Investigating the Upper-Ocean Pathways, Dynamics, and Geometry of the South Atlantic

by

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Earth and Ocean Sciences

Duke University

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Dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Earth and Ocean Sciences in the Graduate School of Duke University

2021
ABSTRACT

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Abstract

The South Atlantic has been of special interest to the overturning circulation as its source waters may have the ability to influence deep water convection in the subpolar North Atlantic, and hence affect the overturning variability or strength. As such, it is important to have a thorough understand of the pathways that regulate the upper-ocean flow in the South Atlantic. This dissertation revisits previously studied aspects of the circulation from an observational perspective focusing on the use of Lagrangian data and statistical tools that complement the observational data. More specifically, surface drifter trajectories, Argo float trajectories, and satellite altimetry products are used to investigate the cold and warm water routes, the subtropical gyre circulation, and the connection between the North Brazil Current and the tropical North Atlantic. The statistical tools used throughout this dissertation are rooted in Markov chain theory, which allows for the construction of probability distribution maps that represent mean pathways and artificially extend the lifetime of observational trajectories. In addition, a new method derived from transition path theory is used to specifically identify pathways that connect a desired source and target region.

The results reveal that the cold and warm water routes share multiple pathways throughout the South Atlantic and contribute comparable amounts to the Benguela Current waters. The cold water route follows internal pathways suggesting a significant role in the subtropical gyre circulation in setting pathways. The analysis of sea surface height data shows no significant trends in the subtropical gyre size and strength over the past 25 years. Finally,
this work highlights the importance of pathways following the Atlantic interior to the tropical North Atlantic from the North Brazil Current.

Future work will focus on understanding the differences between the two-dimensional pathways revealed from the observational trajectories and three-dimensional pathways simulated by model trajectories.
Dedication

To my parents and grandparents.
Contents

Abstract ................................................................................................................................. iv
Dedication ............................................................................................................................. vi
List of Figures ...................................................................................................................... xi
Acknowledgements ........................................................................................................... xiv
1. Introduction ..................................................................................................................... 1
2. The surface pathways of the South Atlantic: Revisiting the cold and warm water routes using observational data .............................................................. 8
   2.1 Introduction .................................................................................................................. 8
   2.2 Data and methods ....................................................................................................... 11
      2.2.1 Surface Drifters and Subsurface Floats ................................................................. 14
      2.2.2 Markov chain derived from surface drifter trajectories .................................... 15
         2.2.2.1 Markov Chain Parameters ............................................................................. 16
      2.2.3 Lagrangian particle simulations in OSCAR ...................................................... 18
      2.2.4 Data Analysis ...................................................................................................... 19
   2.3 Results and discussion ............................................................................................. 20
      2.3.1 Surface drifter and Subsurface Float Trajectories ............................................... 21
         2.3.1.1 Drake Passage ............................................................................................... 21
         2.3.1.2 Agulhas Current ........................................................................................... 24
         2.3.1.3 Interaction Between the Drake Passage and Agulhas Current .................. 28
         2.3.1.4 Benguela Current ........................................................................................ 30
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.3.2 Markov chain</td>
<td>32</td>
</tr>
<tr>
<td>2.3.2.1 Drake Passage</td>
<td>32</td>
</tr>
<tr>
<td>2.3.2.2 Agulhas Current</td>
<td>33</td>
</tr>
<tr>
<td>2.3.2.3 Benguela Current</td>
<td>34</td>
</tr>
<tr>
<td>2.3.3 OSCAR Fields</td>
<td>40</td>
</tr>
<tr>
<td>2.3.3.1 Drake Passage</td>
<td>40</td>
</tr>
<tr>
<td>2.3.3.2 Agulhas Current</td>
<td>41</td>
</tr>
<tr>
<td>2.3.3.3 Benguela Current</td>
<td>42</td>
</tr>
<tr>
<td>2.4 Summary</td>
<td>47</td>
</tr>
<tr>
<td>3. Variability and trends of the South Atlantic subtropical gyre</td>
<td>50</td>
</tr>
<tr>
<td>3.1 Introduction</td>
<td>50</td>
</tr>
<tr>
<td>3.2 Data and methods</td>
<td>54</td>
</tr>
<tr>
<td>3.2.1 SSH estimates</td>
<td>54</td>
</tr>
<tr>
<td>3.2.2 Basin and gyre metrics</td>
<td>57</td>
</tr>
<tr>
<td>3.3 Results and discussion</td>
<td>60</td>
</tr>
<tr>
<td>3.3.1 Basin-wide seasonal variability</td>
<td>61</td>
</tr>
<tr>
<td>3.3.2 Seasonal variability of the gyre</td>
<td>63</td>
</tr>
<tr>
<td>3.3.3 Basin-wide interannual variability and long-term trends</td>
<td>71</td>
</tr>
<tr>
<td>3.3.3.1 Sea surface height</td>
<td>71</td>
</tr>
<tr>
<td>3.3.3.2 Meridional trends in SSH, wind stress, and Ekman transport</td>
<td>76</td>
</tr>
</tbody>
</table>
3.3.4 Interannual variability and long-term trends of the gyre .........................78

3.4 Summary .............................................................................................................85

4. Connecting the North Brazil Current to the RAPID line ....................................88

4.1 Introduction ...........................................................................................................88

4.2. Background ........................................................................................................90

4.2.1 Surface and subsurface circulation of the tropical Atlantic .....................91

4.2.2 Pathways from the North Brazil Current to the Rapid line .......................93

4.2.3 Markov chains and transition path theory in oceanography ....................94

4.3 Data and methods ...............................................................................................95

4.3.1 Eulerian velocity field .....................................................................................96

4.3.2 Surface drifters and Argo floats ....................................................................96

4.3.3 Markov chain .................................................................................................97

4.3.4 Transition path theory ...................................................................................101

4.4 Results and discussion ......................................................................................108

4.4.1 Markov chain probability distributions .......................................................108

4.4.2 Markov chain transit time distributions .......................................................118

4.4.3 Surface pathways from transition path theory .............................................122

4.4.4 Subsurface pathways from transition path theory .....................................126

4.5 Summary ............................................................................................................133

4.6 Future work and transition path theory .............................................................135
List of Figures

Figure 1: Schematic overview of the upper-ocean circulation in the Atlantic Ocean.................7
Figure 2: Overview of the South Atlantic (SA) surface circulation and the study domain.....13
Figure 3: Surface drifter and subsurface float trajectories from the Drake Passage...............22
Figure 4: Surface drifter and subsurface float trajectories from the Agulhas Current...........26
Figure 5: Sensitivity of Agulhas leakage estimates.................................................................27
Figure 6: Surface drifter and subsurface float trajectories in the Agulhas Return Current....29
Figure 7: Surface drifters and subsurface floats reaching the Benguela Current...............31
Figure 8: Distribution of Markov chain particles released in the Drake Passage...............37
Figure 9: Distribution of Markov chain particles released in the Agulhas Current.............38
Figure 10: Distribution of Markov chain particles released in the Benguela Current..........39
Figure 11: Distribution of OSCAR particles released in the Drake Passage.........................45
Figure 12: Distribution of OSCAR particles released in the Agulhas Current......................46
Figure 13: Distribution of OSCAR particles released in the Benguela Current....................47
Figure 14: Schematic of the subtropical circulation of the South Atlantic.........................54
Figure 15: Seasonal variability in mean SSH, wind stress curl, and zonal wind stress averaged across the South Atlantic basin.................................................................63
Figure 16: Seasonal variability in the position and size of the gyre and the local wind field..67
Figure 17: Seasonal variability of gyre metrics.................................................................70
Figure 18: Seasonal range of ocean mass\textsubscript{GRACE} and steric height\textsubscript{Argo}........71
Figure 19: Interannual variability and long-term trends (2004–2016) of SSH in the South Atlantic.................................................................74
Figure 20: Trends of zonally averaged annual SSH components, zonal wind stress, and Ekman pumping ................................................................. 77

Figure 21: Interannual variability and long-term trends in the position and size of the gyre and the local wind field .................................................. 84

Figure 22: Interannual variability and long-term trend in gyre strength ...................... 85

Figure 23: Surface velocity field and schematic of the tropical Atlantic circulation .......... 92

Figure 24: Surface drifter and Argo float trajectories and data density .............................. 99

Figure 25: Summary of Markov chain calculation steps ........................................... 100

Figure 26: Schematic of transition path theory .......................................................... 103

Figure 27: Schematic of the average effective reactive current .................................... 108

Figure 28: Markov chain distribution from the North Brazil Current ............................. 110

Figure 29: Markov chain distribution excluding particles that leave the domain across the southern boundary ............................................................. 111

Figure 30: Distribution of Markov chain particles along the RAPID line at 26.5°N. .......... 112

Figure 31: Markov chain distribution from the North Brazil Current to the Florida Current ................................................................. 115

Figure 32: Markov chain distribution from the North Brazil Current to the Antilles Current ................................................................. 116

Figure 33: Markov chain distribution from the North Brazil Current to the East RAPID line ................................................................. 117

Figure 34: Schematic of the dominant pathways between the North Brazil Current and the RAPID line ................................................................. 118

Figure 35: Transit time distribution from the North Brazil Current to the RAPID line ..... 119

Figure 36: Transit time distribution from the North Brazil Current to the Florida Current via the Gulf of Mexico pathway ................................. 120
Figure 37: Transit time distribution from the North Brazil Current to the Antilles Current. .................................................................................................................................................. 121

Figure 38: Transit time distribution from the North Brazil Current to the Antilles Current. .................................................................................................................................................. 122

Figure 39: Surface pathways from transition path theory connecting the North Brazil Current to the tropical North Atlantic ................................................................................................................. 129

Figure 40: Surface pathways from transition path theory connecting the North Brazil Current with relaxed restrictions ........................................................................................................................................... 130

Figure 41: Subsurface pathways from transition path theory connecting the North Brazil Current to the tropical North Atlantic ................................................................................................................. 131

Figure 42: Subsurface pathways from transition path theory with absolute probabilities. .................................................................................................................................................. 132
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To my dearest parents and grandparents, thank you for your unwavering support and relentless encouragement.
1. Introduction

In 1925 a group of researchers led by oceanographer Alfred Merz left the city of Willemschaven in Germany on board the *Meteor* to embark on a research cruise to the South Atlantic. Their findings revealed the surprising result that heat is transported from the poles to the equator in the South Atlantic (Garzoli and Matano, 2011; Wüst, 1935).

Today we understand that this unusual direction of heat transport is part of the Atlantic Meridional Overturning Circulation. Taking a long-term look at the overturning circulation in the South Atlantic, we find that it is composed of a northward-flowing warm and salty upper limb that is compensated for by a southward-flowing cold and fresh lower limb. In my dissertation, I use observational data to revisit the upper-ocean pathways of the South Atlantic that form part of the overturning circulation.

The South Atlantic itself sources its waters via two primary pathways, one from the Pacific Ocean through the Drake Passage and the other from the Indian Ocean via Agulhas leakage (Figure 1). Following Rintoul (1991) and Gordon (1989), these two pathways are traditionally referred to as the cold water and warm water routes, respectively. As their names suggest, the continued interest in these South Atlantic source waters stems from their inherently different thermohaline properties. The argument is that a prevalence of one over the other could influence the meridional overturning circulation by affecting the formation of deep waters in the subpolar North Atlantic (Beal et al., 2011; Garzoli & Matano, 2011). Some have questioned the ability of these source waters to influence the stratification of the North Atlantic (Weijer & van Sebille, 2014) or even suggested that by the time the pathways
reach the North Brazil Current their properties have become indistinguishable from each other (Rühs et al., 2019). To date, no consensus has been reached on the relative importance of these two sources, with studies supporting the prevalence of one over the other (Donners & Drijfhout, 2004; Gordon et al., 1992; Lee et al., 2019; Macdonald, 1998; Rousselet et al., 2020; Speich et al., 2001; Speich et al., 2007; Sloyan & Rintoul, 2001; You, 2002), or arguing for a more comparable contribution (Rodrigues et al., 2010; Rühs et al., 2019).

Once in the South Atlantic, the subtropical gyre plays a central role in modulating these upper-ocean pathways and may even regulate how much of the upper-ocean waters travel to the North Atlantic via the North Brazil Current (Figure 1, Bower et al., 2019; Durgadoo, 2013). Previous studies have investigated the seasonal variability of the gyre circulation (McClain et al., 2004; Signorini & McClain, 2012) or isolated features of the circulation such as a shift in its southern boundary (Lumpkin & Garzoli, 2011; Yang et al., 2020). Recently, a modeling study found a strengthened subtropical gyre circulation over the past few decades (Marcello et al., 2018) and another study argued for a strengthening of the Southern Hemisphere supergyre using altimetry (Qu et al., 2019). On the other hand, a modeling study by Combes and Matano (2014) as well as a drifter-based study by Goni et al., (2011) revealed no such changes. A comprehensive review of the strength, size, and position of the South Atlantic gyre from observational data is missing from the literature.

The northern boundary current of the subtropical gyre, the South Equatorial Current, bifurcates around 10°S into the Brazil Current and the North Brazil Current (Figure 1). Waters in the Brazil Current return southward as part of the gyre circulation, while
waters in the North Brazil Current are transported to the North Atlantic, as part of the upper limb of the overturning (Figure 1). Past studies have primarily examined the pathways connecting the North Brazil Current to the Florida Current, a route that is considered to be the primary conduit of upper limb waters (Bower et al., 2019; Fratantoni, 2000; Fratantoni, 2001; Halliwell et al., 2003; Lumpkin & Johnson, 2013). Most waters from the North Brazil Current are thought to either flow through the Caribbean Sea to the Gulf of Mexico and then to the Florida Current or become entrained in the Equatorial Current System prior to flowing back to the Caribbean Sea (Figure 1). Less attention has been paid to other potential pathways, such as those that connect the North Brazil Current to the Atlantic interior.

My dissertation focuses on three main aspects of the upper-ocean circulation of the South Atlantic (Figure 1): 1. The pathways of South Atlantic source waters, 2. the subtropical gyre circulation, 3. and the connection between the South and North Atlantic Oceans.

In my second chapter I revisit the pathways and relative contributions of the cold and warm water routes to the Benguela Current from an observational perspective. To that end, I employ three sets of trajectories: surface drifters, subsurface floats, and simulated Lagrangian surface trajectories advected using an observation-based circulation field. My findings reveal that waters following the cold water route escape the Antarctic Circumpolar Current to join the South Atlantic Current further east than previously suggested and can return to the South Atlantic via Agulhas leakage through a shortcut route that does not require a full recirculation through the Indian Ocean subtropical gyre. Additionally, my results highlight the importance of internal pathways and reveal numerous areas in the South
Atlantic where the cold and warm water routes share pathways, hence increasing the possibility of mixing of these two water masses. The latter is important given the historical focus on the relative properties of these source waters and aligns with findings by Rühs et al. (2019), namely that once the waters are on their way to the North Atlantic via the North Brazil Current, there is no memory of their initial properties. Finally, my observational results support a sizeable contribution of Drake Passage waters to the upper limb of the overturning circulation.

Building on previous work, and given that the results from my second chapter suggest a substantial involvement of the subtropical gyre in the pathways of the cold and warm water routes, I investigate the seasonal and interannual variability and long-term trends in key gyre metrics in my third chapter. I use sea surface height from satellite altimetry and its two components, the steric height and ocean mass, to assess changes to the gyre circulation. In agreement with studies by Lumpkin & Garzoli (2011) and Vincent & Combes (2014), my observational study reveals a significant southward migration of the southern gyre boundary and the Brazil-Malvinas Confluence between 1993 and 2018. This southward displacement does not, however, translate to an increased gyre size due to large fluctuations in the eastern gyre boundary. Most importantly, my findings suggest no long-term trend in the gyre strength between 1993 and 2019, which I attribute to a lack of basin-wide changes in the wind stress curl and comparative trends in sea surface height along the gyre boundary and gyre maximum. An increase in strength necessitates a differential increase in one of the two latter variables to allow for a change in the sea surface height gradient.
Finally, my fourth chapter connects the South Atlantic to the North Atlantic circulation by examining the pathways between the North Brazil Current and the RAPID line. To that end, I use a new method called transition path theory, first adapted to oceanographic applications by Miron et al. (2021). This method builds on Markov chain theory to not only allow the construction of probability distribution maps based on observational trajectories, but also directly identify pathways that connect specific sources and targets. My observation-based results recover the text-book pathway that connects the North Brazil Current to the Florida Current via the Caribbean Sea and the Gulf of Mexico, termed here the Gulf of Mexico pathway. While this pathway accounts for roughly 43% of surface waters from the North Brazil Current, the remaining 57% follow pathways through the Atlantic interior to the east of the Florida Current along the RAPID line. Additionally, my analysis reveals a direct connection between the North Brazil Current and the Antilles Current, accounting for about 4% of the total pathways (included in the 57% cited above), an important finding as the Antilles Current has been postulated to carry a portion of upper-limb waters northwards.

My analysis highlights the importance of considering the input to the entire RAPID line when aiming to understand the propagation of upper-ocean waters between the South and North Atlantic and the overturning variability that may be communicated with it. An analysis of transit times reveals no significant difference between pathways through the Gulf of Mexico and the Atlantic with means of 2 ± 0.9 and 2 ± 0.8 years, respectively.
In summary, my dissertation focuses on using observational data in combination with statistical tools to revisit the pathways and circulation of the South Atlantic upper-ocean. As such it serves as an important resource for the validation of modeling studies. It is my intention to build on this foundation to address one of the most important limitations of my studies, the use of two-dimensional trajectories to understand three-dimensional oceanic pathways, with follow-up modeling studies in my future work.
Figure 1: Schematic overview of the upper-ocean circulation in the Atlantic Ocean. Ocean currents are shown in red and ocean basins and relevant geographic features are denoted in blue. The abbreviations refer to the following currents in alphabetical order: AC, Antilles Current; ACC, Antarctic Circumpolar Current; ACS, Agulhas Current System; ARs, Agulhas Rings; BC, Brazil Current; BCS, Benguela Current System; FC, Florida Current; GS, Gulf Stream; IP, interior pathways; LC, Loop Current; MC, Malvinas Current; NAC, North Atlantic Current; NBC, North Brazil Current; NBCr, North Brazil Current Rings; NEC, North Equatorial Current; NECC, North Equatorial Counter Current; SAC, South Atlantic Current; SEC, South Equatorial Current. This figure was modified from its original version by Bower et al. (2019).
2. The surface pathways of the South Atlantic: Revisiting the cold and warm water routes using observational data

This work is published in the *Journal of Geophysical Research: Oceans* (Drouin & Lozier, 2019).

2.1 Introduction

The Atlantic Meridional Overturning Circulation (AMOC) consists of a northward flowing warm and salty upper limb, which compensates a southward flowing cold and fresh lower limb. While this overall depiction of the northward heat flux throughout the Atlantic basin is well understood (Garzoli & Matano, 2011), the relative contribution of the source waters for the upper limb in the South Atlantic is still debated. Specifically, there is disagreement as to whether the upper limb of the AMOC is primarily fed by cold, fresh waters from the Pacific Ocean, which enter the South Atlantic (SA) basin through the Malvinas Current (MC) via the Drake Passage (DP), or by warm, salty waters from the Indian Ocean, which enter the SA via Agulhas leakage in the form of mesoscale eddies and filaments. The former is traditionally referred to as the “cold-water route” following (Rintoul, 1991), while the latter is termed the “warm-water route” following (Gordon, 1986). It has also been suggested that a minor contribution to the source waters of the upper limb stems from local water masses formed within the SA (Stramma & England, 1999).

Interest in these competing sources stems from an expectation that the prevalence of one over the other affects the variability and stability of the AMOC because of their
influence on deep water formation in the North Atlantic (Garzoli & Matano, 2011). For example, Beal et al. (2011) suggested that salinity input via Agulhas leakage acts as a stabilizing mechanism for the AMOC by offsetting freshwater forcing in the North Atlantic. However, modeling results from Weijer and van Sebille (2014) indicated that such salinity input would be too weak to change the stratification of the North Atlantic. Since several studies suggested that Agulhas leakage has increased over the past few decades (Biastoch et al., 2009; Durgadoo et al., 2013) and another predicted a continued increase under current climatic conditions, the relative contribution of the warm water route continues to be of interest.

In the years since the seminal publications of Gordon (1986) and Rintoul (1991), numerous studies have tried to quantify the relative importance of these two pathways, with no consensus to date (Garzoli & Matano, 2011). Gordon et al. (1992) attempted to reconcile the two viewpoints by suggesting an indirect contribution from the Pacific waters. The authors suggested that waters entering the SA via the DP follow the Antarctic Circumpolar Current (ACC) eastward, are subsequently entrained in the Indian Ocean subtropical gyre and then eventually merged with the Agulhas Current (AC) to reenter the SA basin via Agulhas leakage. This route forms part of the super-gyre that connects the Indian, Pacific, and Atlantic Ocean basins (De Ruijter, 1982; Speich et al., 2007).

Both the warm-water route (Donners & Drijfhout, 2004; Lee et al., 2019; Speich et al., 2001; Speich et al., 2007; Weijer et al., 2002) and the cold-water route (Macdonald, 1998; Sloyan & Rintoul, 2001; You, 2002) have found heavy favor in past studies. Two recent
studies, however, suggested a more comparable role for the pathways, while still attributing a larger contribution to the warm route (Rodrigues et al., 2010; Rühs et al., 2019). The divergent estimates of the cold and warm water route contributions can be partially explained by the use of different data sets and methods, as well as the use of coarse resolution models (Donners & Drijfhout, 2004; Rühs et al., 2019).

The majority of these past studies have addressed the contributions of the cold and warm water routes from a modeling perspective, either in the Eulerian or Lagrangian framework. The purpose of this study is to reinvestigate the source waters of the upper ocean in the SA using observational data. The observational data sets available for this study—surface drifters and satellite derived ocean surface current fields—yield information on surface velocities only. To alleviate this constraint, we qualitatively compare the surface drifter trajectories to subsurface floats. However, since these floats are primarily isobaric, they too are unable to capture the full three-dimensional pathways. We admit the constraint placed on this study by this limitation, but in the absence of three-dimensional velocities from the observational record, surface pathways can provide valuable, albeit imperfect, information about the circulation (Mariano et al., 2002; van Sebille et al., 2011). Our purpose then is not to produce a comprehensive assessment of the upper limb pathways but rather to understand what we can learn about surface pathways in the SA, as they pertain to the AMOC upper limb, from the observational database alone. A follow-on study, using numerical modeling output, will examine the full three-dimensionality of the pathways. As such, this present study will also provide important validation for the modeled pathways.
To meet our goal of using available observations to assess surface pathways in the SA, we produce three sets of trajectories: those directly available from surface drifters, those computed from a Markov chain using the surface drifter record, and those computed from surface velocity fields. Additionally, we compare the surface drifter trajectories to subsurface float trajectories. An inspection of the similarities and differences among these sets allows for a more robust evaluation of the surface pathways. Finally, we note that our goal is a description of the mean, rather than temporally varying pathways.

2.2 Data and methods

We define our study region between 70°S–10°S and 70°W–50°E and refer to it as the SA domain (Figure 2). For the analysis of the Markov chain and the trajectories computed from surface velocity fields, we further define four geographical subdomains: the northern SA, the southern SA, the Agulhas Region (AR), and the DP (Figure 2).

Our focus lies on the identification of pathways from the DP (waters entering the SA across 70°W) and the Agulhas Current (AC; water flowing across 32°S between 30°E and 35°E), as well as pathways to the Benguela Current (BEC; waters crossing 30°S between 0° and 15°E). Since this work primarily addresses the geographical origins and pathways of the surface waters of the SA, the cold and warm water routes are henceforth referred to as Drake Passage and Agulhas waters, respectively.

Previous studies involving the upper limb of the AMOC have chosen the North Brazil Current as a region of interest as it acts as a bottleneck for the waters of the upper limb (Rühs et al., 2013; Rühs et al., 2019). However, past studies have indicated that the
connection to the North Brazil Current is at least partially subsurface (Johns et al., 1998; Schott et al., 1998; Schott et al., 2005; Stramma, 1991). A relatively recent study, for example, showed that only 1% of surface trajectories released in the Agulhas Current would reach the North Atlantic over 100 years, a value that increases to 2% when the three-dimensional nature of the pathway is taken into account (van Sebille et al., 2011). To minimize the impact of the surface constraint on our study, instead of choosing the North Brazil Current as the end point for trajectories released at the source locations, we use the upstream BEC. This current is also sourced by the same Pacific and Indian Ocean waters (Garzoli & Gordon, 1996; Garzoli & Matano, 2011) yet is located much closer to the source locations.

We use two observational data sets to produce surface pathways: (1) satellite-tracked surface drifters from the National Oceanic and Atmospheric Administration's Global Drifter Program (GDP; publicly available for download at: https://www.aoml.noaa.gov/phod/gdp/index.php) and (2) the Ocean Surface Current Analysis Real-time (OSCAR) generated by Earth Space Research (publicly available for download at: https://podaac.jpl.nasa.gov/dataset/OSCAR_L4_OC_third-deg). We use a third observational data set, subsurface floats from the World Ocean Circulation Experiment Subsurface Float Data Assembly Center (WFDAC) at Woods Hole (publicly available for download at: https://www.aoml.noaa.gov/phod/float_traj/data2.php), to compare our surface trajectories to subsurface trajectories. These datasets are discussed further in the following sections, as is our use of a Markov chain to compute pathways. For a discussion
and maps of the OSCAR and surface drifter velocity fields we refer the reader to Johnson et al. (2007), Dohan and Maximenko (2010), and Laurindo et al. (2017).

Figure 2: Overview of the South Atlantic (SA) surface circulation and the study domain. Individual study regions are demarcated by dark blue lines. The northern SA is defined between 70°W and 20°E and 30°S and 10°S; the southern SA is defined between 70°W and 20°E and 70°S and 30°S with the exception of the region defined between 70°W and 50°W and 70°S and 50°S, which is defined as the Drake Passage; the Agulhas Region is defined between 20°E and 50°E and 70°S and 10°S. Black contours (0.2 m intervals) are the absolute dynamic topography in meters from AVISO. The background shading indicates the number of surface drifters available per grid box. Grid boxes containing less than the median number of drifters (15) are colored in the same color. The schematic pathways and eddies highlight the traditional cold route from the Pacific Ocean (Gordon, 1986) and warm route from the Indian Ocean (Rintoul, 1991). The abbreviations denote prominent ocean currents: AC = Agulhas Current; ACC = Antarctic Circumpolar Current; ARC = Agulhas Return Current; BEC = Benguela Current; MC = Malvinas Current; SAC = South Atlantic Current.
2.2.1 Surface Drifters and Subsurface Floats

The GDP surface drifter data consists of 15 m drogued and undrogued drifters, whose longitudinal and latitudinal positions are reported every six hours. Here the full GDP data set is subsampled to include surface drifters, henceforth referred to as “drifters,” passing through our SA domain (Figure 2) between November 1989 and June 2018. Since undrogued drifters do not accurately capture the motion of near-surface currents (Lumpkin & Pazos, 2007; Niiler & Paduan, 1995; Pazan & Niiler, 2001), their trajectories are excluded from this analysis. However, the trajectories of drifters that have lost their drogue are included up to the point of drogue loss. Given these constraints, the SA GDP data set is comprised of 3,425 trajectories. Note that while this full SA GDP data set is used for the construction of the Markov chain, the qualitative analysis of the drifter trajectories only includes drifters that are located in the vicinity of the DP, the AC, and the BEC (Figures 3–6) and have a minimum lifetime of thirty days.

Our analysis of the drifters is constrained by their limited temporal and spatial coverage. The average lifetime of the drifters used in this study is 0.5 ± 0.5 years. Additionally, their spatial coverage is nonuniform (Figure 2), as it is subject to sampling bias from cruise routes and targeted sampling strategies. The mean number of drifters per 1° grid box is 22 ± 23. As explained in the next subsections, we remove the lifetime constraint of the observed drifters with the use of a Markov chain (McAdam & van Sebille, 2018; Miron et al., 2017; Miron et al., 2019; van Sebille et al., 2012). We also address the bias from the
non-uniform drifter distribution by using the satellite-derived OSCAR fields to compute Lagrangian pathways, also described below.

Most significantly, the drifters are drogued to a depth of 15 m and constraint to the surface. Hence, as mentioned in the introduction, they do not capture the three-dimensionality expected from water pathways. To partially account for the lack of three-dimensionality, we qualitatively compare the drifters to subsurface floats available through WFDAC. We highlight again that these subsurface floats, henceforth referred to as “floats,” are primarily isobaric and hence, still do not reflect three-dimensional pathways. As mentioned in the introduction, an investigation of three-dimensional and subsurface pathways awaits further study.

2.2.2 Markov chain derived from surface drifter trajectories

In general, a Markov chain describes the transition from a present state to a future (or past) state, based on probability distributions. In this context, it serves as a tool to explore oceanic surface pathways and connections implicit in the drifter record on a longer time scale (McAdam & van Sebille, 2018; van Sebille et al., 2012). A detailed description of the use of Markov chains and their limitations in oceanographic applications can be found in (McAdam & van Sebille, 2018). Though we acknowledged the limits imposed by drifter coverage above, we note here that the validity of the Markov chain is not influenced by the non-uniform sampling of the drifters (see Miron et al., 2019 for details).

To construct the Markov chain from the GDP drifter data, we divide the domain into a discrete grid with a horizontal resolution of dx and dy. Next, we split the drifter
trajectories into subtrajectories of length $dt$ and consider all positions at time $t = t_o$ in a specific grid cell and find the position of those drifters at time $t = t_o + dt$. We then determine the probability of moving from that grid to another grid over the time step $dt$. We repeat this step for all grid cells and summarize the probabilities in a transition matrix. After determining all probabilities for all grids, we initialize particles in a specific grid and compute their probabilistic trajectories over five years.

The steps outlined above largely follow the method outlined in McAdam and van Sebille (2018) with two exceptions: First, we normalize the drifter trajectories by the total number of drifter trajectories in a grid cell at time $t = t_o$, rather than by the number of drifter trajectories that leave a given grid cell over the time step $dt$. This modification accounts for drifters that remain in a given grid cell over the assigned time step $dt$. Second, we construct the transition matrix using only the trajectories of drogued drifters, due to the limitations of undrogued drifters described above.

Here we also construct a backward Markov chain to trace surface waters back to their sources. In this case, the probability distribution for each grid cell is calculated based on the drifter position at time $t = t_o$ and $t = t_o - dt$.

**2.2.2.1 Markov Chain Parameters**

Following McAdam and van Sebille (2018), the spatial grid for the Markov chain is set to $dx = dy = 1^\circ$, which yields a total of 4,887 grid cells in our SA domain. We take advantage of the full SA drifter data set and split the 2,983 drifter trajectories into roughly 2.1 million subtrajectories. This yields an average of $860 \pm 686$ observations per grid cell,
with 237 grid cells (5%) containing less than 50 observations. Note that approximately 1% of the grid cells are absorbing, that is, once a drifter enters an absorbing grid cell it remains there indefinitely, since there is a zero probability of leaving an absorbing grid cell (Miron et al., 2017; van der Mheen et al., 2019). Accordingly, we exclude the absorbing grid cell from our analysis (van der Mheen et al., 2019).

We define \( dt \) as the advective time scale for surface particles. A simple scaling analysis, with a nominal length scale of 40–100 km and velocities of 0.1–1 ms\(^{-1}\), yields a range for \( dt \) of 0.5–10 days. We justify our choice of the midrange value (\( dt = 5 \) day) as follows. First, we conducted sensitivity simulations using \( dt = 1, 5, 10, \) and \( 100 \) day(s) and used two metrics to compare the actual drifter positions to the positions predicted by the Markov chain particles. To ensure the best comparison, we subsampled the drifter trajectories to the time step of each Markov chain. Specifically, we calculated (1) artificial dispersion, defined as the number of grid cells occupied by Markov particles that are not occupied by the original drifters, normalized by the total number of grid cells occupied by the Markov particles and (2) undercapture, defined as the number of grid cells occupied by the original drifters that are not occupied by the Markov chain particles, normalized by the total number of grid cells occupied by the original drifters. Ideally, both quantities should be minimized. A comparison of these metrics for all tested \( dt \) values reveals that after 300 days, \( dt = 5 \) day gives a relatively low artificial dispersion (\( \sim 14\% \)) and small undercapture (\( \sim 10\% \)). For \( dt = 1 \) day and \( dt = 100 \) days, the artificial dispersion is \( \sim 15\% \) and \( \sim 40\% \) and the undercapture is \( \sim 12\% \) and 35%, respectively. Additionally, a time scale of 5 days exceeds the
Lagrangian decorrelation time scale of the surface ocean of two to three days (LaCasce, 2008) meaning that the velocity field is memoryless after five days. This loss of memory is a requirement for the Markov chain (Miron et al., 2017). Finally, this advective timescale also matches the temporal resolution of the OSCAR fields. For more information on artificial dispersion in Markov chains, the reader is also referred to McAdam and van Sebille (2018).

Ideally, one could also construct a Markov chain from the subsurface floats. However, their limited number (480), which results in an average coverage of 4 ± 4 floats per grid cell (compared to an average of 22 ± 23 surface drifters per grid cell), coupled with their scattered distribution throughout the SA and irregular reporting time, precludes this possibility.

2.2.3 Lagrangian particle simulations in OSCAR

The OSCAR fields are two-dimensional velocity fields representative of the upper 30 m of the ocean and are computed from quasi-linear and steady flow momentum equations using *in situ* measurements and satellite altimetry data as input (Bonjean & Lagerloef, 2002). These velocities are available globally at a spatial resolution of one-third degree and a temporal resolution of five days. For this study, we use the 2000–2017 OSCAR fields covering our SA domain. Prior years are excluded from this study as they do not have enough data coverage close to the South African coast.

To optimize the comparison between the drifter trajectories, the Markov chain, and the Lagrangian particle simulations using OSCAR, we release particles daily over a period of ten years. The particles are advected forward in time from the DP and AC, as well as
backward in time from the BEC using a fourth-order Runge-Kutta integration scheme with a time step of one hour. Over the ten-year period, trajectories are integrated for five years, with positions recorded every five days. The OSCAR fields are interpolated to each particle position at each time step bicubically in space and linearly in time. To minimize the number of particles advected onto land, particles close to land (within one degree) are advected using the Forward Euler method instead of the Runge-Kutta scheme. Additionally, in these cases the velocities are not interpolated and only the component parallel to the coast of the closest available velocity is used for the integration.

For our analysis of the OSCAR pathways, we only include particles that last the whole integration period, leave the domain prior to five years (DP and AC), or reach the source regions prior to five years (BEC). For the DP and BEC simulations, approximately 90% of launched particles match these criteria. For the AC simulations this value is slightly lower, at around 75%. The majority of particles are lost close to the shore, due to a lack of data coverage and the needed interpolation and integration scheme. Note that approximately 8% are lost from each launch site, meaning that no one launch site experiences more or less loss than any other.

### 2.2.4 Data Analysis

The GDP drifter trajectories are qualitatively analyzed in terms of their preferential pathways and quantitatively in terms of their travel time to certain sections of the domain. The WFDAC subsurface float trajectories are used as a qualitative comparison of pathways for the surface drifter trajectories.
We create two different probability maps for the results of the Markov chain (Figures 8–10) and the OSCAR fields (Figures 11–13). For the first map, we count the number of particles that pass through each grid cell over five years and normalize this count by the total number of particles released. Note that each particle is only counted once per grid cell. As such, each grid cell can have a maximum value of 100% if all released particles pass through that particular grid cell over the five-year integration time period. This distribution map highlights preferential pathways, since high particle concentrations denote the routes that most of the particles follow.

For the second map, we count the total number of particle positions in each grid cell over the course of five years and normalize this count by the total number of particle positions of all released particles. Thus, the cumulative sum of all grid cells is 100%. While this type of distribution map also shows preferential pathways, it primarily highlights areas of large residence time. Combining these two views allows us to, for example, determine if high particle concentrations result from many particles following a specific path or from strong recirculation in the area (van Sebille et al., 2018).

2.3 Results and discussion

In section 3.1, we discuss what can be inferred from the original GDP data set by qualitatively analyzing the trajectories of drifters passing through the DP, the AR, and the BEC and qualitatively compare the trajectories to subsurface floats. In sections 3.2 and 3.3, we take a more quantitative approach and discuss the results of the Markov chain and OSCAR particle advections, respectively, in the same regions.
2.3.1 Surface drifter and Subsurface Float Trajectories

2.3.1.1 Drake Passage

A total of 517 drifters enter our SA domain through the DP (Figure 3). One fifth of those divert to the north and enter the MC (21%; blue), while the rest remain in the ACC (79%; light blue). The drifters entering the MC primarily pass through the DP north of 60°S. The entanglement, looping, and eddying motion of the MC drifters highlight the energetic and dynamic nature of the Brazil-Malvinas Confluence (Garzoli, 1993; Jullion et al., 2010; Willson & Rees, 2000). As the drifters move eastward, a few that had followed the MC (blue) subsequently rejoin the ACC, while others that had been following the ACC are entrained into the South Atlantic Current (dark blue), highlighting continuous exchange between the two currents (Boebel et al., 1999). Though a previous study had suggested a lack of exchange between the ACC and the South Atlantic Current after 50°W (Speich et al., 2001), our results show continuous exchange up to approximately 35°W, in agreement with previous work by Boebel et al. (1999) and a recent modeling study by Rühs et al. (2019). Some drifter trajectories follow intra-gyre pathways in the SA basin (Figure 3), an observation in agreement with a modeling study by Schmid (2014). The author suggests that the South Atlantic Current may be connected to the southern South Equatorial Current via pathways that cross the interior of the subtropical gyre.
Figure 3: Surface drifter and subsurface float trajectories from the Drake Passage. (a) Trajectories of 517 drifters passing through the grey box (70°S–50°S, 70°W–50°W). The drifters are colored by their preferred pathways: Drifters entering the SA in the MC are colored in blue; drifters remaining in the ACC are colored in light blue. Drifters that enter the SA in the ACC but, subsequently, become entrained in the MC are counted as MC drifters. Drifters that escape the ACC and travel on a more northerly route are colored in dark blue. (b) Similar to (a) but for the trajectories of 37 floats passing through the DP. The average depth of the floats is 783 ± 159 m with a range of 50–1,554 m. Note that there is an updated version of this float data set available, however, the version we employ (version 1.0) has identical data to the newer version (version 2.0) in the SA. The 37 floats include 36 ALACE floats and 1 PALACE float.
Approximately 20% of drifters travel across 10°W. Of those, the majority are located in the ACC and a smaller fraction (6%) is found in the BEC. Drifters traveling in the ACC (light blue; Figure 3) cross 10°W after 0.9 ± 0.2 years. Drifters travelling via the MC (blue; Figure 3) and subsequently the South Atlantic Current only cross 10°W after 1.7 ± 0.4 years. Given the drifters' relatively short lifetime of 0.7 ± 0.5 years, these transit times are likely underestimated, particularly so for the BEC with its longer transit from the DP. In addition to these two pathways, a number of drifters are entrained into the Agulhas Return Current (ARC), suggesting a possible conflation of the cold water and warm water routes closer to the warm source than previously suggested (Gordon et al., 1992; Speich et al., 2007). As mentioned above, earlier work addressed the interaction between the DP waters and Agulhas waters outside of the SA basin. Their primary focus was on DP water recirculating within the Indian Ocean subtropical gyre or entering the Indian Ocean through Tasman Leakage to form a super-gyre (Gordon et al., 1992; Speich et al., 2001; Speich et al., 2007). Instead, here we suggest a mixing of these two sources just southeast of the African continent. Further evidence for this is discussed in the context of Figure 6.

The subsurface float trajectories (Figure 3b) qualitatively agree with their drifter counterparts (Figure 3a). Again, there are two prominent pathways: One follows the ACC, and the other is along the MC and the South Atlantic Current (Peterson & Stramma, 1991; Schmid, 2014). However, in contrast to the drifters, a larger percentage of floats takes the latter route (62%) than the former route (38%). With the caveats of a relatively small sample size (37 floats) and the fact that most of the floats are located in the northern DP, this
difference might indicate that the MC dominates at the subsurface. The floats have a longer average lifetime (2.5 ± 1.7 years) than the drifters (0.7 ± 0.5 years). Given this extended lifetime, a larger fraction of floats (37%; Figure 3b) crosses 10°W, compared to the drifters (21%; Figure 3a). As with the drifters, the travel time to the BEC is longer (5.6 ± 0.1 years) than the travel time to 10°W in the ACC (3.7 ± 1.4 years).

2.3.1.2 Agulhas Current

Seventy-eight drifters are found in the Agulhas domain (Figure 4a). These drifters have an average lifetime of 0.8 ± 0.5 years. The majority of these drifters (72%) stay in the Indian Ocean without leaking into the SA or following the ARC (Figure 4a; grey). A total of 22% exit the domain via the ARC, a few of which subsequently reenter the domain (Figure 4a; dark red). The strong looping and entanglement of the drifter trajectories (Figure 4a) highlights the enhanced eddy activity near the AC and ARC (Biastoch & Krauss, 1999). Approximately 6% of drifters (red) leak into the SA, defined here as crossing 32°S west of 20°E (Figure 4a).

The float trajectories (Figure 4b) again show qualitatively similar pathways to the drifter trajectories (Figures 4a). At depth, fewer floats exhibit the looping motion observed in the drifters and one-quarter of floats exit the domain via the ARC (Figure 4b). Keeping the relatively low number of float trajectories in mind, the amount of leakage seems to be higher at depth (10%).

We emphasize here that the abovementioned percentages are sensitive to the sampling criteria used (Figure 5). For instance, by using a stricter definition of Agulhas
leakage and only including those drifters that pass directly through the AC at 30°S, we observe only one drifter (3%) leaking into the SA (Figure 5a). Repeating this for the latitudes 32°S and 34°S, we obtain 5% and 9%, respectively (Figures 5b and 5c).

These various leakage estimates (3%–9%) are notably lower than previous estimates using the GDP drifters, which range from 25% to 33% (Richardson, 2007; van Sebille et al., 2009). To test whether this discrepancy can be explained by the use of data from different time periods, we resampled the drogued drifters to match the time periods used in these two previous studies: 1994–2004 for Richardson (2007) and 1995–2008 for van Sebille et al. (2009). We calculate Agulhas leakage of 14% and 11% for the 1994–2004 and 1995–2008 periods, respectively (using the 30°S definition of the AC; Figure 5a). Note that the only drifter that leaks into the SA over the shortened time periods is the drifter shown in Figure 4a.

As highlighted above (Figure 5), differences in drifter sampling influence leakage estimates. Since Richardson (2007) does not explicitly state how he defines AC drifters, a likely explanation for the difference in leakage estimates is the difference in what is or is not considered an AC drifter. However, we suggest that the discrepancy in these estimates mainly arises because Richardson (2007) and van Sebille et al. (2009) included undrogued drifters in their calculations. We note here that the differentiation between drogued and undrogued drifters in the GDP data set received more attention after the publication of these two papers (Lumpkin et al., 2013). The inclusion of undrogued drifters for our time
period at 30°S yields a leakage of 19%, still lower than the previous estimates (25%–33%),
yet closer to them.

Figure 4: Surface drifter and subsurface float trajectories from the Agulhas Current. (a) Trajectories of 78 drifters passing through the grey box (34.5°S–15°S, 20°E–50°E). The drifters are colored by their preferred pathways: Drifters leaking into the SA are colored in red; drifters that follow the ARC and subsequently exit the domain via the ARC are colored in dark red. Drifters that do not leak or exit through the ARC are colored in grey. (b) Similar to (a) but for the trajectories of 52 floats. The average depth of the floats is 678 ± 332 m with a range of 4–1,294 m. The 52 floats include 17 ALACE floats, 16 PALACE floats, and 19 RAFOS floats.
Figure 5: Sensitivity of Agulhas leakage estimates. The colors are as defined in Figure 4 caption. The (a) 33 drifter trajectories passing through the AC at 30°S (grey box). The (b) 37 drifter trajectories passing through the AC at 32°S (grey box). The (c) 51 drifter trajectories passing through the AC at 34°S (grey box).

When following our stricter definition of Agulhas leakage discussed above for the drifters and only using floats flowing directly through the AC at 30°S, we observe three
floats leaking into the SA, for a leakage value of 11%. This estimate is also lower than a previous estimate made by (Richardson, 2007), who calculated a leakage of 18% using RAFOS float and 23% using ALACE floats. Since no additional floats were released in that area since Richardson's study, we attribute this difference to the inclusion of a different number of floats according to different sampling criteria.

2.3.1.3 Interaction Between the Drake Passage and Agulhas Current

To further evaluate the interaction between the DP and Agulhas drifters, we next consider the trajectories of 225 drifters located in the vicinity of the ARC (Figure 6a). Strong comingling of DP drifters (blue), Agulhas drifters (red), and drifters originating elsewhere in the domain (grey) is observed (Figure 6a). Thus, these surface drifters illustrate that this interaction not only takes place in the BEC (Rodrigues et al., 2010) but also, as discussed above, just south of the African continent where the AC retroreflects into the ARC (Boebel et al., 2003), as well as within the ARC itself. Specifically, as previously mentioned, some DP drifters (highlighted in dark blue; Figure 6) are able to enter the ARC and leak back into the SA without taking a detour through the Indian Ocean subtropical gyre. This observation is similar to a pathway described by Rühs et al. (2019), whereby waters in the ACC take a small detour in the Agulhas basin before leaking back into the South Atlantic. Similar behavior is observed in the floats, though the apparent interaction between floats from the DP and AC is weaker due to the limited number of floats (Figure 6b).
Figure 6: Surface drifter and subsurface float trajectories in the Agulhas Return Current. (a) Trajectories of 225 drifters passing through the grey box (37°S–34.5°S, 20°E–50°E) at any point during their lifetime. Blue drifters originate west of 10°W and south of 40°S. Red drifters originate within the Agulhas domain defined in Figure 4 (34.5°S–15°S, 20°E–50°E). Grey drifters originate elsewhere in the domain. (b) Same as (a) but for the trajectories of 84 floats passing through the vicinity of the ARC. The 84 floats include 28 ALACE floats, 17 PALACE floats, and 39 RAFOS floats.
2.3.1.4 Benguela Current

There are 89 drifter trajectories that reach the BEC (Figure 7a), with the majority originating in the SA (grey; 85%). A small fraction can be traced back to the DP (blue; 11%) and an even smaller fraction to the AC (red; 4%). The large contribution of drifters from the SA is in agreement with (Garzoli & Gordon, 1996), who, however, also find a significant contribution from the AC. The number of drifters that can be traced back to the DP is, again, likely limited by the relatively short lifetime of these drifters (1.1 ± 0.8 years) relative to the travel time from the DP to the BEC. Note that the more northerly blue drifters could have also originated in the Brazil Current. Given the relative proximity of the AC to the BEC, the lifetime is unlikely to play a significant role, sampling bias could, however, be a contributing factor. Overall, drifters originating in the DP spread across a larger longitudinal range than the drifters from the AC, which are more concentrated near the South African coast. Drifters from the DP (blue) cross the SA in the relatively broad South Atlantic Current, with their pathways spanning approximately 10° in latitude (Figure 7a). In contrast, the drifters leaking from the Indian Ocean (red) are located in the narrow AC and closely follow the South African coastline (Figure 7a).

Though limited in number, the floats (Figure 7b) similarly highlight an interaction between floats coming from the DP (blue), the Agulhas (red), and elsewhere in the SA (Boebel et al., 2003; Rodrigues et al., 2010). Compared to the drifters, floats from the Agulhas (red) are located further away from the South African shore. Both the Agulhas and DP floats (Figure 6b) follow similar pathways to their drifter equivalents (Figure 7a).
Figure 7: Surface drifters and subsurface floats reaching the Benguela Current. (a) Trajectories of 89 drifters reaching the BEC (grey box). These drifters have an average lifetime of 1.1 ± 0.8 years and are colored by their origin, as defined in Figures 3 and 5. (b) Same as (a) but for the trajectories of 15 floats reaching the BEC. The average depth of the floats is 766 ± 232 m with a range of 32–1,039 m. The 15 floats include six ALACE floats, one PALACE float, and eight RAFOS floats.

The drifter trajectories examined above have revealed interesting and confirmed known features of the pathways in the SA (Peterson & Stramma, 1991; Schmid, 2014; Stramma & England, 1999). Drifters coming from the DP mainly remain in the ACC, yet some divert northwestward to merge with the MC and subsequently cross the SA basin in the South Atlantic Current. Drifters in the AC largely recirculate in its vicinity or retroreflect in the ARC. Only a small number of drifters leak into the SA from the Indian Ocean. We
highlight the potential areas for interaction between these two source waters that are
apparent from the drifter record: the BEC, the area just south of the African continent, and
the ARC. Given the limited lifetime of the drifters and their surface constraint, we are
limited in the conclusions that can be drawn from this data set alone, yet, are encouraged
that the subsurface floats show many qualitative similarities. Not only does the similarity
between these two data sets highlight the well-documented barotropic nature of SA south of
30°S (Killworth & Hughes, 2002; Schmid, 2014; Stramma & England, 1999), it also justifies
our use surface drifters to examine pathways in our study region. Next, we turn to our
discussion of the Markov chain.

**2.3.2 Markov chain**

Details on the method used to produce the distribution maps of the Markov chain
and OSCAR fields are outlined in section 2.3.4.

**2.3.2.1 Drake Passage**

Five years after the launch of particles within the DP, a vast area of the southern SA
is occupied by those particles (Figures 8a and 8b). Particles that pass through the DP south
of 60°S tend to stay in the ACC and subsequently leave the study domain via the ARC or
ACC (Figure 8a). The ACC, MC, and South Atlantic Current are revealed as preferential
pathways by the high particle concentrations in Figure 8a. Higher particle concentrations are
also observed in the Brazil-Malvinas Confluence, where particles are trapped in its well-
documented mesoscale eddy field (Berti et al., 2011; Mason et al., 2017; Olson et al., 1988).
The eastern portion of the subtropical gyre is also densely occupied (Figures 8a and 7b),
consistent with its relatively sluggish currents. We note that these higher particle concentrations are also likely a result of the two-dimensionality of the Markov chain. Specifically, downwelling would presumably reduce the concentration of particles at the surface in areas of horizontal convergence such as the subtropical gyre.

After five years, approximately 16% of particles launched in the DP are located in the southern SA (Figure 8a). These particles have either never left the region, returned to the southern SA by completing a circulation in the subtropical gyre, or crossed into the AR and subsequently leaked back into the SA (Figures 8a and 8b). A slightly larger number of particles (17%) can be found in the northern limb of the subtropical gyre (Figure 8a). These particles flow northward in the BEC or follow internal pathways that directly connect the South Atlantic Current to the northern limb of the gyre, consistent with Schmid (2014).

After five years, the largest fraction of particles (67%) can be found east of 20°E in the AR (Figure 8a). While the majority of these particles leave the domain in the ARC (Figure 8a), we observe a smaller number of particles in the vicinity of the AC. Strong recirculation and mesoscale interactions in that region result in the high concentrations shown in Figure 8b.

### 2.3.2.2 Agulhas Current

Qualitatively, the particles launched in the AC largely occupy the same spatial domain (Figures 9a and 9b) as the particles initiated in the DP (Figures 8a and 8b). This similarity is especially apparent in the northern limb of the subtropical gyre. Most particles follow the AC (Figure 9a) or recirculate in its vicinity (Figure 9b) and subsequently retroflect
to form part of the ARC. Specifically, after five years, 80% of particles remain in or return to the Indian Ocean (Figure 9a).

Approximately 20% of particles leak into the SA (Figure 9a), which is higher than the leakage estimated directly from the drifter record (3%–10%; Figure 5), yet at the low range of the 25%–44% leakage cited in the literature (Durgadoo et al., 2013; McAdam & van Sebille, 2018; Richardson, 2007; van Sebille et al., 2009). In contrast to the particles reaching the BEC from the DP (Figures 8a and 8b), the leaked particles from the AC tightly hug the South African coast and are more concentrated in the eastern part of the BEC (Figures 9a and 9b).

Particles with an AC origin that have leaked into the SA are primarily found in the subtropical gyre around 25°S and 20°W to 10°W (Figure 9b). After 5 years, the 20% of leaked particles are distributed as follows: 13% are located in the northern limb of the subtropical gyre, while a smaller fraction has either remained in or circulated back to the southern SA (7%). Some of the latter particles have invaded the western limb of the subtropical gyre and reached the vicinity of the MC (Figures 9a and 9b), highlighting a further area of interaction between DP and Agulhas waters.

2.3.2.3 Benguela Current

Particles initialized in the BEC and traced backward in time fill the entire SA basin after five years, indicating that waters originating in the SA may also provide a source for the BEC (Figures 10a and 10b). However, the majority of particles in the BEC can be traced back to the DP (67%) after a period of five years (Figure 10a). Recall that the majority of DP
surface drifters that reach the BEC pass through the northern part of the DP (Figure 3). Here we instead find a substantial number of particles passing through the southern section of the DP, as well as the northern section (Figure 10a). The second largest source of the BEC are particles originating east of 20°E in the AR (23%; Figure 10a). Within the AR, particles mostly follow the narrow AC before leaking into the SA (Figures 10a and 10b).

A fraction of particles (10%) cannot be traced back to either the DP or the AR over the five years. Most of these (7%) originate north of 30°S. These particles are primarily located in the western limb of the subtropical gyre (Figure 10a), but they also occupy portions of the gyre interior, as evidenced by the high concentrations between 30°S and 10°S (Figure 10b). A smaller portion of these particles (3%) are still located in the southern SA after five (Figure 10a).

Our estimate of the contribution of waters from the DP is substantially higher than most previous studies which range between 6% and 40% (Friocourt et al., 2005; Rodrigues et al., 2010; Rühs et al., 2019; Speich et al., 2001). Our higher estimate likely results from a combination of sampling issues in the vicinity of the AC, which likely does not properly capture the pathway from the AC to the BEC, and the fact that our estimate is derived solely from surface drifters. We note that a direct comparison with previous estimate is challenging due to the use of different methods and different latitudes at which the relative contributions are assessed, ranging from 33°S in Rodrigues et al. (2010) to 20°N in Speich et al. (2001).

As expected, the Markov chain results largely confirm the picture drawn from the drifter record. However, this analysis also reveals additional areas of interaction between the
DP and Agulhas waters. Particles released at both sources occupy the Brazil-Malvinas Confluence, the subtropical gyre, and the ARC. From these Markov chain results, we find that the primary source for the BEC are DP waters, with a smaller contribution from the Agulhas and SA. Since the results of the Markov chain are constrained by the availability of drifter data, we next turn to the results of the OSCAR fields as an independent confirmation of our results.
Figure 8: Distribution of Markov chain particles released in the Drake Passage. The particles are traced forward for five years. The individual subdomains are demarcated by black lines as defined in Figure 2. (a) Markov chain particle distribution normalized by the total number of released particles. The blue percentages show a snapshot of the particle distribution after five years and, thus, sum to 100%. If the particle leaves the domain prior to five years, we use its last position in the domain. The straight black arrows indicate the percentage of particles that cross into a given region over five years (i.e., they do not sum up to 100% as a particle may cross more than one region over the five-year period). The curved black arrows indicate the percentage of particles that recirculate between two adjacent regions, that is, they indicate difference between the two previous percentages. Note that the black arrows do not show the exact crossing location of particles. The gray contours show the climatological dynamic topography (m) as derived from AVISO with contour intervals of 0.25 m. (b) Markov chain particle distribution normalized by the total number of particle positions over the course of five years.
Figure 9: Distribution of Markov chain particles released in the Agulhas Current. The particles are traced forward for five years. (a) Markov chain particle distribution normalized by the total number of released particles. (b) Markov chain particle distribution normalized by the total number of particle positions over the course of five years. Refer to Figure 8 caption for additional details.
Figure 10: Distribution of Markov chain particles released in the Benguela Current. The particles are traced backward for five years. (a) Markov chain particle distribution normalized by the total number of released particles. (b) Distribution normalized by the total number of particle positions over the course of five years. Refer to Figure 8 caption for additional details.
2.3.3 OSCAR Fields

2.3.3.1 Drake Passage

As with the Markov chain results, large portions of the SA basin and AR are occupied by particles launched within the DP 5 years previously (Figure 11a). The number of particles following the ACC and the number of particles following the MC upon exiting the DP are approximately the same in these OSCAR results (Figures 11a and 11b), in contrast to the Markov chain results (Figures 8a and 8b). This difference can be partially explained by the poor coverage of the OSCAR fields and drifter trajectories south of 60°S, which gives preference to more northerly pathways such as the MC and the South Atlantic Current.

As also observed in the Markov chain results (Figures 8a and 8b), particles initialized within the DP are densely concentrated in the eastern portion of the subtropical gyre as a result of convergence at the ocean surface (Figures 11a and 11b). Also similar to the previous results (Figures 8a and 8b), OSCAR particles that reach the BEC from the DP are more concentrated toward the western and central parts of the BEC (Figures 11a and 11b).

Most particles released within the DP exit the domain in the well-defined ARC (Figure 11a), with some particles reaching as far north as 10°S in the AR, where they recirculate between the AC and ARC (Figures 11a and 11b). This spread of particles from the DP into the AR again highlights the coexistence of DP and Agulhas waters in a number of areas of the domain. A small percentage of particles (1%) leak back into the South Atlantic after crossing into the AR, similar to the shortcut pathway observed from the drifter record (Figure 6).
After 5 years, the largest amount of particles are located east of 20°E in the AR (43%), with the remaining particles almost equally distributed in the northern (30%) and southern (27%) portions of the subtropical gyre (Figure 11a).

### 2.3.3.2 Agulhas Current

Approximately one fifth of the particles released in the AC leak into the SA (Figure 12a). This estimate is very similar to the leakage calculated from the Markov chain (20%; Figure 9a) and, again, lower than estimates from past literature (Durgadoo et al., 2013; McAdam & van Sebille, 2018; Richardson, 2007; van Sebille et al., 2009). The majority of these leaked particles in the OSCAR results are found in the northern SA (15%), with a smaller fraction flowing toward the Brazil-Malvinas Confluence and found in the southern SA (5%; Figure 12a). The high concentrations observed near the western limb of the subtropical gyre (Figure 12b) result from the recirculation of a small number of particles (Figure 12a). The rest of the particles launched in the AC (80%) remain east of 20°E in the AR or return to the AR after retroreflecting in the ARC (Figures 12a and 12b). These particles are most densely concentrated in the narrow AC (Figure 12a) but also recirculate in its vicinity (Figure 12b). These observations are remarkably consistent with the results of the Markov chain (Figures 9a and 9b), derived from a completely independent data set.

We again point out that particles released within the DP (Figures 11a and 11b) and particles released in the AC (Figures 12a and 12b) largely occupy the same regions in the domain. Specifically, they share pathways in the Brazil-Malvinas Confluence, the subtropical gyre, and the ARC, as previously suggested by the Markov chain results (Figures 8 and 9).
2.3.3.3 Benguela Current

The results from the OSCAR fields show that over the course of five years, the largest source of the BEC are particles originating east of 20°E in the AR (62%; Figure 13a). About half as many particles (33%) can be traced back to the DP, and the remainder are found in the northern (4%) and southern SA (1%; Figure 13a). With the caveat that these estimates are strictly derived from the surface flow, this distribution of source waters is in better agreement than the Markov chain results with a previous observational study by Rodrigues et al. (2010) that attributed a direct contribution from the DP of 4.7 Sv (36%) and Agulhas leakage of 8.5 Sv (64%). Model results from Rühs et al. (2019) found contributions of 40% and 60% from the DP and Agulhas Leakage, respectively, though their contributions were measured at the North Brazil Current and not the BEC. Keeping in mind the small number of floats in the vicinity of the BEC (15), the results are also in agreement with the distribution of float trajectories (Figure 6b).

However, this distribution differs from the results of the Markov chain (Figures 10a and 10b), which revealed the DP to be a larger contributor (67%) to the source waters of the BEC than the AR (23%). This discrepancy is likely a consequence of insufficient drifter coverage in the vicinity of the BEC. As discussed in the context of the drifter trajectories, very few drifters that arrive in the BEC can be traced back to the AR (Figure 7a). In other words, the drifters may not accurately capture the available pathways. We also note that the difference in this DP and AR divide may be due to an inadequacy on the part of the OSCAR fields. In particular, the OSCAR fields have a limited latitudinal extent and at times do not
cover portion of the ACC. Hence, the OSCAR fields might be under-sampling the number of particles that are traced back to the DP.

The majority of particles that can be traced back to the DP are concentrated in the northern section of the DP (Figure 13a), a preferential pathway previously observed in the drifter trajectories (Figure 3a). Particles coming from the DP are entrained in the MC and subsequently reach the BEC in the wide South Atlantic Current (Figure 13a). Note that prior to their arrival in the BEC, a small number of particles originating in the DP flow east of 20°E into the AR, again highlighting a conflation between the DP and AR sources (Figures 13a and 13b).

The particles that can be traced back to the AR mostly flow through the AC and are closely confined to the South African coast (Figure 13a). Similar to the particles from the DP, they recirculate along their paths, as indicated by the elevated particle concentration in the AR and along the South Atlantic Current (Figure 13b).

In summary, the OSCAR results for particles released in the DP and AC are in good agreement with the results from the drifters, floats, and the Markov chain. Specifically, these OSCAR results yield similar quantitative estimates for the DP and AC distributions and highlight the same areas for interaction between the DP and Agulhas waters. We do note that the particle distributions of the Markov chain are generally more dispersive than those from the OSCAR fields. In other words, the Markov particles (Figures 8–10) occupy a larger portion of the domain after a period of five years than the OSCAR particles (Figures 11–13). In part, this difference can be explained by the two methodologies. The Markov chain may
be connecting areas of the domain that are not connected in the original drifter data set, as explained earlier in the context of artificial dispersion.

The backward particle advection using the OSCAR fields attributes a larger source contribution to the AR than the DP, while the Markov chain showed a larger contribution for the DP. Many past studies state that the DP contribution is negligible compared to the AR input (Donners & Drijfhout, 2004; Speich et al., 2001; Speich et al., 2007). However, keeping the caveat of two-dimensionality in mind, our results indicate that the two contributions are more comparable, as suggested by Rodrigues et al. (2010) and Rühs et al. (2019).
Figure 11: Distribution of OSCAR particles released in the Drake Passage. The particles are traced forward for five years. (a) Distribution normalized by the total percentage of released particles. (b) Distribution normalized by the total number of particle positions over the course of five years. Refer to the caption of Figure 8 for additional details.
Figure 12: Distribution of OSCAR particles released in the Agulhas Current. The particles are traced forward for five years. (a) Distribution normalized by the total percentage of released particles. (b) Distribution normalized by the total number of particle positions over the course of five years. Refer to the caption of Figure 8 for additional details.
Figure 13: Distribution of OSCAR particles released in the Benguela Current. The particles are traced backward for five years. (a) Distribution normalized by the total percentage of released particles. (b) Distribution normalized by the total number of particle positions over the course of five years. Refer to the caption of Figure 8 for additional details.

2.4 Summary

This study investigated the surface pathways of the SA and revisited the relative contributions from the Indian and Pacific Oceans. Limitations imposed by the drifter data set were addressed using a Markov chain and Lagrangian particle advections using OSCAR
surface fields. Given the remaining surface constraint, areas with known subsurface pathways were excluded from the analysis. We summarize the key findings below.

As in previous studies, DP waters preferentially cross the extended SA basin in the ACC or enter it through the MC, with waters crossing through the northern DP generally following the latter. Over five years, DP waters tend to accumulate in the eastern portion of the subtropical gyre.

AR waters mostly recirculate within the AR or exit toward the central Indian Ocean via the ARC. AC waters leaking into the SA tend to be more concentrated on the West African coast than DP waters, but also largely recirculate in the subtropical gyre.

Additionally, this study showed that waters entrained in the ACC can escape to join the SAC and vice versa, further east than suggested in previous studies (Boebel et al., 1999; Speich et al., 2001). Our observation is, therefore, in agreement with a recent modeling study by Rühs et al. (2019). Some waters from the DP enter the AR and potentially reenter the SA basin via the leakage route without recirculating in the Indian Ocean subtropical gyre. The Agulhas leakage is at the lower end of previous estimates from the literature. In particular the surface drifter estimate is lower, partly due to the fact that previous estimates included undrogued drifters (Richardson, 2007; van Sebille et al., 2009). We highlight that the estimate is highly sensitive to the chosen drifter subset criteria.

Over the course of five years, the primary surface source waters of the BEC are composed of AC waters, DP waters, and local SA waters. While the backward Markov chain and OSCAR results are not in quantitative agreement, both suggest that the DP inflow
makes a sizable contribution to the source waters of the BEC region and potentially the upper limb circulation of the AMOC. We highlight the varying traveling times of these source waters, with the DP waters taking approximately twice as long to reach the BEC as AC waters at the ocean surface.

Multiple surface pathways exist that allow for the interaction between the traditional cold and warm routes. Specifically, the AC region, the BEC region, the eastern subtropical gyre, and the Brazil-Malvinas Confluence. This interaction suggests that the properties associated with these two source regions may be indistinguishable by the time these waters flow out of the SA subtropical region (see Rühs et al., 2019). Given that both source waters are strongly represented in the gyre interior, we postulate that gyre dynamics also have an impact on setting the properties of the upper limb.
3. Variability and trends of the South Atlantic subtropical gyre

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3.1 Introduction

The subtropical circulation of the South Atlantic is characterized by an anticyclonic gyre located approximately between 45°S–15°S and 55°W–10°E. This geostrophic subtropical gyre (STG) is forced by wind-driven Ekman convergence; thus, the gyre's center is identifiable as a maximum in sea surface height (SSH). The STG is composed of four main surface currents: the eastward-flowing South Atlantic Current, the northwestward-flowing Benguela Current, the westward-flowing South Equatorial Current, and the southward-flowing Brazil Current (Figure 14).

In large part, we are motivated to study the changing characteristics of the South Atlantic STG because two of its components, the Benguela Current and the South Equatorial Current, act as conduits for the upper limb of the Atlantic Meridional Overturning Circulation. These currents carry water masses from the Indian and Pacific Oceans, and those that are locally formed, toward the North Atlantic. In fact, recent studies have suggested that variability in the strength of the gyre circulation could influence the amount of Agulhas leakage that is exported out of the STG (Durgadoo, 2013; Tim et al., 2018). Specifically, Durgadoo (2013) argued that an increase in westerly wind stress strengthens the STG circulation, thereby favoring a recirculation of Agulhas leakage within the STG over its export to the North Brazil Current and into the North Atlantic. Rühs
et al. (2019) applied the same argument for Pacific waters entering through the Drake Passage: a strengthening STG would favor the recirculation of these waters over their export to the North Brazil Current. Additionally, variability in the bifurcation latitude of the South Equatorial Current, the northern gyre boundary, has been linked to changes in the transport of the North Brazil and Brazil Currents, with a more southerly position favoring the export of water to the North Brazil Current over that to the Brazil Current (Rodrigues et al., 2007).

A number of past studies have investigated the seasonal and interannual variability as well as trends of different aspects of the gyre circulation. For the remainder of this study, the time period covered by individual studies and data sets is referenced as a subscript (e.g., years\textsubscript{1992–1997}). Witter and Gordon (1999) analyzed several years\textsubscript{1992–1997} of altimetry data and identified a South Atlantic basin-scale mode that was associated with an enhanced geostrophic gyre circulation between 1993 and 1994, followed by a more sluggish circulation in 1996. McClain et al. (2004) reported a very small positive trend\textsubscript{1997–2002} in the size of the gyre (0.2% per year) by assessing chlorophyll-a concentration at the sea surface using ocean color satellite data. That same study also found an increasing trend\textsubscript{1997–2002} of 3.3 mm per year in the mean SSH within the gyre and noted a distinct seasonal cycle in mean SSH within the gyre, with a maximum in April and a minimum in September. Accordingly, the gyre reaches its maximum expansion in austral summer and maximum contraction in austral winter (McClain et al., 2004). An updated study confirmed the increase in mean SSH over the gyre (trend\textsubscript{1998–2010}: 2.8 mm per year) and associated it with an overall warming signal (Signorini & McClain, 2012). The authors found a similar seasonal cycle to the previous study (McClain et al., 2004) and attributed it to a strengthening of the gyre circulation in austral summer.
Both studies concluded that any trends of the South Atlantic gyre were much smaller than trends observed in other basins (McClain et al., 2004; Signorini & McClain, 2012).

A modeling study by Marcello et al. (2018) revealed an overall strengthening of the gyre circulation between 1970 and 2015, based on increasing trends in the wind stress curl, SSH, and barotropic stream function. On the other hand, a modeling study by Combes and Matano (2014) and an altimetry and drifter-based study by Goni et al. (2011) identified no changes in the gyre circulation. More recently, Qu et al. (2019) argued for an overall strengthening of the Southern Hemisphere super gyre based on 25 years of satellite altimetry. Their analysis of Argo floats and an ocean state estimate further revealed that changes in the circulation are evident from the surface to a depth of 2,000 m. The authors attributed the spin-up of the gyre to an intensification and poleward shift of the Southern Hemisphere wind stress curl, that is in turn related to the Southern Annular Mode (Qu et al., 2019). The Southern Annular Mode is an important mode of climate variability that has been linked to changes in the circulation of the subtropical South Pacific (Cai et al., 2005; Roemmich et al., 2007; Zhang & Qu, 2015).

More generally, one might expect changes to the gyre circulation as a result of the shifting of surface winds toward higher latitudes, as has, for example, been shown in the context of an intensification and poleward migration of western boundary currents by Wu et al. (2012). Recently, Yang et al. (2020) estimated a small poleward displacement of the South Atlantic gyre circulation of 0.11° per decade based on observational data and 0.06° per decade based on a 150-year model simulation. The authors linked this displacement to the poleward migration of the basin-scale wind fields.
Additional studies related to shifts in the gyre position have primarily focused on seasonal variability, interannual variability, and trends in the position of the Brazil-Malvinas Confluence (Artana et al., 2019; Combes & Matano, 2014; Gan et al., 1998; Goni et al., 2011; Lumpkin & Garzoli, 2011). Lumpkin and Garzoli (2011), for example, used surface drifter trajectories and satellite altimetry to show that the Confluence had migrated southward at a rate of 0.6°–0.8° per decade1992–2007. A modeling study by Marcello et al. (2018) examined the bifurcation latitude of the South Equatorial Current and concluded that it was moving southward at a rate1970–2015 of 0.11° ± 0.03° per year.

Summarizing, previous studies have (1) investigated changes to the South Atlantic gyre on seasonal time scales over a limited number of years (McClain et al., 2004; Signorini & McClain, 2012), (2) argued for a small positive increase in gyre size using six years of data (McClain et al., 2004), (3) found a southward shift at the northern and southern boundaries of the gyre (Lumpkin & Garzoli, 2011; Marcello et al., 2018), (4) argued for an overall strengthening of the South Atlantic gyre circulation using modeling data (Marcello et al., 2018) and a strengthening of the Southern Hemisphere super gyre using altimetry (Qu et al., 2019), or (5) found no change in the gyre circulation (Combes & Matano, 2014; Goni et al., 2011).

Building on previous work that focused on specific aspects and time scales of the South Atlantic gyre circulation, the primary goal of this study is to provide a comprehensive overview of the South Atlantic gyre by investigating three key metrics of change: gyre position, size, and strength. We explore their variability on seasonal and interannual time scales and also investigate their long-term trends. A secondary goal of our work is to address
conflicting results regarding interannual to longer term variability from previous studies, which are partially related to the use of different gyre definitions. Since it is more thoroughly explored and understood, we include an analysis of the seasonal gyre variability to assess the utility of our gyre metrics. This study is based on observational data and akin to past studies, uses satellite altimetry to represent the total SSH. We additionally explore changes to the individual components of SSH, which are the steric height and ocean mass.

Figure 14: Schematic of the subtropical circulation of the South Atlantic. The gray contours indicate the mean climatological SSH (1993–2018) in meters from the E.U. Copernicus Marine Service Information. The climatological position of the STG is shown by the 0.6-m contour in dark gray. Relevant ocean features and currents are sketched and labeled in blue. The area used to calculate the STG maximum is highlighted by the teal box.

3.2 Data and methods

3.2.1 SSH estimates

This study makes use of three primary data sets: (1) satellite altimetry data to represent total SSH, (2) Argo profiling floats to estimate changes in steric height, and (3) GRACE data to assess the contribution of ocean mass. More specifically, the total SSH is
estimated from the satellite altimetry record distributed by the E.U. Copernicus Marine Service Information (formerly AVISO+, referenced here as total SSH_{AVISO}) between 1993 and 2018. This data set is available at daily resolution and one-quarter degree spatial resolution (https://marine.copernicus.eu/). To match the resolutions of the other two data sets, we regrid the total SSH_{AVISO} fields to a one-degree spatial resolution with monthly temporal resolution using area-weighted averages. As recommended by von Schuckmann et al. (2013), we account for glacial isostatic adjustment by applying a correction of 0.3 mm per year to the long-term sea level trends estimated from total SSH_{AVISO} and assume an uncertainty of 30%, a valid approximation in our domain.

We estimate the steric height in two ways. First, we calculate the steric height fields directly using the temperature and salinity fields of the Roemmich-Gilson Argo Climatology from 2004 to 2016, referenced to a depth of 1,975 db (Argo, 2000; Roemmich & Gilson, 2009; steric height_{Argo}). The Argo climatology has a monthly temporal resolution and one-degree spatial resolution and is publicly available (http://sio-argo.ucsd.edu/RG_Climatology.html). Second, we indirectly estimate the steric height field by subtracting the ocean mass component from the total SSH_{AVISO} fields (steric height_{AVISO-GRACE}). These two estimates are not expected to completely match, as the latter also contains contributions from deep ocean steric signals (below 1,975 db).

Similarly, we use two measures of ocean mass. To directly estimate this contribution, we use the ocean bottom pressure anomalies of equivalent water thickness provided by TELLUS GRACE (2002–2017) and GRACE-FO (2018–2019) (ocean mass_{GRACE}; Landerer and Swenson, 2012). These data sets have a monthly temporal resolution and a one-degree
spatial resolution and are publicly available (https://podaac.jpl.nasa.gov/). Second, we indirectly estimate the ocean mass contribution by subtracting the total steric height$_{\text{Argo}}$ from the total SSH$_{\text{AVISO}}$ signal (ocean mass$_{\text{AVISO}}$–Argo). The GRACE and GRACE-FO data (“GRACE”) are available from three main processing centers: the Geoforschungs Zentrum, Potsdam (Landerer 2020c, 2020d), the Center for Space Research at University of Texas, Austin (Landerer 2020a, 2020b), and the Jet Propulsion Laboratory (Landerer 2020e, 2020f). The details for each data set are provided in the references. The GIA correction is automatically applied to the GRACE fields, such that no additional change is needed. Following previous studies, we use the arithmetic average of the data provided by the three processing centers as our estimate of ocean mass$_{\text{GRACE}}$ (Ruiz-Etcheverry et al., 2020; Sakumura et al., 2014). It should be noted that GRACE contains gaps, such that it is not always available at a monthly resolution. Specifically, the years affected by this limitation (followed by the number of months available to calculate the annual means for each year) are 2002 (7), 2003 (11), 2011–2012 (10), 2013–2016 (9), and 2017–2018 (5).

We produce a monthly climatology for all three data sets by averaging available monthly data between 2004 and 2016 (the time period common to all three data sets). Note that the ocean mass$_{\text{GRACE}}$ monthly climatology is calculated from at least 10 years of data for each month. Calculating the monthly climatology using all available years of data (instead of just the common time period) yields insignificantly different results. We produce annual climatologies by averaging over all available months for a given year for a given data set. We estimate the uncertainty in these monthly and annual means as well as derived trends by calculating standard errors. The reported long-term trends are defined over the common
period (2004–2016) of all three data sets, unless otherwise indicated. All trends are calculated using linear regression and statistical significance is reported using Student's t-test ($p < 0.05$).

As in past studies (Foukal & Lozier, 2017; Marcello et al., 2018; McClain et al., 2004), we primarily use SSH as a proxy for changes in the gyre. Since the choice of metric limits us to the examination of the surface expression of the gyre, we acknowledge that changes described here could be different at subsurface levels. This may be especially important in the vicinity of the South Equatorial Current, for example, which is known to shift southward with depth (Palma & Matano, 2017; Schmid, 2014; Stramma & England, 1999). Specifically, compared to the surface, it is located approximately 10°S further south at a depth of 500–1,200 m (Garzoli & Matano, 2011; Schmid, 2014; Stramma & England, 1999). To complement our study of the SSH, we also examine changes to the wind stress and Ekman transports over the South Atlantic basin and the gyre. Wind stress data from the European Centre for Medium-Range Weather Forecast ERA5 model are used for our study (Copernicus Climate Change Service, 2019). This data set is available at monthly temporal resolution between 1993 and 2018, with a spatial resolution of one-quarter degree. It is publicly available through the Copernicus Climate Change Service via https://cds.climate.copernicus.eu/.

### 3.2.2 Basin and gyre metrics

To put changes to the gyre circulation in a broader context, we define a larger domain surrounding the South Atlantic STG that includes oceanic features relevant to our study (60°W–20°E and 45°S–10°S; Figure 14). We assess changes over the South Atlantic by computing the seasonal cycle of mean SSH and wind stress forcing using the years common
to all data sets (2004–2016). We compute annual time series of mean SSH and wind stress forcing over the basin for the years covered by the individual data sets. Additionally, we calculate local and basin-wide trends in total SSH, steric height, and ocean mass. The local trends are computed from the annual mean at each grid cell for the common years (2004–2016). The basin-wide trend is calculated using an area-weighted annual average over the whole domain, both for the common time period and for the full time period available for each data set.

To assess changes to the gyre position, size, and strength, we first define the gyre boundary as the largest closed contour of total SSH\textsubscript{AVISO} in our domain. This and similar definitions have previously been applied to the North Atlantic subpolar gyre (Foukal & Lozier, 2017), the Beaufort Gyre (Regan et al., 2019), and the Ross gyre (Dotto et al., 2018). We choose this definition because we expect the mean circulation, dominated by geostrophic dynamics, to follow closed contours of SSH. Marcello et al. (2018) used a similar definition for the gyre and tracked the values of SSH, wind stress curl, and the barotropic stream function within their respective zero contours. The spatial domain used in that study is larger than our domain: it extends to approximately 40°S and stretches eastward toward the Cape Basin (see Figure 14 of Marcello et al., 2018). Studies by McClain et al. (2004) and Signorini and McClain (2012) defined the gyre boundary based on a threshold of chlorophyll-a at the ocean surface. Dave et al. (2015), however, have shown that changes in surface chlorophyll-a in oligotrophic gyres can at times reflect a horizontal transport of nutrients unrelated to gyre size or strength. Finally, in a study of the South Atlantic super gyre, Qu et al. (2019) use geography (i.e., the entire subtropical Southern Hemisphere) to determine their domain.
Thus, given the goals of our study and the limitations of other metrics, we chose to define the South Atlantic STG with closed SSH contours. Note that a recent study by Artana et al. (2018) identified the 0.3-m contour (Figure 14) in absolute dynamic topography as the Brazil Current Front, which they consider the southern boundary of the South Atlantic gyre. Our southern gyre boundary is located further north because we are focused on a gyre defined by a closed circulation. In order to test the robustness of our results, we also conducted our analyses with a larger spatial domain using three alternate definitions for the gyre. Specifically, we defined the gyre as (1) the last contour to intersect the South American coast (around 15°S), (2) the climatological 0.45 m, and (3) the climatological 0.5-m contour (Figure 14). None of these three alternate metrics altered the results discussed in this study.

The gyre position is assessed by shifts in the closed gyre boundary. We define the most northern and southern positions of the gyre as the point maximum and minimum latitude of the gyre boundary. Similarly, we define the most eastern position of the gyre as the maximum longitude of the gyre contour. Since the southwestern corner of the STG is located near the Brazil-Malvinas Confluence (Figure 14), we can also estimate the migration of the Confluence. We define its monthly position as the average latitudinal position of the total SSH\textsubscript{AVISO} contours west of 45°W and south of 35°S.

The gyre size is estimated by calculating the area enclosed by the gyre boundary. The mean SSH is defined as the mean SSH within the closed gyre boundary. The maximum SSH is defined as the mean SSH within the box centered in the southwestern corner of the gyre (55°W–45°W and 37°S–30°S) and within the corresponding gyre contour (Figure 14, teal box). This box is chosen as it contains the center of the gyre, as expressed by a high in SSH.
or in this case, the 0.7 m contour (Figure 14). We average the maximum over this area to smooth variability that arises from using a point maximum. Note that neither the calculation using a point maximum nor using an average over the climatological 0.7 m contour (Figure 14) changes the conclusions.

Finally, the gyre strength is estimated as the SSH difference between the gyre maximum and the gyre boundary (Foukal & Lozier, 2017). This metric gives an estimate of the net strength of the surface geostrophic flow around the gyre, which is set up by the SSH slope. However, it does not give us an indication of the total flow of the STG and thus represents a limitation of this study. These same calculations of gyre strength are repeated using the steric height and ocean mass fields, over the same closed gyre boundary derived from the total SSH\textsubscript{AVISO} fields. The mean values of steric height and ocean mass at the gyre boundary are obtained by interpolating the steric height and ocean mass fields to the position of the gyre boundary as defined above. Note that all calculations are performed on the monthly fields of total SSH\textsubscript{AVISO}, steric height\textsubscript{Argo}, and ocean mass\textsubscript{GRACE}. The resulting values are averaged into monthly and annual climatologies. We explore the Ekman component of the surface circulation by calculating the mean meridional Ekman transport and Ekman pumping velocity.

### 3.3 Results and discussion

We start with a discussion of the seasonal variability in SSH, wind stress curl, and zonal wind stress over the South Atlantic basin, to compare our chosen data sets to previous work and to set the stage for the analysis of the seasonal variability of the STG.
3.3.1 Basin-wide seasonal variability

The total SSH_{AVISO}, steric height_{Argo}, and steric height_{AVISO-GRACE} follow very similar seasonal cycles (Figure 15a). The three time series exhibit maxima around March or April and minima around September, reflecting the end of the heating and cooling seasons in the Southern Hemisphere, respectively (Figure 15a). The seasonal steric height cycle is in agreement with previous studies (Roemmich & Gilson, 2009; Ruiz-Etcheverry et al., 2020). Referencing the steric height_{Argo} to 150 db instead of 1,975 db yields virtually identical results, confirming the expectation that the majority of steric height changes are confined to the upper ocean on seasonal time scales (Fukumori et al., 1998). Fukumori et al. (1998) used a global primitive equation ocean model to show that sea level variability at midlatitudes is dominated by steric height changes, driven by heating and cooling of the surface ocean via seasonal changes in shortwave radiation.

The ocean mass_{GRACE} and ocean mass_{AVISO-Argo} seasonal cycles show much weaker variability and are out of phase with the seasonal cycle of SSH and steric height (Figure 2a). Specifically, both ocean mass measures reach their maxima in October and their respective minimum in January (ocean mass_{GRACE}) and February (ocean mass_{AVISO-Argo}, Figure 15a). These roughly opposing seasonal cycles result in an overall dampening of the total SSH_{AVISO} signal (Figure 15a), an observation that echoes recent findings by Ruiz-Etcheverry et al. (2020). The amplitude of the seasonal ocean mass signal (0.02 m, Figure 15a) agrees with Johnson and Chambers (2013), who report typical seasonal amplitudes of 0.01–0.04 m for different regions of the global ocean.
Akin to the seasonal ocean mass signal (Figure 15a), the wind stress curl is stronger in austral winter and weaker in austral summer (Figure 15b). Note that the wind stress curl across the South Atlantic is positive, such that positive anomalies indicate a strengthening (Figure 15b). We suggest that the seasonal ocean mass signal is driven by the seasonality of the wind stress curl over the South Atlantic basin, with the wind stress curl leading by one month \( (r = 0.74, \text{Figure 15d}) \). This observation is explored in more detail in the next section. We note as a caveat, that the steric signal could also be influenced by changes in the wind stress curl, through processes such as upwelling near the Benguela Current or the propagation of annual baroclinic Rossby waves from the eastern boundary to the interior of the South Atlantic basin. However, we expect the heating and cooling cycle to dominate the steric signal on seasonal time scales.

In general, wind stress variability on seasonal time scales is dominated by variability in the zonal wind stress. We differentiate between variability in the trade winds (north of 28°S) and westerlies (south of 28°S) and the resulting meridional Ekman transports. The trade and westerly wind anomalies are out of phase: in austral summer, we observe positive anomalies in zonal wind stress north of 28°S, which translate to a weakening of the trade winds, as well as negative anomalies in the zonal wind stress south of 28°S, which translate to a weakening of the westerlies (Figure 15c). As such, both wind stress anomalies (north and south of 28°S) as well as their corresponding meridional Ekman transports are strongest in austral winter.
Figure 15: Seasonal variability in mean SSH, wind stress curl, and zonal wind stress averaged across the South Atlantic basin. A 12-month time series of the mean monthly (a) total SSH$_{AVISO}$ (thick black), steric height$_{Argo}$ (thick pink), steric height$_{AVISO}$–GRACE (thin pink), ocean mass$_{GRACE}$ (thick green), and ocean mass$_{AVISO}$–Argo (thin green), (b) wind stress curl, (c) zonal wind stress of the trades (north of 28°S) and westerlies (south of 28°S), and (d) cross correlation function between the ocean mass$_{GRACE}$ from (a) and the wind stress curl from (b). All values shown in (a–c) are shown as anomalies relative to the 2004–2016 mean. The error bars show the standard error about the mean. SSH, sea surface height.

3.3.2 Seasonal variability of the gyre

Having set the basin-wide context, we now investigate changes to the position, size, and strength of the gyre on seasonal time scales. Given the satisfactory agreement between
the two steric height and two ocean mass estimates on seasonal time scales in the South Atlantic basin (Figure 15), the remainder of this section uses only the three primary data sets (total SSH_{AVISO}, steric height_{Argo}, and ocean mass_{GRACE}) to interpret changes in the STG.

**Position:** The strongest seasonal variability in the position of the STG is observed at the eastern and northern gyre boundaries, as well as in the vicinity of the Brazil-Malvinas Confluence (Figure 16a). Little variability is observed in the gyre's western boundary current along the South American coastline, where the Brazil Current is topographically constrained (Figure 16a). The South Atlantic Current, the STG's southern boundary, also shows little variability east of 40°W (Figure 16a). We further describe the movement of the gyre by looking at the point maxima and minima of its longitudinal and latitudinal extent (Figure 16b). The northern limit of the gyre is located farthest north in March and farthest south in June (Figure 16b). The southern gyre boundary mirrors this migration and is located farthest north in June and farthest south in March. The eastern gyre boundary is located farthest east in October and farthest west in May. Taking an average of the northern position (defined as north of 22°S), southern position (defined as south of 33°S and west of 20°W), and eastern position (defined as north of 30°S and east of 30°W) instead yields a similar seasonal cycle as Figure 15b, but with a smaller range (not shown). We estimate that the southwestern corner of the gyre, the Brazil-Malvinas Confluence, migrates seasonally by 1.5° ± 0.3°, reaching its southernmost position in March and northernmost position in September, in agreement with previous studies (Artana et al., 2019; Gan et al., 1998; Goni et al., 2011; and ; Combes and Matano, 2014; Wainer et al., 2000). As noted by Matano
et al. (1993), the seasonal migration of the Confluence has important consequences for the local climate and local marine fauna.

**Size:** The STG reaches its maximum size in austral summer (January–March) and minimum size in austral winter (May–June Figure 16c), as also seen by tracking the northern and southern boundaries of the gyre (Figure 16b). The northward migration of the southern boundary is accompanied by a southward migration of the northern boundary in austral fall (March–June; Figure 16b), which leads to a corresponding contraction of the gyre (Figure 16c). The opposite is true for the austral summer months. Analogously, the eastern boundary of gyre reaches its easternmost expression in austral summer (January–March) and westernmost expression in austral winter (May–July), which also contributes to the expansion and contraction. The total contraction and expansion of the gyre covers an area of $1.9 \times 10^6 \pm 0.4 \times 10^6$ km$^2$. This seasonal cycle in gyre size is in line with past observational work (McClain et al., 2004).

Given that the size of the gyre is influenced by the seasonal migration of its boundaries (Figure 16b), it is reasonable to assume that processes controlling the migration of the bifurcation latitude and position of Brazil-Malvinas Confluence also affect the gyre size. Past studies have linked the position of the Confluence to changes in the wind stress curl and changes in the transport of its two currents (Matano et al., 1993; Wainer et al., 2000). We find a significant correlation ($r = 0.75, p < 0.05$) between the gyre wind stress curl (Figure 16d) and the southern boundary position (Figure 16b), as well as the gyre wind stress curl and the seasonal cycle of our estimated Brazil-Malvinas Confluence latitude (not shown; $r = 0.67, p < 0.05$).
The wind stress curl averaged over the monthly closed contours of total SSH\textsubscript{AVISO} is strongest in austral winter (June–August) and weakest in austral summer (March; Figure 16d). The corresponding Ekman pumping velocity follows the same seasonal cycle (not shown). Note that the annual mean wind stress curl over the STG is positive, with a resulting negative Ekman pumping so that positive anomalies in wind stress curl (and negative anomalies in Ekman pumping) represent a strengthening relative to annual mean conditions. The seasonal cycle of the Ekman pumping velocity slightly differs from the seasonal cycle described in McClain et al. (2004). While the authors also found a minimum Ekman pumping in March, their results indicate a continued strengthening of Ekman pumping until November. This discrepancy could arise due to the slightly larger geographical area used to define the STG in McClain et al. (2004). In fact, when considering the whole South Atlantic domain, we also find a strengthening in Ekman pumping until November (Figure 16b).

The seasonal cycle of the mean total SSH\textsubscript{AVISO} within the gyre (Figure 16c) is very similar to the mean total SSH\textsubscript{AVISO} described for the South Atlantic basin (Figure 15a). It peaks around April and finds its minimum in September (Figure 16c) and thereby reflects the end of the heating and cooling seasons that predominately drive the steric height\textsubscript{Argo} field on seasonal time scales (Fukumori et al., 1998). Again, the ocean mass\textsubscript{GRACE} contribution is significantly smaller and out of phase with the steric seasonal cycle (Figure 16c) and follows the seasonal cycle of wind stress curl instead (Figure 16d). In fact, the mean ocean mass\textsubscript{GRACE} is also significantly correlated with the wind stress curl ($r = 0.61, p < 0.05$) on the gyre scale. As such, an increase in the wind stress curl in austral winter contributes to stronger Ekman
convergence, which drives an increase in Ekman pumping and ocean mass over the gyre (Johnson & Chambers, 2013).

Figure 16: Seasonal variability in the position and size of the gyre and the local wind field. (a) Monthly climatological (2004–2016) contours of the gyre boundary from total SSHAVISO. The background contours show the climatological mean total SSHAVISO (1993–2018). The teal box in the southwest corner of the domain indicates the geographical area used to calculate the gyre maximum. (b) The most northern (beige, left panel), southern (yellow, left panel), and eastern positions (beige, right panel) of the gyre as given by the monthly contours of total SSHAVISO. (c) The size of the gyre estimated as the area enclosed by monthly contours of total SSHAVISO. (d) Mean wind stress curl over the gyre as defined by the monthly contours of total SSHAVISO. (e) Mean SSH within the monthly gyre contours of total SSHAVISO as calculated from the total SSHAVISO (black), steric heightArgo (pink), and ocean massGRACE (green). All values shown in (b–e) are shown as anomalies relative to the 2004–2016 mean. The error bars show the standard error about the mean. SSH, sea surface height.

To confirm this assumption that changes in wind stress forcing can explain the seasonal variability of ocean massGRACE, we take a closer look at the spatial variability of the ocean massGRACE signal (Figure 18a). We observe the largest seasonal change around 15°W and 20°S (Figure 18a). From this center, the seasonal range in ocean massGRACE shows a gradual decrease toward the South American and South African coasts (Figure 18a).
observed pattern is qualitatively consistent with the seasonal cycle of the barotropic stream function derived from a two-layer wind-driven model by Zhao and Johns (2014; their Figures 10c and 10d). Assuming barotropic flow, the observed seasonal change in ocean mass$_{GRACE}$ between the coast and center of the gyre (0.02 m, Figure 18a) translates to a barotropic transport anomaly of 13 Sv. This anomaly is in agreement with Zhao and Johns (2014), whose seasonal stream functions yield a transport anomaly of 11 Sv. Given this similarity, we conclude that seasonal variability in ocean mass$_{GRACE}$ is largely driven by seasonal variability in wind stress, through a rapid response of the barotropic mode to the seasonal forcing.

**Strength:** The STG is stronger in austral summer (January–February) and weaker in austral winter (June–August; Figure 17a). This observation is in agreement with the modeling results of Gan et al. (1998), who report a weakening of the surface gyre after the austral summer months, as well as Signorini and McClain (2012). The seasonal cycle of the ocean mass$_{GRACE}$ component is again out of phase with the total SSH$_{AVISO}$ gyre strength estimate. The steric height$_{Argo}$ shows strong seasonal variability (Figure 17a), which, as explained below, is attributable to the location of the gyre maximum (Figure 16a).

Recalling that the gyre strength is calculated as the difference between the gyre maximum (Figure 17b) and gyre boundary (Figure 17c), we discuss the contributions of these two components. Both the total SSH$_{AVISO}$ gyre maximum and boundary show their maxima in austral summer and their minima in austral winter (Figures 17b and 17c). Note that the gyre maximum has a flatter distribution in austral summer (Figure 17b), compared to the peaked distribution of the gyre boundary in April (Figure 17c). The steric height$_{Argo}$
component largely exhibits the same seasonal cycle for the gyre boundary (Figure 17c) but shows stronger variability and less distinct seasonality in its gyre maximum (Figure 17b). To that extent, we note that the seasonal range of the steric height_{Argo} field is the largest (0.2–0.3 m) near the gyre maximum (teal box, Figure 18b). The previously mentioned seasonal migration of the Brazil-Malvinas Confluence likely influences the strong seasonal signal observed in this area. As described in the context of the mean SSH in the South Atlantic basin (Figure 15a) and gyre (Figure 16e), the ocean mass_{GRACE} gyre maximum and boundary are weaker than and out of phase with the seasonal signal of the steric height_{Argo} and total SSH_{AVISO} (Figures 17b and 17c).

Putting these observations together, we note that 64% (83%) of the observed variability in the total SSH_{AVISO} gyre maximum (gyre boundary) is explained by variability in the steric height_{Argo} (Figure 17b). As a caveat, we point out that the location of maximum seasonal change in ocean mass_{GRACE} (15°W, 20°S, Figure 18a) does not line up with the location of maximum SSH_{AVISO} and steric height_{Argo} (teal box, Figure 18b). Due to this spatial mismatch, the seasonal signal of ocean mass contribution may be underestimated. Additionally, there is a possibility that the ocean mass_{GRACE} maximum is affected by its proximity to the coast, which is prone to land–ocean leakage errors (Zou & Jin, 2014).

We conclude that on seasonal time scales, the variations in gyre position and size are largely influenced by the positions of the northern and eastern boundary currents, as well as the Brazil-Malvinas Confluence position. The gyre strength follows the seasonal net heating and cooling cycle of the upper ocean and is largely influenced by variability in the gyre maximum. Changes in the ocean mass_{GRACE} are out of phase with the seasonal cycle set by
the steric height$_{\text{Argo}}$ and hence dampen the observed total SSH$_{\text{AVISO}}$ seasonal cycle. Given the alignment with previous work on seasonal time scales, we deem our gyre metrics suitable for examining changes on longer time scales.

Figure 17: Seasonal variability of gyre metrics. (a) Gyre strength calculated as the difference between (b) the gyre max and (c) the gyre boundary using the total SSH$_{\text{AVISO}}$ (black), steric height$_{\text{Argo}}$ (pink), and ocean mass$_{\text{GRACE}}$ (green) fields. (b) Similar to (a) for the maximum SSH within the gyre. (c) Similar to (a) for the SSH along the gyre boundary. All values shown in (a–c) are shown as anomalies relative to the 2004–2016 mean. The error bars show the standard error about the mean.
3.3.3 Basin-wide interannual variability and long-term trends

We begin our discussion of interannual variability and trends by first examining spatial patterns and time series of SSH for the basin scale, followed by an analysis of latitudinal dependence of observed trends.

3.3.3.1 Sea surface height

We first consider the spatial patterns of the local trends of our three data sets over the common time period (2004–2016; Figures 19a–19c). We observe a basin-wide increase in total SSH_{AVISO} over more than 92% of our domain (Figure 19a). Decreases in total SSH_{AVISO} are present near the Brazil-Malvinas Confluence, along the South Atlantic Current and the Benguela Current (Figure 19a). The spatial pattern of SSH_{AVISO} increase is nonuniform, with stronger local trends in the southern and southwestern domain (Figure 19a). The steric
height$_{\text{Argo}}$ trends are weaker than the total SSH$_{\text{AVISO}}$ trends and predominantly positive (Figure 19b). The trends are negative in the Brazil-Malvinas Confluence and in the eastern domain close to the Benguela Current (Figure 19b). Over its full time period 1993–2018, the spatial variability in total SSH$_{\text{AVISO}}$ is much more uniform and local trends are positive in 99% of the domain (not shown). Given the similarities between the local spatial patterns in total SSH$_{\text{AVISO}}$ and steric height$_{\text{Argo}}$ over the common time period (Figures 19a and 19b), we expect that the observed steric height$_{\text{Argo}}$ spatial variability (Figure 19b) would also be smoothed out over a longer time period 1993–2018. Hence, we suspect that the local negative trends in total SSH$_{\text{AVISO}}$ and steric height$_{\text{AVISO}}$ (Figures 19a and 19b) are a manifestation of regional interannual variability.

The ocean mass$_{\text{GRACE}}$ trends are positive over the entire domain and more uniform than the total SSH$_{\text{AVISO}}$ and steric height$_{\text{Argo}}$ trends (Figure 19c). The magnitude of the ocean mass$_{\text{GRACE}}$ trend is larger than the steric height$_{\text{Argo}}$ trend over most of the basin, meaning that the ocean mass$_{\text{GRACE}}$ contribution dominates the total SSH$_{\text{AVISO}}$ trend, in agreement with Ruiz-Etcheverry et al. (2020). That is, however, not the case in the southwestern domain near the Brazil-Malvinas Confluence (Figures 19b and 19c) where the steric height$_{\text{Argo}}$ trend is relatively large and the ocean mass$_{\text{GRACE}}$ trend is relatively weak, as noted by Ruiz-Etcheverry et al. (2020). This observation is discussed further in the context of the maximum SSH within the gyre in the next section.

The mean basin-wide trend$_{2004–2016}$ of total SSH$_{\text{AVISO}}$ is $3.4 \pm 0.5$ mm per year (trend$_{1993–2017}$: $3.5 \pm 0.2$ mm per year; Figure 19d). The trend$_{2004–2016}$ calculated from the indirect measure of total SSH$_{\text{Argo}}$ + GRACE is slightly larger at $3.9 \pm 0.5$ mm per year.
(Figure 19d). Despite the varying time periods and spatial domains, these trends are comparable with the global SSH trend$_{1993–2020}$ of $3.3 \pm 0.4$ mm per year (Beckley et al., 2017; National Aeronautics and Space Administration, 2020a). Steric height$_{\text{Argo}}$ has a mean trend$_{2004–2016}$ of $1.3 \pm 0.5$ mm per year (Figure 19e), which is a good match with the global trend$_{2004–2018}$ of $1.1 \pm 0.2$ mm per year (Llovel et al., 2014; National Aeronautics and Space Administration 2020c). The indirectly estimated steric height$_{\text{AVISO–GRACE}}$ trend$_{2004–2016}$ of $0.7 \pm 0.5$ mm per year (Figure 19e) is around half the steric height$_{\text{Argo}}$ trend$_{2004–2016}$. However, calculated over a longer time period, the steric height$_{\text{AVISO–GRACE}}$ trend$_{2002–2018}$ increases to $1.5 \pm 0.4$ mm per year (Figure 19e). As pointed out previously, we expect discrepancies in these estimates as the indirect steric height$_{\text{AVISO–GRACE}}$ estimate also contains deep steric changes (below 1975 db). Llovel et al. (2014) estimated a deep steric contribution to the global mean sea level of $–0.13 \pm 0.72$ mm per year between 2005 and 2013, while Purkey et al. (2014) estimated a value of $0.18$ mm per year between 1996 and 2006 (with no uncertainty estimate). This suggests (with large uncertainty) that the deep ocean contribution makes a relatively small contribution to total steric height change. However, the contribution of deep waters can be locally significant, for example, Volkov et al. (2017) found that warming in the deep central South Pacific ($>2,000$ m) contributed up to half of the total steric height change trend in that region between 2005 and 2015. In our South Atlantic domain, warming of the deep ocean was observed between 1995 and 2005, but no detectable trend was observed between 2005 and 2014 (Johnson et al., 2014), suggesting that the deep ocean made little contribution to the overall steric height trend over the common period$_{2004–2016}$ of our study.
Figure 19: Interannual variability and long-term trends (2004–2016) of SSH in the South Atlantic. Local trends at each grid point over the common time period (2004–2016) for (a) total SSH$_{AVISO}$, (b) steric height$_{Argo}$, and (c) ocean mass$_{GRACE}$. Red values indicate a positive trend and blue values a negative trend. Time series of the annual basin mean of (d) total SSH$_{AVISO}$ (1993–2018), (e) steric height$_{Argo}$ (2004–2016), steric height$_{AVISO-GRACE}$ (2002–2018), and (f) ocean mass$_{GRACE}$ (2002–2019), ocean mass$_{AVISO-Argo}$ (2004–2016). The trend line for the three primary data sets (total SSH$_{AVISO}$, steric height$_{Argo}$, and ocean mass$_{GRACE}$) is shown in red. The time series in (d–f) are shown as anomalies relative to the 2004–2016 mean. All trends are significant (95%) and calculated for the common time period (2004–2016). Trends over the entire data period of each data set may be found in the text when relevant. Trends are reported with their standard error. In (a–c), the teal boxes highlight the area used to calculate the gyre maximum.

The direct ocean mass$_{GRACE}$ trend$_{2004–2016}$ of $2.7 \pm 0.2$ mm per year (trend$_{2002–2019}$: $2.5 \pm 0.2$ mm per year) is also larger than the indirect estimate of ocean mass$_{AVISO-Argo}$ trend$_{2004–2016}$ of $2.1 \pm 0.3$ mm per year (Figure 19f). The latter is comparable to the global ocean mass trend$_{2002–2020}$ of $2.1 \pm 0.3$ mm per year (National Aeronautics and Space Administration 2020b; Watkins et al., 2015). Again, this mismatch is somewhat expected.
Llovel et al. (2010), for example, noted significant local discrepancies between ocean mass\textsuperscript{GRACE} and ocean mass\textsuperscript{AVISO–Argo} and attributed those differences to errors in the Argo data set, noisy local variability in GRACE, and deep ocean steric contributions that could contaminate the estimate. Most recently, a study by Royston et al. (2020) found that replicating the total SSH\textsuperscript{AVISO} signal from its individual steric and ocean mass components on a local and subbasin scale was difficult. The authors point to small-scale spatial features that are captured by satellite altimetry (but not represented by the steric or ocean mass measurements) as well as data processing differences as potential reasons for the mismatch (Royston et al., 2020).

Compared to the seasonal variability (Figure 15a), the interannual variability in total SSH\textsuperscript{AVISO} and steric height\textsuperscript{Argo} is relatively weak (Figures 19d and 19e), in agreement with Ruiz-Etchevery et al. (2020). Of the observed variability total in SSH\textsuperscript{AVISO}, 34% is explained by the variability in the steric height\textsuperscript{Argo} over the common time period 2004–2016. On interannual time scales, the variability described by the two estimates of total SSH (detrended cor. = 0.7, \( p < 0.05 \)) and steric height (detrended cor. = 0.7, \( p < 0.05 \)) is in good agreement.

In summary, the spatial patterns of total SSH\textsuperscript{AVISO}, steric height\textsuperscript{Argo}, and ocean mass\textsuperscript{GRACE} show predominately positive trends \( 2004–2016 \), with the ocean mass\textsuperscript{GRACE} trend \( 2004–2016 \) dominating the basin-wide trend \( 2004–2016 \) and in agreement with previous work (Ruiz-Etchevery et al., 2020). Specifically, the steric height\textsuperscript{Argo} (Figure 19e) accounts for one third of the total SSH trend\textsuperscript{Argo} (Figure 19d), while the ocean mass\textsuperscript{GRACE} accounts for the remaining two thirds (Figure 19f). 34% of the observed interannual variability in total SSH\textsuperscript{AVISO} can be
explained by the steric signal, while the long-term trend_{2004–2016} is dominated by basin-wide mass loading.

### 3.3.3.2 Meridional trends in SSH, wind stress, and Ekman transport

To complement our analysis of local trends and basin trends in total SSH_{AVISO}, steric height_{AVISO}, and ocean mass_{GRACE}, we briefly describe the zonally averaged trends of these variables at each latitude for the common time period_{2004–2016}.

The zonally averaged trend_{2004–2016} in total SSH_{AVISO} varies between 3 and 4 mm per year north of 30°S and becomes more variable south of that latitude (Figure 20a), as shown by the opposing local trends (Figure 20a). The steric height_{Argo} trend_{2004–2016} is between 1 and 2 mm per year (Figure 20b) and accounts for roughly one third of the total SSH_{AVISO} trend (Figure 20a). The ocean mass_{GRACE} trend shows very little variability with latitude (2.7 ± 0.2 mm per year; Figure 20b) and roughly accounts for two thirds of the total SSH_{AVISO} trend (Figure 20c). Note that the trends are not statistically significant at every latitude (Figures 20a–20c). If we consider the trend_{1993–2018} over the entire period of total SSH_{AVISO}, much of the variability south of 30°S is smoothed out and we instead observe a gradual increase in the trend, which is statistically significant at every latitude (Figure 20a, thin line). This discrepancy primarily arises from the elimination of the areas showing a small negative trend_{2004–2016} in total SSH_{AVISO} (Figure 19a) over the longer time period_{1993–2018}.

Since the variability in total wind stress is largely explained by variability in the zonal wind stress component, we exclude the meridional wind stress component from this analysis. The zonally averaged trends_{2004–2016} in zonal wind stress are negative north of 30°S and positive between 40°S and 30°S (Figure 20c), implying an overall strengthening of the
trade winds (north of $\sim$30°S) and strengthening of the westerlies (south of $\sim$30°S).

However, we note that the trend $^{2004-2016}$ is statistically insignificant. Considering the full study period, we observe negative trends $^{1993-2018}$ at each latitude, which are statistically significant north of 28°S (Figure 20d). The trend $^{2004-2016}$ in Ekman pumping is negative north of 35°S (not statistically significant), which would indicate a strengthening in Ekman convergence (Figure 20d).

Figure 20: Trends of zonally averaged annual SSH components, zonal wind stress, and Ekman pumping. (a) total SSH$_{AVISO}$ (thick: 2004–2016; thin: 1993–2018), (b) steric height$_{Argo}$ (2004–2016) and ocean mass$_{GRACE}$ (2004–2016), (c) zonal wind stress (thick: 2004–2016; thin: 1993–2018), and (d) Ekman pumping (2004–2016) are shown. Circed latitudes indicate that the trend is significant at the 95% level.
3.3.4 Interannual variability and long-term trends of the gyre

Again, having set the basin-wide context for our study, we next focus on the interannual variability of the gyre and identify any long-term trends. Trends are calculated over the common time period 2004–2016 unless otherwise indicated.

*Position:* Similar to the seasonal variability (Figure 20a), most of the interannual variability in gyre position is confined to the northern boundary current, the eastern boundary current, and the Brazil-Malvinas Confluence (Figure 21a). However, contrary to the seasonal position of the gyre (Figure 20a), we also observe substantial variability along the entire southern boundary current of the gyre (Figure 21a).

We take a closer look at the migration of the gyre by considering the point maxima and minima of its position (Figure 21b). Variability in the northern and southern boundaries is stronger prior to 2005 and relatively weak between 2005 and 2018 (Figure 21b, left panel). Variability in the eastern boundary (Figure 21b, right panel) is up to 3 times as large as variability of the northern and southern boundaries (Figure 21b, left panel). Note especially the far eastern excursions in 2004 and 2005 (Figures 21a and 21b, right panel). We detect a small southward trend in the southern position of $-0.04^\circ \pm 0.02^\circ$ per year, 1993–2018. Similarly, using the annual contours of total SSH$_{AVISO}$ (Figure 21a), we calculate a significant southward trend in the Brazil-Malvinas Confluence of $-0.06^\circ \pm 0.02^\circ$ per year, 1993–2018. This estimate updates and is in agreement with previous estimates of $-0.62^\circ$ per decade, 1993–2008 (Combes & Matano, 2014) and $-0.6^\circ$ to $-0.9^\circ$ per decade, 1992–2007 (Lumpkin & Garzoli, 2011). Our estimate using the annual contours of total SSH$_{AVISO}$ over a comparable time period as these previous studies is $-0.09^\circ \pm 0.04^\circ$ per year, 1993–2008. Combes and Matano (2014) attributed this
shift to a general weakening of the subpolar circulation after 2000 and noted no significant changes to the STG circulation in their model \[1979\text{-}2012\].

In contrast to Marcello et al. (2018), our observational analysis reveals no significant trend in the northern boundary of the gyre (Figures 21a and 21b). Our calculated mean position of the northern boundary (based on the total SSH\textsubscript{AVISO} contours) is \(18.3^\circ S \pm 0.7^\circ\), which is just to the south of previous estimates (ranging from \(14^\circ S\) to \(18^\circ S\)) of the mean position of the bifurcation Garzoli & Matano, 2011; Lumpkin & Garzoli, 2011; Stramma & England, 1999). Marcello et al. (2018) report a southward shift in the bifurcation latitude from \(11^\circ S\) to \(16^\circ S\), with an average trend \[1970\text{-}2015\] of \(0.11^\circ \pm 0.03^\circ\) per year. Hence, the bifurcation latitude in their model appears to be located further north than previous estimates of the bifurcation and our northern gyre boundary. As noted in Section 1, the bifurcation latitude is believed to play a role in modulating the amount of throughput to the North Atlantic, with a more southerly position favoring the export via the North Brazil Current over a recirculation in the Brazil Current (Rodrigues et al., 2007).

\textit{Size:} The largest interannual variability in the gyre size is observed between 1997 and 2012 with less variability observed before and after that time period (Figure 21c). The slightly below average size of the gyre observed prior to 1999 (Figure 21c) is reflected in the relatively northern position of the southern boundary and relatively southern position of the northern boundary (Figure 21b, left panel). After 2001, the northern and southern boundary positions of the gyre (Figure 21b, left panel) deviate relatively little from their mean values, such that the observed variability in gyre size (Figure 21c) is explained largely by variability in the eastern boundary (Figure 21b, right panel).
We find no significant trend in gyre size using our metric (Figure 21c). Accordingly, the small southward trend observed in the southern boundary of the gyre is compensated for by the large excursions found in the eastern gyre boundary (Figures 21a and 21b, right panel), such that no net contraction or expansion of the gyre occurs over time. Results from a previous publication by McClain et al. (2004) had suggested a very small expansion of the gyre (0.2% per year) but noted that compared to the Northern Hemisphere, the Southern Hemisphere was undergoing very little change. Recalculating the gyre size over the same time period, we still find no significant trend. Since McClain et al. (2004) define the gyre based on the extent of oligotrophic areas at the ocean surface, we attribute this discrepancy to the difference in gyre definitions.

On interannual time scales, the variability in wind stress curl forcing (Figure 21d) is approximately half of its seasonal variability (Figure 16d). We observe no trend in the wind stress curl over the gyre or basin (Figure 21d). This appears to be contradictory to previous studies that have reported a strengthening of the wind stress curl in the Southern Hemisphere (Marcello et al., 2018; Qu et al., 2019; Wu et al., 2012). For example, Marcello et al. (2018) reported an increasing trend in the positive wind stress curl within the zero-wind-stress-curl contour (1.45 × 10⁻⁸ N m⁻³) and in the zonally averaged maximum wind stress curl (2.92 × 10⁻⁸ N m⁻³) in the South Atlantic. Using these same metrics, we find no significant trend for our time period. Qu et al. (2019), on the other hand, reported an increasing trend in wind stress curl across the entire tropical and subtropical Southern Hemisphere. Accordingly, the discrepancies with our results can likely be attributed to differences in time periods, domains, metrics, and data sets used to assess the strengthening.
In evaluating the impact of wind stress forcing on the gyre (as defined by the total SSH_{AVISO} contours), we consider both the wind stress curl over the gyre itself, as well as over the South Atlantic basin most relevant.

Similarly, the interannual variability of the mean SSH within the gyre (Figure 21c) is much smaller than the observed seasonal variability (Figure 16c). Over the common time period 2004–2016, 42% of the observed variability in total SSH_{AVISO} is explained by variability in the steric height_{Argo}, with ocean mass_{GRACE} explaining 25% (Figure 21c). Contrary to seasonal variability, we find no correlation between interannual variability in wind stress curl (Figure 21d) and ocean mass_{GRACE} (Figure 21e). The observed interannual variation is possibly too weak to capture any dynamical linkage between ocean mass and wind forcing on interannual time scales.

The ocean mass_{GRACE} trend_{2004–2016} (2.4 ± 0.2 mm per year) exceeds the steric height_{Argo} trend (2.2 ± 0.6 mm per year) with respect to the contribution to the total SSH_{AVISO} trend (3.6 ± 0.7 mm per year; Figure 21e). Note that the trends of the two components do not add up exactly to the total SSH trend due to the limitations discussed previously, as well as to the statistical uncertainty of the individual trends. For example, the lower bound of the combined steric and ocean mass trend is 3.8 mm per year, while the upper bound is 5.4 mm per year.

**Strength:** The interannual variability in the gyre strength (st. dev.: ±0.012 m, Figure 22a) as measured by the total SSH_{AVISO} is somewhat smaller than the seasonal variability in gyre strength (st. dev.: ±0.016 m, Figure 17a). In terms of the individual components of SSH, the steric height_{Argo} shows stronger interannual variability (st. dev.:
±0.016 m, Figure 22a) than the ocean mass (st. dev.: ±0.004 m, Figure 22a). The gyre strength (total SSH_{AVISO}, Figure 22a) is significantly correlated to the basin-wide wind stress curl ($r = 0.48, p < 0.05$, Figure 21d). Past studies have related variability in the strength of the STG in the South Pacific to the variability in the basin-wide wind stress curl and Southern Annular Mode (Roemmich et al., 2007; Zhang & Qu, 2015).

Overall, 49% of the variability in gyre strength (total SSH_{AVISO}, Figure 22a) is explained by variability in the gyre maximum (total SSH_{AVISO}, Figure 22b), which is much larger (st. dev.: ± 0.016 m) than the variability in gyre boundary (st. dev.: ±0.009 m, total SSH_{AVISO}, Figure 22c). We point out as a caveat, that the gyre boundary is computed over a much larger area than the maximum and its variability could thereby be smoothed out.

Strong variability in the gyre maximum (Figure 22b) is attributable to its location near the Brazil-Malvinas Confluence (teal box, Figure 21a). The interannual variability in the steric height_{Argo} maximum (st. dev.: ±0.019 m) is almost one order of magnitude larger than the ocean mass_{GRACE} component (st. dev.: ±0.004 m), explaining 88% of the observed variance in total SSH_{AVISO} maximum after 2008 (Figure 22b). The interannual variability in the gyre boundary is comparable between the two components (Figure 22c).

We find no significant trend$_{2004-2016}$ in gyre strength, even over the full time period$_{1993-2018}$ of the data (total SSH_{AVISO}, Figure 22a). This finding is consistent with the fact that we detect no trend in wind stress curl across the basin and gyre (Figure 21d), which has previously been linked to a spin-up of the gyre circulation (Qu et al., 2019; Roemmich et al., 2007). One of the SSH components, the ocean mass_{GRACE}, exhibits a small negative trend in gyre strength. However, since the observed spatial pattern (Figure 19c) is in broad
agreement with the sea level fingerprint derived from mass changes in Greenland and Antarctica and from land water storage (Hsu & Velicogna, 2017; their Figure 1d), the trend is likely related to changes in the gravity field and as such, has no dynamical significance.

We report a significant trend\textsubscript{2004–2016} in gyre maximum for total SSH\textsubscript{AVISO} and ocean mass\textsubscript{GRACE} (Figure 22b). We postulate that the trend\textsubscript{2004–2016} in steric height\textsubscript{Argo} is masked by strong interannual variability. A significant trend\textsubscript{2004–2016} in all components is observed for the boundary of the gyre (Figure 22c) and is comparable to the previously discussed basin-wide trends\textsubscript{2004–2016} (Figures 19d–19f).

A recent modeling study Marcello et al. (2018) suggested a strengthening\textsubscript{1970–2015} of the gyre, based on proxies of wind stress curl, SSH, and barotropic stream function. Our observational estimate of gyre strength does not align with these findings. Qu et al. (2019) report a strengthening of the super gyre across the Southern Hemisphere from altimetric data and Argo floats, but since the spatial domain of their study and ours does not meaningfully overlap, a comparison of their results with ours is not warranted. As mentioned earlier, a modeling study by Combes and Matano (2014) also found no significant changes to the gyre circulation between 1972 and 2012. Similarly, work by Goni et al. (2011) found no change in the Sverdrup transport of the gyre between 1993 and 2008. In our study, we attribute the lack of a trend\textsubscript{1993–2018/2004–2016} in the gyre strength (total SSH\textsubscript{AVISO}) to the fact that the trends of the gyre maximum (Figure 22b) and gyre boundary (Figure 22c) are comparable and, hence, cancel each other out. An increase in strength would require a change in the slope of the SSH and, thus, call for the gyre maximum or boundary to rise or fall faster than the other.
We conclude that the interannual variability in gyre position, size, and strength is smaller than the seasonal variability and largely controlled by variations in the steric height field. We observe a small southward trend in the southern boundary of the gyre, which is compensated for by large variations in the eastern boundary of the gyre and, thus, results in no net expansion or contraction of the gyre. We find no significant trend in the strength of the gyre.

Figure 21: Interannual variability and long-term trends in the position and size of the gyre and the local wind field. (a) Annual climatological contours of the gyre boundary calculated from total SSH$_{AVISO}$ (1993–2018). The background contours show the climatological mean total SSH$_{AVISO}$ (1993–2018). The teal box in the southwest corner of the domain indicates the geographical area used to calculate the gyre maximum. (b–e) Similar to Figure 16 but showing the annual time series to assess interannual variability and long-term trends. All values shown in (b–e) are shown as anomalies relative to the 2004–2016 mean. The error bars show the standard error about the mean. All shown trends are significant at the 95% level and are calculated for the common time period (2004–2016). Trends over the entire data period of each data set may be found in the text when relevant. Trends are reported together with their standard error.
Figure 22: Interannual variability and long-term trend in gyre strength. (a) Gyre strength as calculated from the total SSH_{AVISO} (black), steric height_{Argo} (pink), and ocean mass_{GRACE} (green). (a) is calculated as the difference between (b) and (c). (b) Similar to (a) for the maximum SSH within the gyre. (c) Similar to (a) for the SSH along the gyre boundary. All values shown in (a–c) are shown as anomalies relative to the 2004–2016 mean. The error bars show the standard error about the mean. All shown trends are significant at the 95% level and are calculated for the common time period (2004–2016). Trends for the gyre strength based on steric height_{Argo} (1.2 ± 1.1 mm per year) and the total SSH_{AVISO} (0.1 ± 1.0 mm per year), as well as the gyre maximum based on steric height_{Argo} (2.9 ± 1.4 mm per year) are not statistically significant. Trends over the entire data period of each data set may be found in the text when relevant. Trends are reported together with their standard error.

3.4 Summary

This study focused on investigating the seasonal variability, interannual variability, and long-term trends in the position, size, and strength of the STG in the South Atlantic. To that extent, we used three observational data sets to estimate changes to the total SSH, steric height, and ocean mass.
In agreement with past work, the seasonal variability in SSH over the South Atlantic is dominated by the steric signal, which is driven by heating and cooling of the surface ocean (Fukumori et al., 1998; Roemmich & Gilson, 2009; Ruiz-Etcheverry et al., 2020). The ocean mass contribution is out of phase with the steric signal and thereby dampens the overall SSH signal (Johnson & Chambers, 2013; Ruiz-Etcheverry et al., 2020). The ocean mass variability is driven by the seasonality of the wind stress curl, through a rapid response of the barotropic mode.

On seasonal timescales we find that most variability in the gyre position stems from migrations in the northern and eastern gyre boundary. Seasonal variability along the southern boundary is concentrated near the Brazil-Malvinas Confluence, whose migration is related to the seasonal variability in wind stress curl as described previously by Matano et al. (1993) and Wainer et al. (2000). Generally, the gyre is located farther south in austral winter and farther north in austral summer. We observe a maximum in gyre size in austral summer, followed by a minimum in late fall and early, in agreement with past work (McClain et al., 2004; Signorini & McClain, 2012). The strength of the gyre follows the same seasonal cycle. Most of the variability in the gyre maximum and gyre boundary is explained by variability in the steric signal.

Compared to the seasonal variability, the basin-scale interannual variability in SSH is relatively weak but dominated by the steric height as also shown by Ruiz-Etcheverry et al. (2020). The trend in SSH and its two components is in agreement with global estimates, with the ocean mass accounting for two thirds of the trend and the steric height the remaining one third.
On interannual time scales, we again observe large variability in the position of the gyre, which is dominated by changes along the eastern gyre boundary. Significant variability in gyre area, observed from the mid-2000s to the early 2010s, is largely attributable to variability in the eastern boundary. We find that the interannual variability in gyre strength is smaller than the seasonal variability and again largely explained by the variability in the gyre maximum. Past studies had related the strength of the Pacific STG to changes in the wind stress curl (Roemmich et al., 2007; Zhang & Qu, 2015). Here, we confirm a correlation between the basin-wide wind stress curl and the South Atlantic gyre.

We identify a significant southward displacement of the southern boundary of the gyre, which is especially prominent near the Brazil-Malvinas Confluence, in agreement with past work (Lumpkin & Garzoli, 2011; Vincent & Combes, 2014). Despite this southward migration of the southern gyre boundary, we identify no long-term trend in the gyre area. The southward shift is compensated for by large variability in the eastern boundary of the gyre, resulting in no net long-term expansion or contraction of the gyre. We observe no long-term trend in the gyre strength as pointed out by Goni et al. (2011) and Combes and Matano (2014). We attribute this to (1) a lack of long-term trends in the gyre and basin-wide wind stress curl over our domain, and (2) the comparable positive trends in SSH for the gyre boundary and the gyre maximum.
4. Connecting the North Brazil Current to the RAPID line

This work is planned for submission to Geophysical Research Letters in collaboration with M. Susan Lozier, F. Javier Beron-Vera, Philippe Miron, and M. Josefina Olascoaga.

4.1 Introduction

The pathways of the upper limb of the overturning circulation in the South and North Atlantic Oceans have been studied extensively (Burkholder & Lozier, 2014; Donners & Drijfhout, 2004; Fratantoni et al., 2013; Gary et al., 2014; Hazeleger & Drijfhout, 2006; Rühs et al., 2019; Speich et al., 2007). Most recently, Bower et al. (2019) provided a comprehensive review of both upper and lower limb pathways in the Atlantic from a Lagrangian perspective. Yet, fewer studies have focused on the pathways that connect these two ocean basins (Fratantoni et al., 2000; Halliwell et al, 2003; Hazeleger & Drijfhout, 2006).

In this chapter, we investigate said connection from an observational perspective. We choose the North Brazil Current as the starting point in the South Atlantic, as it is commonly described as a bottleneck that funnels upper-ocean waters between the two hemispheres (Johns et al, 1998; Lumpkin and Speer, 2003; Rühs et al., 2015; Zhang et al., 2011). The RAPID line serves as the target location in the North Atlantic, both because we understand the Gulf Stream to serve a similar purpose to the North Brazil Current in that it collectively advects upper-ocean waters towards higher latitudes, and because the pathways connecting the RAPID line to the subpolar North Atlantic have been the subject of previous studies (Burkholder & Lozier, 2014, Foukal & Lozier, 2016).
According to past literature, pathways leading through the Caribbean Sea and then on to the Gulf of Mexico serve as the primary conduit for connecting the South and North Atlantic basins, with the Florida Current acting as the dominant target (Bower et al., 2019; Fratantoni, 2000; Fratantoni, 2001; Lumpkin & Johnson, 2013). The Antilles Current has been tossed about as a secondary target and carrier of overturning upper limb waters. Its role is not well understood, and its transport sometimes considered negligible in comparison with the Florida Current (Duchez et al., 2014; Frajka-Williams et al., 2019; Meinen et al., 2019). As such, we have a good understanding of pathways connecting the North Brazil Current with the Florida Current, but gaps remain in the literature regarding other possible pathways that may carry upper ocean waters from the South Atlantic towards the entire RAPID line. For instance, pathways connecting the North Brazil and Antilles Currents have not been explicitly investigated.

The importance of taking additional pathways to the RAPID line into account is highlighted by the fact that there seems to be a mismatch between the overturning transport along the entire RAPID line compared with the overturning transport in the Florida Current. A past study has estimated that the contribution of waters coming from the southern hemisphere through the Gulf of Mexico to the Florida Current was around 13 Sv (Schmitz & McCarthy et al., 1993). However, the mean overturning along the RAPID line is around 17 Sv on average (Frajka-Williams et al., 2019), suggesting that the Florida Current alone cannot capture the entirety of the overturning transport. As pointed out by Bower et al. (2019), this implies that at least part of the overturning transport reaches the RAPID line east of the Florida Straits.
To summarize, improving our understanding of the pathways responsible for connecting the basins is essential to study the variability and meridional coherence of the overturning circulation. For instance, using the Florida Current as the sole target of upper-ocean waters in the North Atlantic may prevent us from capturing the true magnitude and variability communicated northwards from the North Brazil Current.

To build on the existing literature this chapter explores the following questions:

1. What are the dominant pathways connecting the North Brazil Current and the RAPID line?
2. What are the pathways connecting the North Brazil Current and the Antilles Current?
3. What are the advective timescales associated with these pathways?
4. What is the relative importance of the different pathways?

These open questions are addressed using observational trajectories from surface drifters and Argo floats and probabilistic trajectories derived from Markov chain theory as well as dynamical systems theory.

4.2. Background

The following section will describe the known circulation features in the tropical Atlantic, elaborate on the findings of previous studies regarding the pathways connecting the South and North Atlantic, and, finally, provide background information on the tools used in this chapter.
4.2.1 Surface and subsurface circulation of the tropical Atlantic

The subsurface-intensified North Brazil Current extends to a depth of 1,200 m and originates around 10°S from the South Equatorial Current (Schott et al., 2005; Zhang et al., 2011). From its origin, the North Brazil Current travels northwestward, tightly hugging the South American coast (Figure 23; Lumpkin and Garzoli, 2005). Around 5-8°N, its waters either retroflect into the eastward, highly seasonal North Equatorial Countercurrent or follow pathways through the Caribbean Sea and Yucatan Channel to the Gulf of Mexico and ultimately merge with the Florida Current (Bower et al., 2019; Halliwell et al., 2003; Lumpkin and Garzoli, 2005). The equatorial current system is mainly characterized by bands of alternating eastward and westward zonal currents (Ollitraut et al., 2006; Schmid et al., 2001; Schmid et al., 2003). Because of the northward Ekman transport found in the region, waters entrained in the North Equatorial Countercurrent can subsequently escape and merge with the westward-flowing North Equatorial Current instead. As such, these waters can also flow into the Caribbean Sea (Bower et al., 2019).

North Brazil Current rings that are shed around the retroflection and move north-northwestward also play a role in transporting waters towards the Caribbean Sea (Fratantoni et al., 1995; Garzoli et al., 2003; Lumpkin and Garzoli, 2005; Wilson et al., 2002). The North Brazil Current rings may be responsible for as much as half of the northward transport of the overturning circulation (Garzoli et al., 2003; Johns et al., 2003).
Figure 23: Surface velocity field and schematic of the tropical Atlantic circulation. (a) Surface drifter velocity field derived by Laurindo et al. (2017), the vectors are colored by their velocity. (b) Schematic of relevant circulation features. Note that a continuous arrow does not imply a continuous circulation or continuous current. Basins and seas are denoted in orange and ocean currents in blue. (c) Bathymetry of the domain with the 900 m contour shown in white.
4.2.2 Pathways from the North Brazil Current to the Rapid line

As briefly outlined in the Introduction, previous studies that have investigated the connection between the North Brazil Current and the tropical North Atlantic, have focused primarily on pathways leading to the Florida Current through the Caribbean (e.g., Fratantoni et al., 2000; Halliwell et al., 2003; Richardson, 2005).

Most notable, Halliwell et al. (2003) released three-dimensional simulated trajectories in HYCOM to model the flow of the upper limb between the South and North Atlantic Oceans. Their results reveal two distinct pathways: (1) A direct western boundary current route, that accounts for three-quarters of released particles, where particles follow the North Brazil Current along the South American coast prior to entering the Caribbean Sea, from which the particles travel through the Yucatan Channel and Gulf of Mexico before merging with the Florida Current. The authors note that particles following this direct route can feature excursions to the interior along the equator, but not once they cross into the Northern Hemisphere. (2) An interior route, accounting for the remaining one-quarter of released particles, whereby particles first take excursions into the North Atlantic basin prior to entering the Caribbean. These excursions include entrainment in the North Equatorial Current System and looping motion in the basin interior (Halliwell et al., 2003). Typical transit times between the North Brazil Current and the tropical Atlantic are between one and four years depending on the specific pathway (Halliwell et al., 2003).

The mean circulation within the Caribbean Sea was studied by Richardson (2005) using 212 surface drifter trajectories. The author distinguishes between two bands of a westward flowing current that occupies the Caribbean Sea. The northern one sources its
waters from the North Atlantic via the North Equatorial Current and North Brazil Current rings, while the southern pathway entrains South Atlantic waters, also partly from North Brazil Current rings (Richardson, 2005). Richardson (2005) argues that the southern pathway is the primary carrier of upper limb waters. Approximately 19% of all drifter trajectories are found in both anticyclonic and cyclonic eddies throughout the Caribbean Sea.

The southern pathway was also identified as the primary conduit of upper limb waters by Fratantoni et al. (2000) and Wilson and Johns (1997). More specifically, the numerical model analysis of Fratantoni et al. (2000) reveals three pathways of roughly equal importance that transport waters northward from the South Atlantic to the tropical North Atlantic. First, a western boundary current route in the intermediate layer. Second, a northward flow concentrated in the western boundary that is accompanied by North Brazil Current rings. Third, a pathway whereby waters entrained in the North Equatorial Current escape into the tropical North Atlantic through Ekman transport. The importance of Ekman transport in transporting waters northward is emphasized in a study by Lumpkin and Garzoli (2005), who show that in an Ekman-removed velocity field, simulated trajectories tend to recirculate in the equatorial circulation instead of escaping to the tropical North Atlantic.

### 4.2.3 Markov chains and transition path theory in oceanography

The Markov chain tools used in this study have been applied to surface drifters and RAFOS floats (Drouin and Lozier, 2019; McAdam and van Sebille, 2018; Miron et al., 2017; Miron et al., 2019; van Sebille et al. 2012). Here, the Markov chain tools are extended to Argo float trajectories. As in previous applications, we use the Markov chain transition matrix to advect particles forward in time to generate probability distribution maps. In
addition, we follow Miron et al. (2021) to compute most probable pathways from the transition matrix. More specifically, Miron et al. (2021) use tools from transition path theory to calculate probable pathways of plastic at the ocean surface and their accumulation in oceanic garbage patches. In this study, the same tools are applied to understand the most probable pathways responsible for connecting the South and North Atlantic Ocean basins.

4.3 Data and methods

The domain encompasses the Gulf of Mexico, Caribbean Sea, and Atlantic Ocean between 100°W to 20°E and 10°S to 30°N. We define our source, the North Brazil Current, between the Brazilian coast and 48°W and between 2°N to 3°N. We choose this more northern location of the North Brazil Current compared to its 6°S location used in previous studies (Rühs et al., 2015; Rühs et al., 2019, Zhang et al., 2011) to minimize the impact of the drifters’ surface constraint. Specifically, around 6°S the North Brazil Current has a significant subsurface component, the North Brazil Undercurrent, and hence has maximum strength at 200 m (Hurrell et al., 2006; Rühs et al., 2019). Thus, the surface drifter trajectories, which are drogued to a depth of only 15 m, do not necessarily capture the pathways of the core waters of the North Brazil Current at 6°S. At 2°N the North Brazil Current is surface intensified, giving us more confidence that the surface pathways are the dominant pathways to the subtropical North Atlantic. Additionally, this northern location also allows us to capture thermocline waters that retroflect into the interior and are upwelled along the equator before they rejoin the North Brazil Current at the surface via the South Equatorial Current branches (Halliwell et al., 2003; Hurrell et al, 2006).
We do note though that simulations performed with the source set to 6°S yield virtually identical results for both the Markov chain and transition path theory pathways.

We define our three targets along the longitude of the RAPID line between 26°N and 27°N (Frajka-Williams et al., 2019). Specifically, the Florida Current is defined between the Florida coast and the Bahamas around 77°W (Leaman et al. 1987; Schmitz & Richardson, 1991), the Antilles Current between Abaco Island and 76°W (Meinen et al., 2019), and the East RAPID line between 76°W and the African continent (Figure 23).

4.3.1 Eulerian velocity field

The Eulerian velocity field used in this study was developed by Laurindo et al. (2017) using approximately 38 years of drogued and undrogued drifters from the Global Drifter Program (https://www.aoml.noaa.gov/phod/gdp/mean_velocity.php). The method employed by Laurindo et al. (2017) corrects the velocities for wind-slip and features less spatial smoothing than previous studies. The velocity climatology has a spatial resolution of one degree.

4.3.2 Surface drifters and Argo floats

We use surface drifter trajectories from the Global Drifter Program, which provides longitudinal and latitudinal positions of the drifters every six hours. We include only 15-m drogued drifters that travel within our domain, as past studies have shown that undrogued drifters do not accurately represent surface currents (Lumpkin & Pazos, 2007; Niiler & Paduan, 1995; Pazan & Niiler, 2001). Given these constraints, we use a total of 4394 surface trajectories between October 1989 and June 2020.
The Asia-Pacific Data-Research Center reports the longitudinal and latitudinal positions of Argo floats as they drift along their programmed parking depth during each cycle in the YoMaHa’07 dataset. From the entire data set available between August 1997 and September 2020, we use floats located in our domain between a parking depth of 950 m and 1050 m, which is the approximate lower reach of the overturning upper limb in the Atlantic (Bower et al., 2019). We highlight that the trajectories of the Argo floats are somewhat constrained by the shallow bathymetry around the Florida Straits (Figure 23c). Given these constraints and applying the same criteria described for the drifters, 1401 Argo trajectories are used in our study. The Argo floats are further naturally constrained by the shallow bathymetry around the Florida Straits (Figure 23c).

To account for the limited lifetime of the surface drifter and Argo floats, we construct a Markov chain from their trajectories, as described next.

We understand that the two-dimensional nature of the surface drifters and Argo floats limits our ability to draw conclusions about all pathways connecting the North Brazil Current and the tropical Atlantic. In particular, we note that the pathways described by Halliwell et al. (2003), which involve deflections into the interior by the North Equatorial Counter Current, may be underrepresented in our study since these pathways subduct in the North Equatorial Current prior to merging back into the Caribbean Sea (Hurrell et al., 2006).

### 4.3.3 Markov chain

Markov chains allow us to describe the evolution of a present state to some future state based on a transition probability matrix. In the context of this study, the transition matrix has dimensions of N by N, where N represents the number of grid cells in the
domain. As such, the matrix summarizes the probability of moving from one grid cell to any other grid cell in the domain. This probability is calculated from the observational trajectories.

The big advantage of the Markov chain method is that it allows us to produce trajectories of unlimited lifetime, by connecting different trajectories together (Drouin and Lozier, 2019; Froyland et al., 2014; McAdam and van Sebille, 2018; Miron et al., 2017; Miron et al., 2019; van Sebille et al. 2012). For example, the raw surface drifter trajectories allow us to describe localized pathways in the North Brazil Current, in the Caribbean Sea, or Gulf of Mexico (Figure 24a). However, there is not a continuous trajectory that connects all these places in our domain. Combining the information obtained from all surface trajectories, however, allows us to observe pathways that do connect the North Brazil Current to the Florida Current (Figure 24a). The same example holds for the subsurface trajectories (Figure 24b). As a result of the shallow bathymetry in the western domain (Figure 23c) relatively few of the subsurface floats (Figure 24c,d) travel through the Caribbean Sea and Florida Straits compared to the surface drifter trajectories (Figure 24a,b).
Figure 24: Surface drifter and Argo float trajectories and data density. (a) Select surface drifter trajectories passing through different sections of the domain. Colors relate to the boxes the drifters pass through. (b) Number of 6-hour drifter observations available in each grid cell. Background contours show the sea surface height at 0.1 m intervals. (c) Same as (a) for Argo trajectories. (d) Same as (b) for Argo data. The background contours show the 900 m bathymetry (thick line) and 3500 m bathymetry (thin line).

To construct the transition matrix, we divide our domain into a regular grid with a resolution of dx (Figure 25a). Next, we split our observational trajectories into segments of length dt (Figure 25b). This allows us to determine a grid cell position at an initial time $t_0$ and a final time $t_0 + dt$ for each trajectory segment. From this information, we calculate the probability of moving to a different grid cell from the current grid cell (Figure 25c). As an example, in Figure 25c, four trajectory segments start in grid box 1. Two of the trajectory segments end in grid box 2, and one trajectory segment each moves to grid boxes 4 and 5. We summarize the probability of moving from grid box 1 to all other grid boxes in row one of the transition matrix (Figure 25d). Over the chosen time step, the probability of staying in
box one is zero, hence, $P_{11} = 0$, the probability of moving from box one to box two is 0.5, hence, $P_{12} = 0.5$, and so on (Figure 25d).

![Figure 25: Summary of Markov chain calculation steps.](image)

In this study, the drifter transition matrix has a five-day temporal (dt) and one-degree spatial (dx) resolution following Drouin et al. (2019). The Argo float transition matrix has a coarser resolution of 15 days and two-degrees, to account for the longer integral timescale (LaCasce, 2009; Miron et al. 2018), lower advective velocities of the deeper ocean, and the reduced coverage (Figure 24d) compared to the surface drifter coverage (Figure 24d). Sensitivity tests reveal no significant difference in the results for time steps of 1 to 10 days for the surface drifters and 5 to 20 days for the Argo floats.
Our choices for the temporal and spatial scales yield 757,097 trajectory segments for the surface drifters, which translate to an average of 178 ± 143 positions per grid cell and 10% of grids containing less than 35 data points. Similarly, the choices for the Argo floats yield 626,765 trajectory segments, which translate to an average of 173 ± 139 data points per grid cells, with 10% of grids containing less than 39 data points.

Once constructed, we use the transition matrix to advect particles from one grid cell to another based on the calculated probabilities. Here, the North Brazil Current (as defined earlier) serves as the particle source. Particles are tracked for a period of five years following their release, based on the expected transit times calculated by Halliwell et al. (2003). The results are presented in the form of probability distribution maps, which give us a sense of the average particle spread from a given source over a define time period. We release 200,000 particles at each source grid cell. Experimental simulations using 100,000 grid cells yield virtually identical results.

While this method allows us to gain an overall understanding of possible pathways from particles initiated in the North Brazil Current, we can take the analysis one step further using a method from transition path theory. In addition to specifying a source, this method allows us to specify a desired target, resulting in direct pathways that connect the two. The equivalent of this in more familiar terms would be to isolate Lagrangian particle trajectories released in a model domain that stem from a desired source and reach a specific target.

4.3.4 Transition path theory

Transition path theory is a framework that allows us to study the direct transitions between states of a Markov chain (Helfmann et al., 2020; Miron et al., 2021). In the context
of this study, it allows us to use our transition matrix to find pathways that directly connect source grid cells to target grid cells. Since this method originated in the field of chemistry, to understand transitions from reactants to products, the terminology is reminiscent of the original application. Throughout this paragraph we first stick to the original terminology for ease of comparison to past literature, but later provide new terminology to be used in the context of this study. We start with a conceptual explanation of the terminology followed by a mathematical explanation. For a thorough derivation of the associated theories and equations, we refer the reader to Helfmann et al. (2020) and Miron et al. (2021).

The basic components needed to apply transition path theory are the transition matrix and two predefined sets of grid cells which act as a source and target. Recall that the transition matrix describes the probability of moving from one grid cell to any other grid cell in the domain. For this study, the sources and targets are defined as subsets of those grid cells.

The first term that has to be introduced is reactive trajectories. This term describes all possible pathways that connect our source to our target. The term reactive stems from its traditional application of describing the transitions of chemical reactions between reactants and products (Helfmann et al., 2020). From all of the reactive trajectories we can calculate what is historically referred to as the current of reactive trajectories or reactive currents. These currents can be interpreted as the probabilities associated with moving from source to target along different reactive trajectories. From the reactive currents, we finally arrive at the effective current of reactive trajectories or effective reactive currents, which are the net currents of reactive trajectories. These effective reactive currents remove any unproductive detours a
reactive trajectory might take. Consider the following example, adapted from Helfmann et al. (2020) for clarity (Figure 26).

![Diagram of transition path theory](image)

**Figure 26: Schematic of transition path theory.** (a) A visual representation of the transition matrix with the blue circles representing five distinct grid cells in a theoretical domain. The arrows indicate the transitions between different grid cells and the associated probabilities. All outgoing probabilities add to one. (b) Visual representation of the reactive currents and their probabilities. The green circles represent the chosen source and target locations. (c) Visual representation of the effective reactive current with the most probable pathway highlighted in yellow. This example was adapted from Helfmann et al. (2020).

In this simplified example, the domain consists of five grid cells with an associated transition matrix that has dimensions of five by five. A graphical representation of the transition matrix is shown in Figure 26a. The arrows indicate the possible transitions between different grid cells and the numbers indicate the probability associated with that particular transition. For example, starting from grid cell 1, there is a 0.8 probability of moving to grid cell 2 and a 0.2 probability of moving to grid cell 3. Note that the transition matrix is row stochastic meaning that all outgoing probabilities from any grid cell add up to one. For this example, grid cell 1 will serve as the source and grid cell 5 will serve as the target (Figure 26b). The reactive trajectories are then all paths that connect grid cell one to
grid cell five. As an example, three possible reactive trajectories are $1 - 2 - 5$, $1 - 3 - 4 - 3 - 5$, or $1 - 3 - 5$. The current of the reactive trajectory is the probability associated with these different reactive trajectories, which is derived from the transition matrix (Figure 26b). In this example, the probability has been normalized by the total current. Hence, the outgoing current from the source and the incoming current into the target are the same and add up to one. For the remaining grid cells, the outgoing current has to add up to the incoming current. From the transition matrix probabilities alone (Figure 26a), we could have already deduced that some reactive trajectories were more likely than others, and hence, were going to have a higher current. Building on the previous example, we see that the probability of following $1 - 3 - 4 - 3 - 5$ or $1 - 3 - 5$ is less than the probability of following $1 - 2 - 5$ (Figure 26a,b).

In the final step, we find the effective reactive current by eliminating any unproductive detours. In the above example, $1 - 3 - 4 - 3 - 5$ would be considered an unproductive detour, because the trajectory has to move back from grid cell 4 to grid cell 3 prior to reaching the target grid cell five (Figure 26b). From a physical perspective, this last step removes recirculation and the effective current yields only the most direct pathways available (Figure 26c). Both the reactive current and effective reactive currents can be informative and in this study their differences are negligible. Specifically, the mean percent difference between the magnitude of the reactive current and the magnitude of the effective reactive current is 6.1%, with 75% of the currents having a difference smaller than 7.6%.

The mathematical derivation of this method is slightly more nuanced as it involves several additional steps, which are summarized next. For Equations 1 through 5 presented
below, recall the following definitions. The transition matrix has size N by N, where N represents the total number of grid cells in the domain. The source A and target B are defined as a subset of all grid cells N and have length a and b, respectively. All grid cells other than the source and target grid cells are represented in the subset C of length c. The letters i and j denote two arbitrary grid cells.

**Equation 1:** Transition matrix (P)

\[
P_{ij} = \frac{\text{# of trajectories in grid } i \text{ at time } t_0 \text{ that move to grid } j \text{ at time } t_0 + dt}{\text{total # of trajectories in grid } i \text{ at time } t_0}
\]

**Equation 2:** Forward committor (q⁺)

\[
q_{i \in A}^+ = 0 \\
q_{i \in B}^+ = 1 \\
q_{i \in C}^+ = (I_{|C|} - P_{|C \times C|})^{-1} \sum_{j=1}^{b} P_{|C \times B|}
\]

**Equation 3:** Backward committor (q⁻)

\[
q_{i \in A}^- = 1 \\
q_{i \in B}^- = 0
\]
where $P_{\text{back}}$ is the backward transition matrix and $p$ is the limiting distribution of $P$ (or the first left eigenvector).

**Equation 4: Reactive currents ($f^{AB}$)**

$$f^{AB} = q^- p P q^+$$

**Equation 5: Effective reactive currents ($f^+$)**

$$f^+_{ij} = f_{ij}^{AB} - f_{ji}^{AB}$$

From the transition matrix (Equation 1), we first calculate the forward and backward committors. The forward committor (Equation 2) represents the probability of going to the target from each grid cell in the domain in forward time. The backward committor (Equation 3) represents the probability of coming from the source to each grid cell. Next, we calculate the reactive current from the product of the transition matrix (Equation 1), its limiting distribution, and the committors (Equation 4). We need to include the limiting distribution in this calculation, in order to account for the non-uniform sampling of the drifters. The reactive current gives the average probability of moving from one grid cell to the next when travelling from the source to the target. Finally, we find the effective reactive current by subtracting the reactive current out of a grid cell from the reactive current into a grid cell. The resulting effective reactive current is a matrix, similar to the transition matrix, as it describes the current from each grid cell in the domain to another grid cell.
It is possible to further extend this method by imposing additional restrictions on the number of grid cells a reactive current is allowed to visit. For example, instead of just specifying the source and target grid cells as in Figure 26b, one could further specify that grid cell 2 cannot be visited. The only effective reactive current that would remain is pathway 1 – 3 – 5.

As noted earlier, the final product of this calculation, the effective reactive current, is a matrix which contains the effective reactive current between each grid cell with all other grid cells. For ease of visualization, we present the results as the average direction and magnitude of each effective reactive current (Figure 27). Our primary focus is the relative contribution of the local effective reactive current to the different pathways leading to the target. Towards that end, we normalize the effective reactive current by the total reactive current. We can then interpret these pathways in terms of their percentage probabilities.

For the remainder of this chapter, the effective reactive currents can be thought of as all pathways that directly connect the source and target regions. Each pathway is associated with a probability, giving us the opportunity to differentiate between less and more probable pathways. In our previous example, pathway 1 – 2 – 5, would, for example, be considered as the most probable pathway (Figure 26c).

Summarizing, transition path theory serves as an extension of Markov chain theory, which allows us to identify pathways that connect a specified source and target
location. Since these pathways are identified directly from the transition matrix, this method does not require the release of particles and is, as a result, highly computationally efficient.

![Figure 27: Schematic of the average effective reactive current.](image)

**4.4 Results and discussion**

This section starts with a discussion of the results from the particle trajectories calculated from the Markov chain. Specifically, we discuss their probability distribution over the domain and the advective timescales associated with different pathways. We close this section with a discussion of the pathways calculated using transition path theory. This section includes a comparison between the pathways described by surface drifters and pathways described by Argo floats.

**4.4.1 Markov chain probability distributions**

To understand the surface connection between the North Brazil Current and the tropical Atlantic, we release particles along the source and track them for a period of five years or until they leave our study domain (Figure 23). The probability distribution maps are normalized by the total number of particle positions. These maps show the cumulative distribution of all particle positions since their release from the North Brazil Current. Six months after release, particles have entrained in the North Brazil Current, closely hugging
the South American coast (Figure 28a). Around 6°N some particles get entrained towards the Atlantic interior, while others continue their northwestward journey towards the Caribbean Sea (Figure 28a). After one year the particles continue along these two pathways (Figure 28b). In addition, a third route becomes apparent whereby particles remain in the Atlantic, but instead of getting entrained in the interior, flow outside of the Caribbean Islands (Figure 28b). After two years, most particles have reached the tropical North Atlantic and start to exit the domain to the north (Figure 28c). The small accumulation of particles shown around the Gulf of Guinea (Figure 28c,d) has recently been identified as a secondary garbage patch in the South Atlantic (Miron et al., 2021). Since we are primarily interested in the northward pathways to the tropical North Atlantic, we filter out all particles that exit the domain in the south (Figure 29), which is around 9% of the total particles. The previous description of the pathways (Figure 28) holds for this modified distribution (Figure 29).
Figure 28: Markov chain distribution from the North Brazil Current. The value of each grid cell is normalized by the total number of particle positions. The cumulative distributions are shown after (a) six months, (b) one year, (c) two years, and (d) five years after release from the North Brazil Current. For example, (a) includes all particle positions over the six months since their release from the North Brazil Current.
Figure 29: Markov chain distribution excluding particles that leave the domain across the southern boundary. Refer to the caption of Figure 28.

Note the apparent dominance of particles in the Atlantic over the Caribbean Sea in Figures 28 and 29. The above results are in general agreement with previous studies.
(Halliwell et al, 2003; Hazeleger & Drijfhout, 2006) that illustrate the connecting pathways between the North Brazil Current and the tropical North Atlantic. However, these first results also emphasize that pathways other than the traditional pathway through the Caribbean and the Gulf of Mexico may play a significant role in transporting water northwards.

To evaluate this possibility, we plot the longitude of particle arrival along the RAPID line (Figure 30) and find that around 43% of launched particles cross the RAPID line in the Florida Current around 80°W. The remaining 67% cross the RAPID line in the Atlantic Ocean interior, mostly west of 50°W. Around 4% of these particles arrive through the Antilles Current. Setting the source at 6°S instead of 2°N yields 40% of particles in the Florida Current and 60% of particles arriving elsewhere along the RAPID line.

![Distribution of Markov chain particles along the RAPID line at 26.5°N.](image)

Figure 30: Distribution of Markov chain particles along the RAPID line at 26.5°N. The percentages are normalized by the total number of particles cross the RAPID line over the course of five years.
We next identify pathways connecting the North Brazil Current to the Florida Current, the Antilles Current, and the RAPID line east of the Antilles Current (‘East RAPID’), by only looking at the distribution of particles that reach those specific destinations (Figures 31, 32, and 33). All particles that reach the Florida Current from the North Brazil Current flow into the Caribbean Sea, through the Yucatan Channel and the Gulf of Mexico. A few particles show excursions into the Atlantic interior around the North Equatorial Current (Figure 31) and as far north as Puerto Rico and the Dominican Republic. Though, it is notable that no particle can reach the Florida Current without entering the Gulf of Mexico first (Figure 31). We roughly differentiate between particles that move towards the interior of the basin (north of 5°N and east of 50°W) versus those that travel directly to the Caribbean and find relative percentages of 25% and 75%, respectively. These values are in agreement with Halliwell et al. (2003) who found that one-fourth of particles travelling towards the Florida Current took a detour to the basin interior. In contrast, most particles that reach the Antilles Current remain in the Atlantic basin and follow a more or less direct northwestward pathway between the North Brazil Current and the Antilles Current (Figure 32). Only 5% of particles follow the same pathway as the Florida Current particles through the Caribbean Sea and Gulf of Mexico. Particles that reach the Antilles Current are also more likely to get entrained in the North Equatorial Current system towards the basin interior (Figure 32) than particles that reach the Florida Current (Figure 31).

Finally, we examine the pathways taken by particles that reach the RAPID line east of the Antilles Current. Similar to the Antilles Current particles, we observe the majority of particles taking a direct northwestward pathway towards the RAPID line with excursions
into the basin interior (Figure 33). Less than 1% of particles visit the Gulf of Mexico prior to reaching the East RAPID line (Figure 33).

Separating the particles by their location of arrival at the RAPID line has revealed two distinct pathways. One, which is commonly referred to in past literature (Halliwell et al., 2003), connects the North Brazil Current to the Florida Current through the Caribbean Sea and the Gulf of Mexico, and the other bypasses the Gulf of Mexico and instead connects the North Brazil Current to the Antilles Current and the rest of the RAPID line through the Atlantic interior. We refer to the former as the Gulf of Mexico pathway and the latter as the Atlantic pathway (Figure 34). Both pathways feature occasional excursions into the North Atlantic interior in the North Equatorial Current. Northward Ekman transport in this region, however, allows the particles to escape the current and re-embark on a northwestward trajectory towards the RAPID line. The direct western boundary route and interior route described by Halliwell et al. (2003) and discussed in section 4.2.2 both fall into the Gulf of Mexico pathway using our definition.

Using these two definitions we can make the following distinctions. About 43% of particles that reach the RAPID line travel through the Gulf of Mexico pathway, while the remaining 57% follow the Atlantic pathway. Of the particles reaching the Florida Current, 100% pass through the Gulf of Mexico pathway. 95% of particles that reach the Antilles Current travel through the Atlantic pathway and the remaining 5% travel via the Gulf of Mexico pathway. Finally, less than 1% of particles that reach the East RAPID array travel through the Gulf of Mexico and instead, the large majority follow the Atlantic pathway.
Next, we examine the transit time distributions of these two pathways based on their target locations.

Figure 31: Markov chain distribution from the North Brazil Current to the Florida Current. Refer to the caption of
Figure 32: Markov chain distribution from the North Brazil Current to the Antilles Current. Refer to the caption of Figure 28.
Figure 33: Markov chain distribution from the North Brazil Current to the East RAPID line. Refer to the caption of Figure 28.
Figure 34: Schematic of the dominant pathways between the North Brazil Current and the RAPID line. The Gulf of Mexico pathway is defined as all pathways that pass through the Gulf of Mexico as defined by the green box. The Atlantic pathway is defined as all other pathways. Only a few examples of all possible pathways are shown.

4.4.2 Markov chain transit time distributions

On average, it takes particles under two years to travel between the North Brazil Current and the RAPID line (Figure 35). There is little difference between the arrival time of particles travelling through the Gulf of Mexico pathway and that via the Atlantic pathway (Figure 35a, b). After 1.5 (1.5) years 50% of particles have reached the RAPID line when following the Gulf of Mexico (Atlantic) pathway.

The mean transit time to the Florida Current is also 1.7 years via the Gulf of Mexico pathway, with a range of 0.3 to 5 years and 50% of particles reaching within 1.5 years (Figure 36). Recall that no particles follow the Atlantic pathway to the Florida Current (Figure 31). Similarly, the Atlantic pathway to the Antilles Current takes an average of 1.7 years (Figure 37b). However, the Gulf of Mexico pathway to the Antilles Current takes about half a year
longer (Figure 37a), owing to particles having to travel a longer zonal distance to reach the current. Note that the transit time distribution via the Gulf of Mexico pathway shows less of a peak and is much broader (Figure 37a) than the previously discussed distributions (Figures 35, 36). Finally, the transit time distribution to the East RAPID line east of the Antilles Current is very similar to transit time distribution to the Antilles Current (Figure 38). Recall that both targets show a strong preference for the Atlantic pathway. The long tails associated with all transit time distributions are the result of the previously described excursions into the basin interior.

Figure 35: Transit time distribution from the North Brazil Current to the RAPID line. The Gulf of Mexico and the Atlantic pathway distribution refer to the pathways defined in Figure 34. The solid line indicates the mean transit time to the target. The shading increments show the time it takes for 25%, 50%, and 75% of particles to reach the target. (a) Transit time through the Gulf of Mexico pathway and (b) Transit time through the Atlantic pathway.
These results are in overall agreement with past estimates (Halliwell et al., 2003). Here we add that there is no significant difference in transit time between the Gulf of Mexico pathway \((1.7 \pm 0.9 \text{ years})\) and the Atlantic pathway \((1.7 \pm 0.7 \text{ years})\) when considering the entire RAPID line. The transit time to the Antilles Current and the RAPID line east of the Antilles Current is slightly longer \((2.3 \pm 0.9 \text{ to } 2.5 \pm 0.9 \text{ years})\) than the transit time to the Florida Current \((1.7 \pm 0.9 \text{ years})\) via the Gulf of Mexico pathway.

\[
\begin{align*}
\text{Figure 36: Transit time distribution from the North Brazil Current to the Florida Current via the Gulf of Mexico pathway. No transit time distribution for the Atlantic pathway is shown, since all particles travel through the Gulf of Mexico to reach the Florida Current. Refer to the caption of Figure 35.}
\end{align*}
\]
Figure 37: Transit time distribution from the North Brazil Current to the Antilles Current. Refer to the caption of Figure 35.
4.4.3 **Surface pathways from transition path theory**

Having discussed the results of the Markov chain, we next present the results of the transition path theory calculation. Recall that the advantage of this method is the ability to specify the source and target location and calculate pathways directly from the transition matrix, i.e., without releasing particles. We first focus on surface pathways.

As a reminder, the vectors shown in Figures 39 through 41 show the probability associated with a particular pathway. For example, in Figure 39a, 100% of pathways leave the North Brazil Current and the colored vectors in each grid indicate the percentage of those
that follow individual pathways to the Florida Current. The expectation is that these pathways will resemble the distributions previously described by filtering the Markov chain particles by their different destinations.

In this first example, we have not only defined the source and target regions, but we further impose the restriction that pathways are not allowed to visit any other grid cell along the target line (Figures 39 and 40). For example, for Figure 39a, the target is the Florida Current and no other grid cell along the same latitude (26°N) is allowed to be visited. This restriction was imposed to mimic the case in which we cut the Markov chain trajectories as soon as they traveled north of their destinations (Figures 31-33).

We first consider the pathways connecting the North Brazil Current to the Florida Current. The most probable pathways connecting this source and target (Figure 39a) leads along the coast of South America before entering the Caribbean Sea and subsequently the Gulf of Mexico through the Yucatan Channel. This pathway is commonly assumed to carry most of the waters of the upper limb of the overturning circulation (Fratantoni et al., 2000; Halliwell et al., 2003). Secondary, less probable pathways, are revealed whereby waters first travel towards the interior of the Atlantic around 6°N before returning westward to the Caribbean Sea. Similar to the Markov chain particle distribution, there appears to be no pathway that connects the North Brazil Current to the Florida Current that entirely remains in the Atlantic Ocean – a detour through the Gulf of Mexico is required. While the deflection into the basin interior is referenced in prior literature, previous studies put little emphasis on this pathway. These pathways further reveal that about 4% of waters are able to travel in the Atlantic basin as far north as Puerto Rico and the Dominican Republic, before
leaking into the Caribbean Sea between the two islands or between Haiti and Cuba (Figure 39a). Overall, the most probable pathways (Figure 39a) closely resemble the southern pathway described by Richardson (2005), confirming the idea that waters originating in the North Brazil Current are concentrated in the southern Caribbean. The pathways also beautifully recover the circulation in the Panama Colombia gyre (Figure 39a). The probability of recirculating in this gyre is lower compared to the probability of getting swept up in the zonal currents of the Caribbean Sea (Figure 39a), in agreement with observations by Richardson (2005).

Next, we consider the pathways between the North Brazil Current and the Antilles Current. As for the Markov chain particle distributions, the large majority of pathways are in the Atlantic Ocean, with only 2% of pathways connecting the North Brazil Current to the Antilles Current via the Gulf of Mexico (Figure 39b). Interestingly, pathways to the Antilles Current are at first most likely to remain in the North Brazil Current until around 10°N. There, pathways show an approximately equal probability of retroreflecting into the basin interior or continuing on a more direct northwestward path. Around the Dominican Republic both these pathways converge once more and flow northwestward to the Antilles Current. Between 5% and 10% of pathways flow into the Caribbean, but subsequently rejoin the Atlantic basin by escaping between Puerto Rico and the Dominican Republic (Figure 39b). Due to the divergence of pathways around 10°N, the most probable pathway is less distinct than the Florida Current pathway.

Surface pathways to the East RAPID line (i.e., the RAPID line east of the Antilles Current, Figure 39c), show even more deflections into the basin interior than pathways to
previous targets. As described previously, northward Ekman transport in this region allows waters to escape the North Equatorial Current and join the subtropical gyre circulation. Similar to the Antilles Current pathways, we observe a convergence of waters just east of the Dominican Republic and Puerto Rico. The large majority of pathways reach the East RAPID line west of 60°W (Figure 39c), in agreement with the Markov chain study (Figure 30).

When considering the entire RAPID line as our target (Figure 39d), we recover a combination of the pathways leading to the three previous described targets. Most notable, the most probable pathways are pathways through the Atlantic Ocean, not the Gulf of Mexico or Caribbean Sea. This observation confirms the results of the Markov chain, and emphasizes the idea that cumulatively it is more probable that waters reach the RAPID line through the Atlantic basin as opposed to the traditional upper limb route through the Gulf of Mexico. These results suggest that pathways through the basin interior (i.e., the exterior of the Caribbean) are a dominant contributor and infiltrate the entire western half of the subtropical gyre. The conclusions are unchanged if we set the source along the width of the entire Atlantic basin at 2°N (Figure 39e).

As mentioned in the beginning of this section, we restricted the grid cells that pathways were allowed to visit to mimic the behavior of the Markov chain particles. If we relax this restriction and allow pathways to travel anywhere in the domain prior to reaching their designated target we observe only slight differences in the pathways. This ability to restrict pathways is a large advantage of transition path theory. For the Florida Current we observe that the relaxation allows for a connection between the Antilles Current and the
Florida Current (Figure 40a). Though it is relatively unlikely, it suggests the possibility of reaching the Florida Current without traveling through the Gulf of Mexico. Setting the target at the Antilles Current with the relaxed restrictions similarly allows for pathways that approach the Antilles Current from the east (Figure 40b). We also observe a small increase in the probability of the easternmost pathways (Figure 40b). Given that pathways are already allowed to visit most of the grid cells along the same latitude when the larger targets are used (RAPID and East RAPID), we observe no significant changes by relaxing the restrictions for these pathways (not shown).

4.4.4 Subsurface pathways from transition path theory

Next, we compare the surface pathways described in the previous section to subsurface pathways.

Subsurface pathways connecting the North Brazil Current and the Florida Current are less direct and more dispersive (Figure 41a) than their surface counterparts (Figure 39a). Still, the most likely pathway to the Florida Current is also through the Caribbean Sea (Figure 41a). We suspect that this particular subsurface pathway is an artifact created by a few isolated floats that are able to overcome the bathymetry constraint (Figure 23c), perhaps as they float along the surface ocean when transmitting their data in-between cycles (Figure 24c).

Similarly, the subsurface pathways to the Antilles Current (Figure 41b) are less direct from source to target compared to the surface pathways (Figure 39b). These subsurface routes show more deflections towards the interior around 45°W and 5°N (Figure 41b), whereas the surface pathways remain constrained to the coast in the North Brazil Current.
The most probable pathway is harder to identify as both the Gulf of Mexico pathway and the Atlantic pathway appear equally probable. This is not expected given the shallow bathymetry of the Caribbean Sea and Florida Straits that prevent most Argo floats from entering. We refer to the previous explanation that mentioned that the Gulf of Mexico pathway is likely the consequence of a few Argo floats escaping the bathymetry constraint (Figure 23c) as they float along the surface ocean. More importantly, recall that the presented probabilities were normalized by the total effective reactive current leaving the North Brazil Current. While it appears that the pathway through the Gulf of Mexico is a dominant pathway, that is misleading. When we look at the absolute probabilities and compare the pathways across different targets (Figure 42), we see that pathways leading to the Florida and Antilles Current targets (Figure 42a and b) are one to two order of magnitude less probable than pathways through the Atlantic interior to the East RAPID line (Figure 42c). This is also emphasized in the pathways shown in Figure 41d and Figure 42d, where the entire RAPID line is chosen as the target. Here, the Gulf of Mexico pathway is much less probable as its contribution is insignificant compared to the Atlantic interior pathways.

Going back to our description of subsurface pathways, the dominant connection between the North Brazil Current and the East RAPID line is found through pathways that traverse the Atlantic interior and reach the western limb of the subtropical gyre (Figure 41c). The dispersion noted for the previous subsurface pathways is also visible for this target (Figure 41c). When considering the entire RAPID line as the target, the pathways are virtually identical (Figure 41d). Similarly, setting the source along the width of the entire Atlantic basin at 2°N yields the same results (Figure 41e).
We emphasize here that the described surface and subsurface pathways merely indicate the probability of certain pathways and are not necessarily reflective of absolute volume transports. In addition, both the surface and subsurface pathways are constructed from two-dimensional observational trajectories, a caveat that should be kept in mind. Future work is planned to address these limitations using Lagrangian model trajectories.
Figure 39: Surface pathways from transition path theory connecting the North Brazil Current to the tropical North Atlantic. The vectors are colored by their probability. A total of 100% leave the source at the North Brazil Current and reach the respective targets. The vectors then show the probability of a particular path connecting source and target. The background contours show the sea surface height field at 0.1 m intervals.
Figure 40: Surface pathways from transition path theory connecting the North Brazil Current with relaxed restrictions. Pathways are allowed to travel to grid cells along the target latitude prior to reaching the target. Refer to the caption of Figure 39 for more detail.
Figure 41: Subsurface pathways from transition path theory connecting the North Brazil Current to the tropical North Atlantic. Refer to the caption of Figure 39 for more information.
Figure 42: Subsurface pathways from transition path theory with absolute probabilities. Here, the vectors are colored by their actual absolute probabilities instead of normalized probabilities to show the relative differences between the probabilities of reaching different targets.
4.5 Summary

This study explored the pathways that connect the North Brazil Current to the tropical Atlantic using Markov chain theory and a new method derived from transition path theory to enhance observational trajectories. In accordance with the questions posed at the beginning of this chapter, we arrive at four main conclusions.

1. The most probable pathways between the North Brazil Current and the tropical North Atlantic strongly depend on the desired target. The most probable pathway to the Florida Current passes through the Caribbean Sea and Gulf of Mexico, as suggested by previous studies. Less probable pathways exist, whereby waters first get entrained towards the basin interior before returning to the Caribbean Sea. Notably, this study reveals that waters can travel as far north as the Dominican Republic and Cuba before merging into the Caribbean Sea in between the two islands. The most probable pathways to the entire RAPID line flow through the Atlantic basin, with an approximate equal probability of reaching the RAPID line anywhere west of 55°W.

2. There is a direct connection between the North Brazil Current and the Antilles Current through pathways that remain in the Atlantic Ocean (95%). There is only a 5% probability of reaching the Antilles Current through the Gulf of Mexico pathway.

Summarizing the previous two points we can say that there is a Gulf of Mexico pathway that predominately leads to the Florida Current with a very minor contribution to the Antilles Current or the RAPID line east of the Antilles Current. There is an Atlantic
pathway that mostly funnels waters to the Antilles Current and the RAPID line west of 55°W. Both of these pathways feature excursions to the Atlantic interior and funnel through the Caribbean Islands.

3. The transit time scales depend upon the exact target. Considering the entire RAPID line as the target, there is no difference between the transit time through the Gulf of Mexico (1.7 ± 0.9 years) and the Atlantic (1.7 ± 0.7 years). On average, the fastest pathway to the Florida Current is through the Gulf of Mexico (1.7 ± 0.9 years) and to the Antilles Current through the Atlantic (1.7 ± 0.7 years). It takes approximately half a year longer to reach the Antilles Current through the Gulf of Mexico (2.3 ± 1.0 years).

4. The relative importance of the Atlantic versus the Gulf of Mexico pathway strongly depends on the target site. The Markov chain particles suggest a relative contribution from the North Brazil Current of 43% to the Florida Current and 57% to the remaining RAPID line. Pathways from transition path theory emphasize this by predominantly revealing the Atlantic pathway to the RAPID line target. This result underscores the importance of taking the entire RAPID line into account when aiming to understand the contributions of the South Atlantic to the North Atlantic overturning circulation.
4.6 Future work and transition path theory

The primary limitations of this study are the two-dimensional nature of the surface drifters and Argo floats as well as their inherent sampling bias. Both of these contribute to the fact that these two-dimensional trajectories may not faithfully represent all pathways connecting the North Brazil Current to the tropical North Atlantic. Nevertheless, in our particular domain, we expect the two-dimensional circulation to be more representative of the three-dimensional circulation than in other areas. For example, examining surface pathways at the convergent center of the North Atlantic subtropical gyre around 30°N would represent much more of a limitation. Beron-Vera et al. (2016) showed that simulated surface trajectories and surface drifters used in their study have maximum accumulation north of our target latitude (26°N).

To address this constraint, simulated model trajectories will be used. Using these model trajectories, we will explore the following questions.

1. Can the two-dimensional circulation in this region be used to approximate or represent the three-dimensional circulation?
2. What are the volume transports associated with the different identified pathways?

To validate the method of transition path theory, we will also apply the same methodology to the model trajectories. As highlighted throughout this chapter, the main advantage of transition path theory is its ability to identify pathways that directly connect a source to a target region. In future work, we can capitalize on this method further by using the reactive effective currents to identify a single most probable pathway, as well as the shortest pathway, and the fastest pathway.
The computational efficiency of transition path theory makes it an invaluable tool to be used in conjunction with Markov chain theory in oceanographic applications. Together with Miron et al., (2021), who used this method to identify garbage patches in oceanic gyres and their corresponding sources, this chapter is the first application of this method to examining the ocean circulation. Applying this method to model trajectories has the ability to greatly impact the way we study and view oceanic pathways.
5. Conclusions

In this dissertation I focused on revisiting the upper-ocean pathways of the South Atlantic as they relate to the overturning circulation from an observational perspective. To that end I used a combination of observational drifter and float trajectories in conjunction with Markov chain and transition path theory, as well as satellite altimetry data sets.

I first focused on a prominent discussion in the literature concerning the relative contributions of the cold and warm water routes. Through observational trajectories I revealed that waters following the cold route mostly flow through the northern Drake Passage, can join the South Atlantic circulation further east than previously assumed, can recirculate just south of the African continent to leak back into the South Atlantic through Agulhas leakage, and follow internal pathways in the interior of the South Atlantic basin. I further showed that waters from both routes share multiple pathways throughout the South Atlantic, especially within the eastern and northern limbs of the subtropical gyre. Finally, my analysis illustrated that the cold water route contributes a sizeable amount to the waters of the South Atlantic in agreement with recent modeling work by Rühs et al. (2019) and a subsurface float study by Rodrigues et al. (2010).

Given the importance of the subtropical gyre in setting the pathways of South Atlantic upper-ocean waters, I used measurements of sea surface height and its two components the steric height and ocean mass to investigate the seasonal and interannual variability and long-term trends in gyre position, size, and strength between 1993 and 2018. On a basin-scale, my analysis showed that seasonal variability in the ocean mass is driven by the seasonal variability in the wind stress curl. My findings indicated that the seasonal
variability in gyre position is mostly controlled by the northern and eastern gyre boundaries. The sea surface height variability of the gyre maximum and along the gyre boundary is mostly explained by variations in the steric height field. The interannual variability in gyre strength is much weaker than its seasonal variability and correlated to the basin-wide wind stress curl. My analysis confirmed a southward displacement of the gyre along its southern boundary as previously identified by Lumpkin & Garzoli (2011) and Vincent & Combes (2014). However, my results revealed that this southward migration does not result in a net expansion or contraction of the gyre. I attribute this to a compensation by the highly variable eastern gyre boundary. Finally, my observations-based study showed no trend in gyre strength between 1993 and 2018 due to two factors. First, there is no trend in the basin-wide or gyre-wide wind stress curl over the chosen domain and second, the sea surface height maximum within the gyre and the sea surface height along the boundary are rising at comparable rates. A net increase in strength would require a change in the sea surface height gradient, which can only be achieved by a differential increase or decrease in either the gyre boundary or the gyre maximum.

Finally, I used observational trajectories and statistical tools from Markov chain theory and transition path theory to examine the connection between the North Brazil Current and the tropical Atlantic. My results recovered the traditional pathway that funnels upper-ocean waters through the Caribbean Sea and the Gulf of Mexico to the Florida Current. Most importantly, however, I showed that surface pathways through the Atlantic interior that reach the tropical Atlantic east of the Florida Current account for 58% of released particles. One prominent pathway I identify is a direct connection between the
North Brazil Current and the Antilles Current, which had previously been thought to carry part of the overturning upper limb. My findings highlighted the importance of taking the entire Atlantic basin into account when trying to explain overturning variability in the RAPID array, as a substantial number of waters stemming from the North Brazil Current may carry that information to places other than the Florida Current. The observation-based transit time estimates showed that it takes an average of 1.7 years for waters to travel between the North Brazil Current and the RAPID line, regardless of the exact pathway that is taken.

Overall, the results of my dissertation have improved our understanding of pathways that contribute to the cold and warm water routes, showed that the subtropical gyre circulation has not undergone substantial changes over the past 25 years, and highlighted the importance of interior Atlantic pathways in connecting the North Brazil Current to the tropical North Atlantic.

In the context of the overturning circulation, my analysis showed that the traditional cold and warm water routes share many paths within the South Atlantic, which suggests ample opportunity for mixing and exchange of properties prior to reaching the North Brazil Current. This calls into question the importance of their relative properties and their net impact on the overturning circulation in the subpolar North Atlantic. Additionally, I showed that waters from the Drake Passage significantly contribute to the waters of the Benguela Current and infiltrate the southern subtropical gyre boundary along their path. This not only highlighted the importance of monitoring and considering both source water masses, but also confirmed that the subtropical gyre may play a substantial role in regulating their relative
contributions. Finally, in order to properly assess the influence of the South Atlantic on the overturning circulation in the tropical North Atlantic, all pathways connecting the two basins have to be taken into account, especially previously neglected interior Atlantic pathways that communicate with the tropical Atlantic east of the Florida Current.

Concluding, I would like to highlight that this dissertation focused on the use of observational data in advancing our understanding of the circulation. Given this choice, the most prominent limitation is the fact that two-dimensional trajectories may not be able to capture all available pathways and circulation features across the South Atlantic. As such, my future work will focus on using three-dimensional model trajectories to better understand these limitations and explore the statistical tools introduced throughout this dissertation in the modeling world.
References

Argo (2000). Argo float data and metadata from Global Data Assembly Centre (Argo GDAC). SEANOE.


Copernicus Climate Change Service. (2019). *ERA5 monthly averaged data on single levels from 1979 to present ECMWF*. https://doi.org/10.24381/CDS.F17050D7


144


Schmid, C. (2014). Mean vertical and horizontal structure of the subtropical circulation in
the South Atlantic from three–dimensional observed velocity fields. Deep Sea Research

intermediate depths in the tropical Atlantic. In Elsevier Oceanography Series (Vol. 68, pp.


Geophysics, 31, 29–49.


shallow and deep western boundary circulation of the South Atlantic at 5–11 S.

circulation in the western tropical Atlantic. Journal of Physical Oceanography, 28(10),
1904–1928.


Biography

Kimberley Laverne Elisabeth Claudie Drouin graduated *cum laude* from the University of Miami in 2014 with a B.S. in Marine Sciences and Biology and a minor in Chemistry. She subsequently earned her M.S. in Meteorology and Physical Oceanography from the University of Miami in 2017. Kimberley has authored three scientific publications published in the *Journal of Geophysical Research: Oceans* and the *Marine Pollution Bulletin* (“Lagrangian simulations of oil trajectories in the Florida Straits,” “The surface pathways of the South Atlantic: revisiting the cold and warm water routes using observational data,” “Variability and trends in the South Atlantic subtropical gyre”). Kimberley has also co-authored two further publications in *Journal of Geophysical Research: Oceans*. Kimberley received the International Student Scholarship from the University of Miami in 2012, 2013, and 2014 and the University of Miami Graduate Student Fellowship in 2016 and 2017. Kimberley was on the Dean’s and Provost’s Lists at the University of Miami. She is a member of the American and European Geophysical Unions.