here we demonstrate that the long-term change of the low-passed

Table 7: Total shift depicted by different periods in the time series from Figure 15. Shown are only the shifts corresponding to statistically significant linear trends, at the 95% confidence level. The 1970-2015 separate period is marked in red, for reference.

Time series	Period	Total shift	Rate (yr ⁻¹)
a) SVT0n	1948-2015	-1.92°	-0.028°
a) SVT0n	1970-2015	-4.03°	-0.059°
b) SSH0s (40°-20°W)	1948-2015	-0.94°	-0.014°
b) SSH0s (40°-20°W)	1970-2015	-1.00°	-0.015°
b) SSH0s (10°W-10°E)	1948-2015	-0.97°	-0.014°
b) SSH0s (10°W-10°E)	1970-2015	-0.99°	-0.015°
c) BSF0s (50°-20°W)	1948-2015	-0.83°	-0.012°
c) BSF0s (50°-20°W)	1970-2015	-0.63°	-0.010°
c) BSF0s (10°E)	1948-2015	-2.10°	-0.031°
c) BSF0s (10°E)	1970-2015	-2.49°	-0.037°
d) SST10°C (30°W)	1948-2015	-0.48°	-0.007°
d) SST10°C (30°W)	1970-2015	-2.49°	-0.037°

SBL is consistent with the migration of the latitude of zero WSC line integrated from east to west over the South Atlantic basin.

In the case of SSH0s, the contour is migrating southwards at the same rate ($-0.014^{\circ}\text{S yr}^{-1}$) at the western ($40^{\circ}\text{-}20^{\circ}\text{W}$, solid line) and at the eastern ($10^{\circ}\text{W-}10^{\circ}\text{E}$, dashed line) portions of the basin. On the other hand, the contour of BSF0s interestingly migrates at a much bigger rate ($-0.031^{\circ}\text{S yr}^{-1}$) at the eastern portion of the basin (10°E) than at the western ($-0.012^{\circ}\text{S yr}^{-1}$, along $50^{\circ}\text{-}20^{\circ}\text{W}$).

Curiously, however, the isotherms do not seem to follow the same variation as these other indices, expressing a different behaviour: most contours appear to undergo a "drifting disruption" before and after the 80's, besides pronounced multidecadal variability. Only in the 10°C isotherm, at 30°W , a continuous southward migration can be identified from the 70's, later on.

3.4 Long-term change of SAO currents transport

Followed by the investigation of changes in the sSBL and in SASG dynamics, it seems now suitable to explore changes in the transport of the ocean currents. Primarily the SASG northern and western limbs (the sSEC and the BC, respectively) plus the low-latitude, equatorward WBC formed after the sSEC bifurcation (the NBUC).

Thus, total velocity transports as well as the barotropic transports are assessed for the bifurcating sSEC and generated NBUC and BC; while only the barotropic transports are assessed for the SAC and the MC, since these currents consist of "secondary members" (relative to our focus) embedded in this basin-wide circulation which can shed some light to our interpretation in terms of interconnected large-scale dynamics.

3.4.1 Total Transports

The mean flow field is separated into meridional (Fig. 16a) and zonal (Fig. 16b) velocities. Figure 16, as a whole, suggests the idea of the SEC flow diffusely coming across the South Atlantic basin and then spreading around the South American coast, upon advancing westwards towards its northern and southern extents (the NBUC and the BC, respectively). On the map of zonal velocities (16b), both of these flows appear as negative velocities, which are progressing upstream to the north or south; yet, both directed to the west, owing to the alignment of the coast. Only the initial portion of the NBUC is directed eastward. In the left panel (16a), north and south of the mean SBL (yellow dot), these meridional flows can then be more clearly identified as western boundary currents outlining the coast. The contour of $|0.02| \text{ m s}^{-1}$ is marked as reference in dashed lines, for both the meridional and zonal velocities, and both for the horizontal picture (longitude-latitude domain, Figure 16) as well as for the vertical profiles (longitude/latitude-depth domain, Figures 17, 18 and 19).

Hereafter, we ascribe the overall westward flow of the subtropical gyre circulation as sSEC, which is the branch that is known to form the northern limit of the subtropical gyre and to bifurcate into the NBUC and BC. The general westward flow of the SEC includes a part that turns northward near 30°W (Stramma, 1991), to form the South Equatorial Countercurrent (SECC), which merges into the complex equatorial current system, eventually giving rise to the northern (nSEC), equatorial (eSEC) and central (cSEC) branches, as well as the South Equatorial Undercurrent (SEUC). This flow configuration can be visualized in detail in Figure 2 from Stramma and England (1999).

Even though Stramma (1991) defines the sSEC as the flow between 10°S and 25°S and R2007 use the $6^\circ\text{--}22^\circ\text{S}$ band, the use of different ranges of latitude to derive the westward transport yields just negligible differences with respect to the magnitude of the transport; the variability of the time series is not affected. Here, we adopt the band of $6^\circ\text{--}22^\circ\text{S}$, as in R2007. The sSEC can be understood as an BeC extension which includes both the MOC and the return flow of the subtropical gyre (Richardson, 2007).

It is worth mentioning that the northward flow along the Brazil coast between 5° and 10°S occurs as an undercurrent (the NBUC), whereas near-surface currents are weak or even southward; only near 5°S, when it gains an easterly inflow contribution, the NBUC loses its undercurrent character and is then called the NBC (Schott et al., 1998).

Figure 16 | Climatological flow field (1948-2015). | Depth integrated horizontal velocities in which positive velocities (northward, eastward) are in red, while negative velocities (southward, westward) are in blue. The zero-velocity line is marked in black-bold and the $|0.02| \text{ m.s}^{-1}$ contour, used for reference, is marked by the black-dashed lines. The vertical black line along 30°W at the right panel (b) indicates whereupon the spatial domain transcends that of the left panel (a). **(a)** 0-200 m mean meridional velocities. Positive (negative) values denote northward (southward) flow. Yellow dot centered at 19°S represents the 0-200 m mean SBL ($<4^\circ$ longitude off the coast) and solid yellow lines at 6.5°S from 35°-32°W and at 28.5°S from 48°-44°W represent transects for the calculation of NBUC and BC transports, respectively. **(b)** 0-200 m mean zonal velocities. Negative (positive) values denote westward (eastward) flow. Solid yellow line at 30°W from 6°-22°S represent the transect for the calculation of the sSEC transport.

As described in Stramma (1991), the SASG has its northernmost current band as the westward flowing sSEC which is found to be a broad sluggish flow, fed by the BeC. Upon approaching the western boundary and splitting into two branches, a small part of the water turns poleward to form the BC, whereas the bulk of the flow contributes to the NBUC. The results here presented confirm this described flow pattern – yielding vigorous sSEC and NBUC, contrasting with a weak and more steady BC (Figures 17, 19 and 18, respectively, with transect locations indicated in Figure 16).

Figure 17 | sSEC vertical profile characterization and transport time series. | (a) sSEC mean vertical profile across 30°W represented by the 1948-2015 average zonal velocity field along 0°-30°S latitude and up to 980 m depth. The westward flow is indicated by the negative values in blue. The eastward core (positive values, in red) centered in the equator above 200 m represents the SECC. The zero-velocity line is marked in bold and the $|0.02| \text{ m.s}^{-1}$ contour used for reference as in Fig. 16 is indicated by the dashed lines. (b) Low-passed time series of the respective westward transport fluctuations at 30°W (along 6°-22°S and above 200 m) about its mean volume of 12.95 Sv.

Figure 18: | BC vertical profile characterization and transport time series. | (a) BC mean vertical profile across 28.5°S represented by the 1948-2015 average meridional velocity field along 49°-44°W longitude and up to 980 m depth. The southward flow is indicated by the negative values in blue. The zero-velocity line is marked in bold and the $|0.02| \text{ m.s}^{-1}$ contour used for reference as in Fig. 16 is indicated by the dashed lines. (b) Low-passed time series of the respective southward transport fluctuations at 28.5°S (along 48°-44°W and above 200 m) about its mean volume of 4.32 Sv.

Figure 19: | NBUC vertical profile characterization and transport time series. | (a) NBUC mean vertical profile across 6.5°S represented by the 1948-2015 average meridional velocity field along 36°-31°W longitude and up to 980 m depth. The northward flow is indicated by the positive values in red. The zero-velocity line is marked in bold and the $|0.02| \text{ m.s}^{-1}$ contour used for reference as in Fig. 16 is indicated by the dashed lines. **(b)** Low-passed time series of the respective northward transport fluctuations at 6.5°S (along 35°-32°W and above 200 m) about its mean volume of 12.47 Sv.

The monthly anomalies of volume transports (i.e., not considering seasonal oscillations) of the sSEC and the NBUC present a peak-to-peak variability of about 1.53-1.58 Sv; while, with regard to the BC, the corresponding value is only of 0.68 Sv. As to the mean transport values, it was found 12.95 Sv and 12.47 Sv for the sSEC and the NBUC, respectively, while only 4.32 Sv for the BC. These values are in close agreement with the literature: R2007 found an average transport of 15 Sv for the sSEC and 14 Sv for the NBUC, across the same coordinates and between same transects, but integrated up to 400 m; while for the BC, across 22°S, the authors found an average transport of 6 Sv. Schott et al. (1998) found an average transport of 14.6 Sv for the NBUC across 5°S (above the 26.8 isopycnal) and Stramma and Peterson (1990) found 16 Sv for the sSEC across 30°W (upper 400 m). For the BC, Evans and Signorini (1985) found 5.5 Sv across 25°S (upper 400 m), while Stramma et al. (1990) found 4 Sv across 20°S (upper 500 m).

Finally, the long-term change of the volume transports reveal stronger currents after the 70's: the SASG northern (sSEC) and western (BC) limbs strength increase by 2.90 Sv and 0.26 Sv (or 0.32 Sv, if considered the period after 1980), respectively. The linear trends shown in Figures 17 and 18 are statistically significant at the 95% confidence level). This finding is consistent with the results from Section 3.3, which suggest an intensified gyre circulation.

However, the increase in the northward transport with the NBUC is of the same magnitude as that of the sSEC transport, of 2.90 Sv⁵. The time series of these standardized anomalies are even highly correlated, with a coefficient of 0.87 between the low-passed time series (Figure

⁵All the 1970-2015 liner trends, in sSEC, BC and NBUC transports, are statistically significant at the 95% confidence level.

20) and of 0.75 between monthly anomalies (not shown). This indicates that most of the sSEC transport increase is being destined towards the equator and the northern hemisphere, through the NBUC.

Figure 20 | Highlights of the synchrony between sSEC and NBUC transport anomalies. | Comparison of the (standardized, low-passed) time series of the sSEC (blue, same as in Fig. 17) with the NBUC anomalies (red, same as in Fig. 19). The value on top of the plot indicates the correlation coefficient between the series.

Several studies have linked variations in the NBUC transport with the AMOC strength, considering it is inserted in the surface return flow destined to feed the North Atlantic heat sink (e.g., Zhang et al., 2011; Chang et al., 2008; Vellinga and Wu, 2004).

To investigate this hypothesis, the basin-integrated MOC transport is derived for the same latitude as the NBUC estimated transport (6.5°S) as well as for the latitude where mooring arrays are deployed in order to monitor the AMOC - at 26.5°N.

Figure 21 | Attribution of NBUC transport increase to MOC intensification. | Comparison of the (low-pass-filtered) time series of the NBUC anomalies (red) at 6.5°S with the corresponding MOC anomalies at this latitude (light gray) and the MOC anomalies at 26.5°N (black). Both MOC streamfunctions are vertically integrated above 1000-m depth; their time series are scaled by a factor of 10^{-6} . The dashed lines indicate the respective linear trends for the period 1970-2015, which are all statistically significant at the 95% confidence level. Values on top of the plot indicate the correlation coefficient between the normalized, detrended time series: the NBUC transport and the MOC at 6.5°S (cc1); the NBUC transport and the MOC at 26.5°N (cc2); and between the MOC at 6.5°S and the MOC at 26.5°N (cc3).

Both resulting time series yield increasing northward MOC recirculation after the 70's; nevertheless, the MOC streamfunction at 26.5°N increases at a rate similar to that of the NBUC transport (total increase of 3.37 Sv, against 1.05 Sv for the MOC at 6.5°S - Figure 21).

3.4.2 Barotropic Transports

Time series of the barotropic transports were derived for the same locations as for the total transports shown in Section 3.4.1, in the case of the sSEC, BC and NBUC (at 30°W, 28.5°S and 6.5°S, respectively). Additionally, time series were also derived for: **1**) a considerably wider meridional band for the sSEC transport at 10°W which covers nearly the whole climatological extent of the negative BSF field within the SASG; **2, 3**) a southerly preceding (succeeding) transect along the coast after the sSEC bifurcation for the NBUC (BC) at 10.5°S (34.5°S); **4, 5**) a zonal (meridional) transect at 50.5°S (30°W) for the positive barotropic transport of the MC (SAC), outside the SASG domain delimited by the BSF0.

Figure 22 shows all the transects used to derive the barotropic transport time series mentioned above, which are displayed in Figure 23. Table 8 lists the magnitude of increase in the barotropic transports associated with periods of positive linear trends in each of the time series.

Figure 22 | Climatological BSF field (1948-2015). | Solid yellow (gray) lines represent transects used to derive the barotropic transport time series of SASG boundary currents (of SAO currents outside the subtropical gyre). Contours are every 5 Sv.

Since the barotropic transport is a result of full-depth integration, it is expected that its magnitude (listed in Table 8) exceeds that of the total transports. The comparison is made in terms of percentage increase.

Figure 23 | SAO barotropic transport variation. | Low-passed anomalies of the barotropic transport of SAO currents at the locations indicated in Figure 22.

Table 8: Total increase in barotropic transports corresponding to linear trends from the time series in Fig. 23. The linear trends are all statistically significant at the 95% confidence level.

Time series	Period	Total increase
a) sSEC (10°W)	1970-2015	3.28 Sv
b) NBUC (6.5°S)	1970-2015	1.54 Sv
b) NBUC (10.5°S)	1970-2015	2.69 Sv
c) BC (28.5°S)	1980-2015	0.58 Sv
c) BC (34.5°S)	1980-2015	2.50 Sv
d) SAC (30°W)	1960-2015	5.36 Sv

Although the barotropic transport of the sSEC at 30°W does not present a long-term change, at 10°W a considerable increase can be identified after the 70's, of 23.62%, comparable to that of the total transport of the sSEC at 30°W, from Section 3.4.1, which is of 24.12%. The increase in the barotropic transport of the NBUC (52.51% across 6.5°S and 69.33% across 10.5°S) is more pronounced than that of the total transport (26.26% across 6.5°S). The total transport of the BC in Section 3.4.1 increased only by 7.67%; the modest increase holds for the barotropic transport across this same latitude as well (9.52%), while across 34.5°S, the increase in the barotropic transport is almost twice as big (17.21%). The decrease in SAC barotropic transport at 30°W (of 8.28%) could be interpreted as a poleward displacement of the gyres' system. As the barotropic transport of the SAC was derived using only positive values of the barotropic stream function, with a southward migration of the zonal current band, the occurrence of positive BSF values dropped, as they were being replaced by negative BSF values from within the gyre. The positive barotropic transport of the MC, which flows against the poleward BC, shows nearly subdecadal fluctuations around its mean value — providing no information about long-term variations.

3.4.3 Linkage between SBL variability and currents' transports

The bifurcation latitude variability is a manifestation of changes in the flow of the currents involved. It is observed that when the SBL shifts southward (northward) the NBUC transport increases (decreases) and the BC transport decreases (increases) (R2007). Figure 24 explores the relationship between the SBL and the SEC, NBUC and BC transports time series.

Figure 24 | sSBL relationship with sSEC, NBUC and BC transports. | Low-passed (35-month), standardized time series of the sSBL (in light blue, for all panels) and the total (solid lines) and barotropic (dashed lines) transports of (a) the sSEC across 30°W, (b) the NBUC across 6.5°S and (c) the BC across 28.5°S. Values on top of the plot indicate the correlation coefficient between the series: cc1 (cc2) quantifies the relation between the SBL and the total (barotropic) transports.

Our results show that the SBL and the NBUC are well correlated: as the sSEC bifurcates in southerly positions, the northward NBUC transport increases, and vice versa (Figure 24b). The correlation coefficient (cc) is nearly the same for total and barotropic transports (-0.85 and -0.83,

respectively). The SBL and the sSEC total transport show a strong relationship as well ($cc=-0.79$): as the sSEC total transport increases, the impinging sSEC bifurcates in southerly positions (Figure 24a). On the other hand, the barotropic sSEC transport yields a negligible relation with the SBL; since there is a transition between a positive and negative relationship along the total period, the cc is insignificant. When comparing the BC transport response to the SBL variation, however, a counter-intuitive relation is observed: as the SBL migrates southward (northward), the BC transport increase (decrease) (Figure 24c). This is contrary to what was expected.

The SBL, therefore, presents an indirect relationship with the sSEC, NBUC and BC transports. This relation holds from interannual to subdecadal variability and long-term trends (the correlation coefficients between the 15-month low pass-filtered time series are almost as high, if not higher). The 35-month low-pass is applied in order for the relationship to be visually clearer: after the 70's, the SBL is observed to continuously migrate to the south up to the early 21st century; while sSEC, NBUC and BC transports all show an intensification.

This leads to the idea that more waters are arriving against the western boundary with the sSEC, which are, in part, bending southward and contributing to the modest BC transport increase; nevertheless, the actual bulk of it, is really heading towards the north along with the NBUC and, therefore, consisting of the prevailing mechanism which ends up pushing the bifurcation latitude poleward.

3.5 Last Millennium change perspective

In this Section, we address the relative amplitude of the observed changes along the 20th-21st century transition, in relation to a longer record - such as the period covered by the Last Millennium. In order to accomplish this, we analyze the results from the *Last Millennium Ensemble* experiment (CESM-LME) to understand the past physical behaviour of the SAO.

The Last Millennium - Short theoretical background:

The climate variability of the period corresponding to the Last Millennium (e.g., Jones and Mann, 2004; Jones et al., 2001) encompasses three major climatic episodes: the "Medieval Climate Anomaly", the "Little Ice Age" and the "Recent Warming" (Diaz et al., 2011; Mann et al., 2009). By studying the records of climate variability and forcing mechanisms in the recent past, it is possible to establish how the climate system varied before anthropogenic forcing became significant. Natural forcing mechanisms will continue to operate in the 21st century, and will play a role in future climate variations, so regardless of how anthropogenic effects develop it is essential to understand the underlying background record of forcing and climate system response (Bradley et al., 2003).

The results derived from CESM-LME show that, during the Last Millennium the observed changes in the post-industrial period and mainly along the passage from the 20th into the 21st century reveal to be unprecedented.

SBL

The SBL time series both at the surface and at 100 m (Figure 25a, b and 25c, d; respectively) show a southward migration starting during the mid-late 19th century (the vertical green dashed line demarks the year of 1850 in Figure 25a, c), from where it progressively enhances, reaching positions far out of the range of natural variability within the long record, by the end of the 20th century (where the vertical blue dashed line demarks the year of 1980).

Despite varied higher-frequency oscillations, all ensemble members (in light gray) undergo the described southward migration. Only the time series of the control-run (CTRL, in yellow) remains around the mean position, strongly suggesting that the recent poleward shift of the SBL is related to human-induced climate change forcings. Therefore, the signal expressed by the average of the 10 ensemble members (the Ensemble Mean) is clear. And the spread across the members, used to quantify uncertainties (denoted by red and blue time series in Figure 25b, d⁶), reduces toward the end of the time series at the surface (top-right panel), corroborating the southward migration.

⁶The spread of the ensemble members is calculated following Zhai et al. (2014): for the temporally varying variables, the spread in each month among ensemble members is defined as the standard deviation of the departure of ensemble members from the Ensembles' mean in that month.

Figure 25 | SBL time series for the Last Millennium. | Low-passed (30-yr) time series of the SBL at the surface (the sSBL - **a**, **b**) and at 100 m (**c**, **d**). Subplots (a, c) show the time series for the 10 ensemble members of the CESM-LME (in gray) plus the control-run (CTRL, yellow) — which is not subject to external forcings. Solid black-bold lines denote the average of the 10 ensemble members (the *Ensembles' mean*). Vertical dashed green (light blue) line indicates the year of 1850 (1980). Subplots (b, d) show the Ensembles' mean anomaly time series with the spread (red) and spread times -1 (blue).

In the CESM-LME results, the southward shift of the SBL is also accompanied by a rise in the northward NBUC volume transport as well as in the MOC streamfunction at the same latitude (6.5°S). As can be seen in Figure 26, the maximum NBUC transport and MOC strength observed since the late 20th century were never matched in the last millennium, and thus represent an exceptional event.

Figure 26 | Late NBUC transport increase and MOC intensification relative to the Last Millennium. | Low-passed (30-yr) anomalies of the NBUC transport (red) at 6.5°S and the corresponding MOC streamfunction at this latitude (light gray). As in Figure 21, the MOC streamfunction is vertically integrated above 1000-m depth and its time series is scaled by a factor of 10^{-6} . The correlation coefficient between the standardized time series is indicated by **cc1**. Vertical dashed green (light blue) line indicates the year of 1850 (1980).

SASG dynamics

In this section, the dynamical fields are zonally averaged for: the Last Millennium climatology (850-1850), a climatology covering the 20th century (1850-2005) and the 1980-2005 climatology (Figure 27). All fields manifest pronounced changes during the late 20th century (1980-2005) which contrast with the 850-1850 and 1850-2005 climatologies.

Figure 27 | Recent transition in South Atlantic zonally averaged fields. | (a) Wind Stress Curl, along 30°-10°W; (b) Sea Surface Temperature, along 40°-20°W; (c) Sea Surface Height, along 35°-25°W and (d) Barotropic Stream Function, along 50°-20°W. The gray line represents the Last Millennium climatology (850-1850), blue line represents roughly the 20th century climatology (1850-2005) and red line the climatology from the last 25 years of the CESM-LME record (1980-2005).

The change pattern of the WSC resembles that described by Pontes et al. (2016), using a set of 19 models from the Coupled Model Intercomparison Project phase 5: there is a weakening between approximately 15°S and 35°S and a concurrent strengthening south of this region. The increase in SST occurs especially within the tropics, north of 30°S; while the increase in SSH resembles that of in the BSF field — centered in the regions of maximum values, just north of 40°S.

Figure 28 | Southward shift of the SASG system relative to the Last Millennium. | Low-passed latitudes of: **(a)** maximum WSC, **(c)** SSH and **(e)** BSF; and of SASG dynamical boundaries — **(b)** SVT0 at northern limb, **(d)** SSH0 and **(f)** BSF0 at southern limbs. Vertical dashed green (light blue) line indicates the year of 1850 (1980).

From Figure 28 one can note that starting around 1850, the latitudes associated with the wide-ranging dynamical positions of the gyre (i.e., latitudes of maximums approximately in the center and of contours at the boundaries) seem to start a subtle drift towards the south. In the late 60's, the southward drift progresses more intensely.

It should be noted that the time series in the left (right) column from Figure 28 are analogous to those of the right (left) column from Figure 13 (15) for the CESM-OCN, in Section 3.3.

4 Conclusions and Discussion

The patterns of gyre-scale flow in global subtropical oceans seem to be changing, as do the associated atmospheric forcings under anthropogenic global warming. Using the ocean component of the CESM and the fully coupled CESM-LME experiment, the results presented here support our hypothesis that the SAO is indeed subject to these changes.

More specifically, it has been suggested that midlatitude subtropical gyres, especially those of the Southern Ocean, are concurrently spinning up their circulations whilst drifting to southward positions, in response to changes in the surface wind stress field (Roemmich et al., 2007; Cai et al., 2005; Cai, 2006; Saenko et al., 2005; Zhang et al., 2013; Li et al., 2013).

For the CESM-OCN period ranging the mid 20th into the early 21st century (1948-2015), signals in WSC, SSH and BSF fields point to an intensification of the subtropical gyre circulation, inferred from increasing values of these diagnostic variables within their dynamical rims of the SASG domain (i.e. their zero contours) which confine the governing dynamics of subtropical SAO circulation: positive WSC, positive SSH and negative BSF. A synchronous poleward migration of the system is also indicated by the signals in these basin-scale dynamical fields. This is demonstrated by significant differences between the mean climatologies straddling the 80's, as well as linear trends in time series of the latitude of WSC, SSH and BSF core-maximums and null-edges (generally defined by the zonally averaged maximums and zero contours, respectively).

Although it would be expected that the gyre's spin up and associated BC transport increase would push the SASG northern limb equatorward, it has been found that the mean position of the SBL at the northwestern boundary of the gyre shifted southward from 11.5°S to 15°S, at a rate of 0.051°S yr⁻¹. This is twice as big than the shift of its Pacific Ocean counterparts (studied by Chen and Wu, 2012 and Zhai et al., 2014).

Besides being in agreement with the reported poleward movement of the whole system, this southward shift of the SBL is largely attributable to a substantial increase in the northward transport of the NBUC along the path of the upper branch of the AMOC. When deriving the basin-integrated MOC transport both for the same latitude where derived the NBUC transport and at the 26.5°N latitude of the RAPID-MOC observing system, a considerable recirculation increase is found consistent with the NBUC intensification. This suggests that the SBL southward shift, accompanied by the NBUC strengthening, might be related to variations in the MOC. Modifications of the water masses participating in the return flow within the South Atlantic can potentially lead to alterations of the thermohaline circulation and the associated meridional heat and freshwater fluxes.

Finally, the perspective of a longer time frame provided by the CESM-LME experiment reveals that, lately, the observed changes in the SBL and the SASG dynamics have reached proportions with no precedents since the year of 850.

Here we have inferred a spinned-up gyre circulation associated with increased torque over the basin (through signals in the WSC field by Sverdrup dynamics and through increased

barotropic transport and sea level anomalies). We must clarify that the focus of this work is related to a large-scale scenario, associated with low-frequency variability; however, exist anomalous, higher-frequency variations which are superimposed to the mean circulation, as well as regional scale signals which are embedded in these concurrent circulation changes and are out of the scope of this work.

Our results confirm that important changes are taking place in the evolving upper-ocean circulation, at least with respect to the SAO. The SASG spin up and poleward shift are likely to have important consequences to the global climate system as well as regional climate and ecosystems.

As mentioned by Bryden et al. (2012), the key issue for the next years is to understand how the ocean circulation varies on interannual to decadal time scales and to quantify the impacts of varying ocean circulation on climate and biological productivity, for instance. This work was intended to investigate the main large-scale features that constitute the SAO subtropical circulation and to describe the associated results and spatiotemporally varying signals, providing a dynamical framework to identify potential new states of the system in view of ongoing global climate changes.

In any case, our conclusion that in the late 20th into early 21st century the time series of SAO dynamical signals reached levels that had rarely, if ever, been exceeded in (at least) the preceding 1000 years seems to be an extremely robust result from the simulation results here analyzed; indicating that this recent short record is subject to unique conditions.

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Appendix I - *Resumo Informal*

Este estudo investiga a ocorrência de mudanças na circulação do giro subtropical do oceano Atlântico Sul (AS). Essa circulação é primariamente regida pelo vento e ocorre na camada superior do oceano, girando no sentido anti-horário (esquema na Figura 29).

Figura 29 | Representação esquemática do Atlântico Sul e da região equatorial. | Contornos em preto representam as correntes superficiais e cores de fundo, a Temperatura da Superfície do Mar (*Sea Surface Temperature*). O giro subtropical do AS é formado por parte do sistema de correntes da Benguela na borda leste (*Benguela Current System*), o ramo sul da Corrente Sul Equatorial (CSEs) na borda nordeste/norte (*southern South Equatorial Current*), a Corrente do Brasil (CB) na borda oeste fluindo para sul (*Brazil Current*) e a Corrente do Atlântico Sul fluindo para leste no limite inferior (*South Atlantic Current*). Extraído de Cabos et al. (2016).

No Atlântico Sul, a circulação do giro subtropical é acoplada à circulação que é regida por diferenças de densidade entre as massas de água (por variação de temperatura e salinidade — a *circulação termohalina*). Juntos, esses dois regimes de circulação compõem a Circulação de Revolvimento Meridional (CRM), que tem proporção global, conectando todas as bacias oceânicas (Atlântico, Índico e Pacífico).

O oceano Atlântico é o palco principal onde ocorrem os processos mais importantes relativos à CRM. O acoplamento da circulação do giro subtropical do AS com a CRM ocorre principalmente através de um braço da CRM que passa na camada superior do AS, vindo lá da borda sudeste da bacia oceânica e pegando carona no giro subtropical pelo contorno da sua borda nordeste-norte, a partir de onde segue em direção ao equador, rumo ao Hemisfério Norte.

Portanto, como no AS a CRM está embutida na circulação do giro subtropical, podendo influenciá-la, este fator externo deve ser levado em consideração ao se estudar a variabilidade do giro. Para isso, a sua borda norte é investigada à parte, e definida como o ponto em que a corrente fluindo nesse limite superior do giro se aproxima da costa da América do Sul e bifurca

para norte e para sul. Sendo que a porção de águas que vai para norte segue em parte com o braço da CRM, enquanto a porção de águas que vai para sul recircula no giro subtropical.

As ferramentas usadas para investigar esses fatores são dois conjuntos de dados: X1 (o qual cobre o período de 1948 à 2015) e X2 (que cobre o período desde 850 até 2005). Esses conjuntos de dados representam informações sobre a variação temporal de indicadores do estado de circulação do Atlântico Sul, tais como o campo espacial (domínio latitude *versus* longitude e dependendo da variável, profundidade também) das velocidades, da altura do mar e do vento soprando sobre o oceano. Esses dados são gerados por modelos numéricos que simulam o comportamento do oceano.

Em relação à dinâmica geral do giro subtropical, esses dados mostraram que houve mudanças significativas na circulação do AS, as quais se iniciaram principalmente após os anos 70/80 (visível nos resultados de X1), e que quando vistas da perspectiva temporal mais ampla de X2, assumem proporções imprescindíveis em relação à toda linha de tempo do último milênio. Mais especificamente, essas mudanças reveladas apontam para uma aceleração da circulação do giro, *além de* uma migração de toda a estrutura do giro para sul, em direção ao pólo.

A borda norte do giro, representada pela bifurcação, também migra para sul.

Enquanto essa migração para sul da bifurcação está de acordo com a migração para sul de *todo* o giro, é contra-intuitiva em relação à aceleração da circulação anti-horária — pois o aumento do transporte de águas fluindo para sul com a circulação do giro faria com que a bifurcação da corrente ocorresse cada vez em posições mais a norte.

No entanto, ao investigar também o transporte de águas que vão para norte após a corrente bifurcar, observa-se que este aumenta em proporção muito maior que o transporte para sul — nos fornecendo uma explicação plausível do porque a bifurcação também migra para sul.

Portanto as conclusões finais são:

- ▶ A circulação anti-horária do giro subtropical do AS fica mais intensa/acelerada *ao passo que* a estrutura espacial do giro se desloca em direção ao pólo (para sul);
- ▶ A borda norte do giro subtropical (definida pela bifurcação) também migra para sul;
- ▶ A migração pra sul da bifurcação está de acordo com a migração para sul de todo o giro; mas contra a aceleração da sua circulação. No entanto, parece estar associada ao aumento substancial do transporte de águas para norte, que ‘empurra’ a bifurcação para sul.

A circulação dos giros subtropicais está intimamente ligada à variabilidade climática global e pode, por exemplo, impactar e modular o clima dos continentes arredores e influenciar processos importantes como o sequestro de carbono para o oceano profundo (que ajuda a diminuir a quantidade de CO₂ na atmosfera). Estudos da variabilidade da circulação do giro, portanto, podem nos fornecer pistas e informações acerca desses assuntos.

Essas descobertas referentes à mudanças na circulação do giro subtropical e em outras componentes da circulação do oceano AS, representam um potencial cenário em vista às mudanças climáticas globais recorrentes, em consequência do aumento dos gases do efeito estufa e da influência da atividade humana no aquecimento global.