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The Role Of ENSO On The Agulhas Current Leakage Region

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THE ROLE OF ENSO ON THE AGULHAS CURRENT LEAKAGE REGION

by

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ABSTRACT

The southern end of the African continent marks the division between the Atlantic Ocean and the Indian Ocean where warm, saline waters propagate into the Atlantic Ocean in the form of rings, eddies, and filaments. These warm, saline waters released during the retroflection of the Agulhas Current are referred to as Agulhas leakage. The Agulhas Current is a poleward flowing western boundary current that forms the limb of the wind-driven anti-cyclonic circulation of the south Indian Ocean. The current originates south of Madagascar fed by the Mozambique Channel and the East Madagascar Current. Small-scale variations have been identified in Agulhas leakage that further impact the strength of Meridional Overturning Circulation sequentially altering the climate patterns as well as interact with the Benguela current altering Benguela upwelling. Numerous mechanisms have been identified by previous studies as potential factors resulting in Agulhas leakage fluctuations but these studies fail to determine the driving source of changes to Agulhas leakage. This study proposes El Niño Southern Oscillation (ENSO) as a driving force behind the changes in Agulhas leakage dynamics. Altimetry-derived sea surface height (SSH) anomalies, Advanced Very High Resolution Radiometer (AVHRR) sea surface temperature (SST) data, sea surface salinity (SSS) Simple Ocean Data Assimilation (SODA) reanalysis product, and in-situ datasets of ARGO profiles of salinity and temperature are utilized to explore signal response in both the surface and depth to an ENSO event. This thesis determines that an ENSO event originating in the Pacific Ocean alters the salinity and temperature properties of the Indian Ocean basin in
both the surface and subsurface. The resulting signal, which is opposite for El Niño compared to La Niña, further propagates via westward propagating Rossby waves into the Agulhas Current system to influence the Agulhas leakage region between 20 to 26 months after the peak of an ENSO event. The salinity and temperature signal of the Agulhas leakage region [37°-45°S, 10°-20°E] is observed as anomalously warm and fresh transitioning to warm and saline in response to El Niño. Oppositely, in response to La Niña, the Agulhas leakage region is anomalously cool and saline transitioning to cool and fresh. Furthermore, it is revealed that the subsurface (~500 m depth) temperature and salinity anomalies across the Indian Ocean and within the Agulhas leakage region reflect this surface response at depth and persist for a longer duration (~1 to 2 years) compared to the surface signal.
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CHAPTER 1
INTRODUCTION

1.1 AGULHAS CURRENT LEAKAGE REGION

The Agulhas Current and associated Agulhas leakage is the primary region of focus for the research presented in this thesis. The Agulhas Current is a western boundary current originating south of Madagascar at 28°S forming a narrow flow stabilized by Africa’s steep continental slope. Past the southern tip of Africa at 39°S, the flow retroflects eastward as the Agulhas Return Current shedding warm, saline waters in the form of rings, cyclones, and filaments into the Atlantic Ocean referred to as Agulhas leakage [Lutjeharms et al., 2001 and Panven et al., 2006]. For consistency, the Agulhas leakage region is defined at 37°–45°S and 10°–20°E. Agulhas leakage further propagates into the Atlantic Ocean to influence the Benguela Current ultimately impacting Meridional Overturning Circulation sequentially altering climate patterns [Beal et al., 2011].

The Agulhas Current is not an isolated system but rather a limb of the wind-driven anti-cyclonic circulation of the south Indian Ocean. The Indian Ocean contributes nearly 12.6 Sv to Agulhas leakage [Durgadoo et al., 2017]. Therefore, a connection exists between changes to the Agulhas Current and changes further upstream in the equatorial Indian Ocean basin. An eastern region (0°–20°S and 90°–105°E) and western region (10°–30°S and 60°–80°E) are used to represent the Indian Ocean basin. The
Mozambique Channel (MC) and the East Madagascar Current (EMC) are the two major source currents of the Agulhas Current (Figure 1.1) and are connected to Indian Ocean circulation by the South Equatorial Current (SEC) after it bifurcates along the Madagascar coast. The Indonesian Throughflow (ITF) connects the Pacific Ocean to the Indian Ocean and feeds into the SEC. Nearly half of the Indian Ocean’s contribution to Agulhas leakage can be traced back to the ITF.

The circulation patterns of the Indian Ocean connect the Pacific Ocean and the Atlantic Ocean. The work in this thesis explores this connection to link a Pacific Ocean phenomenon known as El Niño Southern Oscillation (ENSO) to changes in the transport of water to the Atlantic by Agulhas leakage. Understanding changes to the Indian Ocean basin and circulation patterns are key to understanding this connection.

1.2 EL NIÑO SOUTHERN OSCILLATION

El Niño Southern Oscillation is an ocean-atmosphere coupled phenomenon originating in the Pacific Ocean and has two contrasting phases, El Niño and La Niña. El Niño, the warm phase, refers to the warming of sea surface temperatures (SST) across the central and east-central Equatorial Pacific. La Niña, the cool phase, represents periods of below-average SST’s across the east-central Equatorial Pacific. The influence of ENSO is not limited to the Pacific Ocean but rather has global-wide impacts. In particular, corresponding changes in Walker Circulation link variability in the southwest Indian Ocean to ENSO events [De Ruijter et al., 2004]. The pressure gradient force resulting from a high-pressure system over the eastern Pacific Ocean, and a low-pressure system in the western Pacific over Indonesia causes Walker Circulation. During an El Niño event,
the eastward movement of the low-pressure system and ultimately Walker Circulation accompanies weakening trade winds and the eastward movement of the warm pool. During a La Niña Event, the Walker Circulation intensifies with greater convection over the western Pacific.

This thesis connects ENSO events originating in the Pacific Ocean to the Indian Ocean basin and ultimately to the Agulhas Current to impact the Agulhas leakage region. Chapter two defines the relationship between ENSO events and variability in the sea surface salinity (SSS) and SST signal of the Agulhas leakage region. This chapter cites past literature to identify the various mechanisms and systems involved in signal propagation including Rossby waves and wind stress curl. These studies serve to provide evidence and support the notion that such a relationship between Agulhas leakage and ENSO exists. Chapter two then presents novel research that describes the observed effects of ENSO on Agulhas leakage to define the relationship in response to El Niño as compared to La Niña as well as the impact of ENSO strength on this relationship. Furthermore, the temporal perspective is evaluated to define the lag between the peak of an ENSO event and the response of Agulhas leakage. The third chapter extends upon the material presented in chapter two by incorporating a new parameter, the subsurface signal. The third chapter evaluates the propagation of ENSO signal into the Indian Ocean to better explain the response of the Agulhas leakage region identified in chapter two. In particular, changes of temperature and salinity properties of the Indian Ocean basin at both surface and lasting influence in the subsurface are considered in this chapter as well as potential Rossby wave signal in sea surface height (SSH). The fourth and final chapter draws conclusions about the insights the research has provided thus far to better
understand ENSO signal transmission and impact. This chapter also proposes the potential for future research. Most notably, the Benguela Current lies just to the northwest of Agulhas leakage (Figure 1.2) and preliminary results, presented by chapter four, indicate that fluctuations of Agulhas leakage have the potential to impact upwelling events.
**Figure 1.1:** SST for 23 May 2009, showing water at 23-25°C in the Agulhas Current and Retroflection. Leakage takes place largely by means of Agulhas rings. Main circulation features are highlighted to show schematic of circulation patterns in this region. [Figure adapted from Beal et al., 2011].
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CHAPTER 2

ROLE OF EL NIÑO SOUTHERN OSCILLATION (ENSO) EVENTS ON TEMPERATURE AND SALINITY VARIABILITY IN THE AGULHAS LEAKAGE REGION

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2.1 Abstract

This study explores the relationship between the Agulhas Current system and El Niño Southern Oscillation (ENSO) events. Specifically, it addresses monthly to yearly variations in Agulhas leakage where the Agulhas Current sheds waters into the Atlantic Ocean, in turn affecting meridional overturning circulation (MOC). Sea surface temperature (SST) data from the National Oceanic and Atmospheric Administration’s (NOAA) Advanced Very High Resolution Radiometer (AVHRR) combined with sea surface salinity (SSS) from Soil Moisture Ocean Salinity (SMOS) and Simple Ocean Data Assimilation (SODA) reanalysis are used to explore changes in Agulhas leakage dynamics. Agulhas leakage is anomalously warm in response to El Niño and anomalously cool in response to La Niña. The corresponding SSS signal shows both a primary and secondary signal response. At first, the SSS signal of Agulhas leakage is anomalously fresh in response to El Niño, but this primary signal is replaced by a secondary anomalously saline signal. In response to La Niña, the primary SSS signal of Agulhas leakage is anomalously saline, while the secondary SSS signal is anomalously fresh. The lag between the peak of ENSO and the response in SST and the corresponding primary SSS signal of Agulhas leakage is about 20 months, followed by the secondary SSS signal at a lag of about 26 months. In general, increasing ENSO strength increases the extremes of the resulting anomalous SST and SSS signal and impacts the Agulhas leakage region earlier during El Niño and slightly later during La Niña.
2.2 Introduction

The Agulhas Current, a western boundary current, is a limb of the wind-driven anti-cyclonic circulation of the South Indian Ocean. The current originates south of Madagascar forming a narrow flow stabilized by east Africa’s steep continental slope. Past the southern tip of Africa, the flow retroflects eastward as the Agulhas Return Current forming the southern arm of the Indian Ocean subtropical gyre which is a part of the Southern Hemisphere super gyre [Ridgway and Dunn, 2007]. A phenomenon known as Agulhas leakage occurs at the area of retroflection and transports warm saline water into the Atlantic through the shedding of Agulhas rings, cyclones, and filaments. This system feeds the upper arm of the Atlantic meridional overturning circulation (AMOC). Variability in leakage may impact the strength of overturning sequentially altering climate patterns [Beal et al., 2011]. Fluctuations in the strength of Agulhas leakage are controlled by long-term and short-term fluctuations in the Agulhas Current and source current dynamics [Simon et al., 2013]. This paper uses sea surface temperature (SST) and sea surface salinity (SSS) to explore the influence of the El Niño-Southern Oscillation (ENSO) on the Agulhas Current system and, ultimately, Agulhas leakage. Previous work by Biastoch et al. [2015] established a link between Agulhas leakage and changes in heat and salt transports into the Atlantic. Specifically, Agulhas rings are distinguishable from surrounding waters by their high salt content derived from strong evaporation occurring in the retroflection region which boosts the salinity within the rings [Ruijter et al., 1999]. In other words, a close relationship exists between SST, SSS, and circulation supporting our use of SST and SSS as a proxy for Agulhas leakage.
The aim of the study is to define the relationship between ENSO and Agulhas leakage in terms of SST and SSS response. This relationship cannot be fully understood without first connecting the influence of the ENSO signal across the three ocean basins involved: the Pacific Ocean, the Indian Ocean, and the Atlantic Ocean. In terms of global circulation, the Indian Ocean acts as the link between the Pacific and the Atlantic Ocean, contributing nearly 12.6 Sv to Agulhas leakage, of which, about 7.9 Sv originates from the Pacific moving into the Atlantic [Durgadoo et al., 2017]. Nearly half of the Indian Ocean contribution to Agulhas leakage comes from the Indonesian Throughflow (ITF) with a smaller portion originating south of Australia by Tasman leakage [Durgadoo et al., 2017]. The ITF has been found to increase during La Niña and decrease during El Niño [Meyers, 1996]. An analysis by Le Bars et al. [2013] suggests changes to ITF strength influences Agulhas leakage because the two currents are codependent. Within the Indian Ocean basin, the westward flowing South Equatorial Current (SEC) circulates water from the Indian Ocean subtropical gyre and ITF to the Madagascar coast. This westward transport of water between 60°E and 100°E is modeled at mean speeds of ~0.1 m·s⁻¹, taking ~1.3 years for waters from the ITF to reach 77°E [Durgadoo et al., 2017]. Upon reaching the Madagascar coast, the SEC splits at 17°S into a northern and southern branch. The southern branch feeds into the East Madagascar Current (EMC) while the northern branch bifurcates against the African coast into the Mozambique Channel (MC) [Stramma and Lutjeharms, 1997]. A shift in the intensity and position of the tropical and subtropical gyre in response to positive (negative) SSH anomalies associated with ENSO wind anomalies (see next paragraph) changes the intensity of the SEC, thus altering flow through the MC and EMC [Putrasahan et al., 2016]. The EMC sheds eddies near the tip
of Madagascar [De Ruijter et al., 2004], contributing ~25 Sv to the Agulhas Current [Stramma and Lutjeharms et al., 1997]. The MC consists of a train of westward flowing eddies [De Ruijter et al., 2004] which contribute ~5 Sv to the Agulhas Current [Simon et al., 2013].

Furthermore, the formation of eddies in the EMC and MC can be related to incoming Rossby waves crossing the Indian Ocean (see next paragraph) [Schouten et al., 2002], and during El Niño years more eddies are released [De Ruijter et al., 2004]. While the exact mechanics driving Agulhas leakage are still highly debated, a robust link has been identified between these eddies and the westward shift of the retroflection loop as well as the generation of a “Natal Pulse”, a large solitary meander in the current that progresses downstream to influence retroflection dynamics. Recent research suggests that although Agulhas Current meanders may not be the dominant mode of variance, they destabilize the flow, causing increased Agulhas leakage events [Schouten et al., 2002; Elipot and Beal et al., 2015]. It is important to note that De Ruijter et al. [2004] traced the propagation of eddies from south of Madagascar at 5–10 cm·s⁻¹. Therefore, it takes approximately 6 months after formation for eddies from the MC and EMC to influence Agulhas leakage.

A clear connection established by circulation patterns links the Pacific Ocean to the Indian Ocean into the Atlantic Ocean. We are interested in the processes that alter this system to explain why we are seeing the anomalous SST and SSS patterns highlighted in this paper. However, the mechanisms involved in ENSO signal propagation have yet to be deciphered. For this study, the work of Putrasahan et al. [2016] is used to define the proposed process by which an ENSO signal originating in the Pacific Ocean propagates
into the Indian Ocean basin and ultimately alters the properties of Agulhas leakage. During the mature season of El Niño (La Niña), fluctuations of Walker Circulation cause anomalous easterly winds (strong westerly) winds to form over Indonesia, generating upwelling (downwelling) Kelvin waves. Anomalous easterly (westerly) winds actively suppress (enhance) convection, causing a basin-wide warming (cooling) trend [Loveday et al., 2014]. The wind anomalies over Indonesia combined with Ekman pumping generate off-equatorial Rossby waves that travel westward. Note, this process explains the previously mentioned ENSO-associated SSH anomalies that Palastanga et al. [2006] found to be influencing the SEC, further impacting the MC and EMC. The ENSO signal also enters the Indian Ocean along the western Australian coast by a pathway known as the subtropical North Pacific ray-path. North Pacific Rossby waves generated during ENSO events impinge on the western boundary and move equatorward along the “ray-path” of Kelvin–Munk waves to reflect as equatorial Kelvin waves. When the reflected Kelvin waves impinge upon the Australian continent they become coastally trapped and move poleward along the coast, where they radiate Rossby waves into the south Indian Ocean [Cai et al., 2005]. Ultimately, an ENSO event triggers two sets of westward-propagating Rossby waves at 12°S and 25°S from wind forcing and Kelvin waves, respectively. As previously mentioned, the eddy activity of the EMC and MC are influenced by Rossby-wave propagation at 25°S and 12°S, respectively [Schouten et al., 2002].

Rossby waves alone cannot explain signal propagation. A second parameter, wind stress, also plays an important role. The previously described anomalous wind and SST conditions in the Indian Ocean basin that form in response to ENSO are correlated with a
wind-stress anomaly along the equator [Feng and Meyers, 2003]. This is further supported by the strong correlation present between weakened trade winds in the Pacific, a characteristic of an El Niño, and strengthened trade winds in the tropical Indian Ocean. Strengthened trade winds along the tropical Indian Ocean create a zonal band of positive wind stress curl over the tropics, forcing the continued propagation of the Rossby waves at 25°S and 12°S [Putrasahan et al., 2016]. Using SSH, Putrasahan et al. [2016] was able to correlate SST anomalies of Agulhas leakage to wind stress and found a lag of approximately 2 years. In other words, it takes approximately 2 years for tropical warm anomalies formed from El Niño-associated wind anomalies to reach the Agulhas leakage region. This is relatively consistent with the earlier mentioned time scales of ocean circulation, where it takes a little more than ~1.3 years for waters to cross the Indian Ocean basin [Durgadoo et al., 2017] and then ~6 months for eddies from EMC and MC to interact with Agulhas leakage [De Ruijter et al, 2004].

Our study aims to define the relationship between ENSO events and SST and SSS variability in the Agulhas leakage region. In other words, the results presented in this paper are intended to describe the observed effects of ENSO on Agulhas leakage, focusing on defining the relationship itself rather than determining the various driving mechanisms of signal propagation. The previous paragraphs highlight the potential mechanisms of signal propagation serving as evidence and support the notion that such a relationship between Agulhas leakage and ENSO exists. Our study is predominantly important with respect to SSS because the response of SSS in the Agulhas leakage region to ENSO is a novel topic yet to be understood. Newly launched satellite-derived salinity missions used in this study, such as the National Aeronautics and Space Administration’s
(NASA) Soil Moisture Active Passive (SMAP) and the European Space Agency’s (ESA) Soil Moisture and Ocean Salinity (SMOS), are an innovative approach to studying SSS. In respect to SST, Putrasahan et al. [2016] established a link between the interannual variability of SST of Agulhas leakage and ENSO, then determined the lag in response of Agulhas leakage to be about 2 years. However, the Putrasahan et al. [2016] study does not specifically investigate the difference between El Niño and La Niña but rather relies on a correlation analysis to distinguish between the phases and the influence of ENSO strength. The results presented in this paper further the work done by Putrasahan et al. [2016] by evaluating the SST signal propagation from a different perspective and distinguishing El Niño events from La Niña events. This paper uses spatial plots to illustrate the entire propagation of an ENSO signal, from where the SST and SSS signal originates to movement of the signal across the Indian Ocean basin to surround the source currents and ultimately signal interaction with the Agulhas current system, changing Agulhas leakage SST and SSS properties.

2.3 Materials and Methods

ENSO events were determined using the Oceanic Niño Index (ONI) obtained from the National Weather Service and Climate Prediction website. The SST anomalies used to calculate the ONI are from the Extended Reconstructed Sea Surface Temperature (ERSST) version 4 dataset derived from the International Comprehensive Ocean-Atmosphere Dataset (ICOADS). Threshold values were calculated from the anomalies in the Niño 3.4 region (5°N–5°S, 120°–170°W) with an applied 3-month running mean and are based on a centered 30-year base period updated every 5 years.
Satellite-derived measurements from the Advanced Very High Resolution Radiometer (AVHRR) by the National Oceanic and Atmospheric Administration (NOAA) were the sole source of SST data used to interpret temperature trends in the Indian Ocean and Agulhas leakage region. The data included in this study is entitled NOAA NCEI OISST (version 2) daily SST data and was obtained from http://iridl.ldeo.columbia.edu/SOURCES/.NOAA/.NCDC/.OISST/.version2/.AVHRR/.sst/. The data includes a combination of both AVHRR and in-situ data for optimal interpolation. The data set spans from October 1981 to December 2015 with daily intervals at $0.25^\circ \times 0.25^\circ$ spatial resolution that we converted to monthly averages. AVHRR is appropriate for the purposes of this study because of this long time span of data coverage that allows the majority of previous ENSO events to be evaluated; 21 ENSO events occur between 1981 and 2015. Furthermore, the data set is bias-corrected to achieve a uniform performance throughout a wide range of atmospheric and oceanic conditions. Comparisons with in-situ buoys indicate that the global accuracy of current Pathfinder algorithm is $0.02^\circ \pm 0.5^\circ$ C [Kilpatrick et al., 2001]. Satellite-derived salinity measurements from Soil Moisture Ocean Salinity (SMOS) and model-based products from Simple Ocean Data Assimilation (SODA) reanalysis were used to evaluate SSS. SMOS version 2.0 level 3 monthly SSS data at a $0.25^\circ \times 0.25^\circ$ spatial resolution was obtained from Barcelona Expert Centre (http://bec.icm.csic.es/). This data set spans from January 2010 to June 2016 and is still operational. SODA version 3.3.1 reanalysis is obtained from the Asia Pacific Data Research Center (APDRC) at a monthly temporal resolution and a $0.25^\circ \times 0.25^\circ$ spatial resolution spanning from 1980–2015.
This study classifies all ENSO events between 1981 and 2015 as an El Niño if the ONI value was at or exceeding a +0.5° anomaly threshold for 3 consecutive months, and a La Niña if the ONI value was at or below a −0.5° anomaly for 3 consecutive months. Any remaining years are considered to be neutral. This classification process is consistent with that used by NOAA’s Climate Prediction Center (http://www.cpc.ncep.noaa.gov/). The threshold is further divided into weak events with a 0.5°–0.9° anomaly range, moderate events with 1.0°–1.4° anomaly range, and strong events with anomalous values greater or equal to 1.5° established by Jan Null at Golden Gate Weather Services (http://ggweather.com/enso/oni.htm). Table 2.1 represents the strong, weak, and moderate classifications of La Niña and El Niño. The months of January–March were selected to represent the relationship between ENSO and leakage dynamics because it is during the mature season of ENSO (December–March) [Tokinaga and Tanimoto, 2004].

The SST interannual anomalies used throughout the study were obtained by computing the average monthly SST from the full AVHRR data set (1981–2015) and subtracting them from the monthly average of a given year. The same process was used for SSS anomalies except using SODA reanalysis from 1980–2015 and SMOS data from 2010–2016. In other words, the mean seasonal cycle was removed.

We defined the Agulhas leakage region based on the location in which prevalent transport of warm saline waters is observed. This region spans from the tip of the African continental shelf to the oceanic subtropical front (37°–45°S) [Ruijter et al., 1999] and has a western limit established by the Good Hope transect [Swart et al., 2008] and an eastern limit at the point of retroflection (10°–20°E) [Loveday et al., 2014]. The box-averaged SST and SSS of this region were obtained to create a time series of SST and SSS changes.
in the Agulhas leakage region to further represent possible changes in Agulhas leakage dynamics. Note that Dencausse et al. [2010] defines the Agulhas retroflection loop as having an average position at 18°E meaning that the retroflection loop is present within our defined box for the Agulhas leakage region. However, the results of box-averaged time series are not observed as being largely skewed by the retroflection signal because the position of the retroflection loop is highly variable, and using the box-average mitigates the influence of extreme values that may come from retroflection interaction within the defined Agulhas leakage region.

A Pearson Product-Moment Correlation Coefficient analysis was performed to obtain Figure 2.11 representing the lag between the peak of ENSO signals and box-averaged SST and SSS at the point of Agulhas retroflection. The peak in ENSO signal was defined as the average ONI value during the peak (December–March) of defined El Niño or La Niña years. This was correlated with the 3-month running mean of box-averaged SST and SSS at monthly lag intervals from corresponding El Niño or La Niña years.

2.4 RESULTS

A. Sea Surface Temperature (SST) and Sea Surface Salinity (SSS) Signal Response to El Niño and La Niña

Figure 2.1 and Figure 2.2 illustrate the average AVHRR SST and SODA SSS anomalies during the peak, the following year, and two years after the peak (January to March) of all La Niña years and El Niño years, respectively (listed in Table 2.1). Figure 2.3 is an extension of Figure 2.1 and Figure 2.2 showing the continuation of the SSS
signal in the Agulhas leakage region in the months beyond two years following the peak of ENSO to up to three years following the peak of ENSO.

During the peak of La Niña, SST anomalies in the Indian Ocean basin are dominantly cool, excluding warming off the west coast of Australia (Figure 2.1a). This is opposite of El Niño where SST anomalies are dominantly warm excluding cooling off the coast of Australia (Figure 2.2a). In respect to SST, there is a single dominant warming (cooling) signal during El Niño (La Niña). The corresponding SSS is composed of two simultaneously occurring but contrasting signals each reflecting an area of either dominantly fresh or saline SSS. Furthermore, the original region of these anomalously fresh and saline signals switch during El Niño and La Niña. In other words, La Niña shows high salinity in the north-west in the Equatorial Indian Ocean with low salinity in the south-east near the coast of Sumatra (Figure 2.1b), and El Niño shows low salinity in the north-west with high salinity in the south-east (Figure 2.2b). Throughout the paper, this dual SSS signal is referred to as a primary signal and a secondary signal. The primary SSS signal is the region of anomalously low (high) SSS originating in the north-west Equatorial Indian Ocean during El Niño (La Niña). The secondary SSS signal refers to the anomalously high (low) SSS occurring simultaneously in the south-east Indian Ocean near the coast of Sumatra. If a zero-lag correlation were to exist between Agulhas leakage and ENSO, Figure 2.1a,b and Figure 2.2a,b would show that La Niña is related to warm saline leakage and El Niño is related to cool fresh leakage, respectively. However, the SST and SSS signal directly surrounding the African coast during the peak of ENSO does not correspond to the SST and SSS signal observed in the leakage region at this same
time. Near the tip of the African coast, waters are warm and saline (cool and fresh) during the peak of El Niño (La Niña).

When evaluating the SST anomalies for one year following an ENSO event, the established warming (cooling) trend identified during the peak of El Niño (La Niña) is now isolated near the region east of Madagascar at \(\sim 15^\circ–35^\circ\)S (Figure 2.1c and Figure 2.2c). The spatial variation of SSS identified during a peak ENSO event remains consistent into the next year, but the secondary signal is pushed further west and the primary signal surrounds Madagascar (Figure 2.1d and Figure 2.2d). One year after the peak of El Niño (La Niña), the dominant positive (negative) SST and the primary fresh (saline) SSS signal surround Madagascar.

The initial impact on Agulhas leakage from the propagating dominant SST signal and primary SSS signal is not strongly observed until two years after the peak of ENSO (Figure 2.1e,f and Figure 2.2e,f). At this time, the SST and SSS signal of Agulhas leakage exhibits opposite temperature and salinity trends for El Niño compared to La Niña. Two years after the peak of El Niño, Agulhas leakage is anomalously warm and fresh (Figure 2.2e,f). In contrast, two years after the peak of La Niña Agulhas leakage is anomalously cool and saline (Figure 2.1e,f). Note, this is the same signal that surrounded Madagascar the year prior. The initial primary fresh (saline) SSS signal in the Agulhas leakage region is replaced by the secondary saline (fresh) SSS signal, but the SST signal of Agulhas leakage remains consistent. The secondary SSS signal did not reach the Madagascan coast until April–June of two years after La Niña (Figure 2.3a) and January–March of two years after El Niño (Figure 2.2f). Therefore, interaction with Agulhas
leakage by the secondary saline (fresh) SSS signal occurs as late as the end of two years (start of three years) following El Niño (La Niña) (Figure 2.3d,f,g).

B. Variability of Agulhas Leakage in Response to Strength of El Niño Southern Oscillation (ENSO) Events

During the 36-year period between 1980–2016, a total of 11 El Niño and 10 La Niña events occurred (Table 2.1). The events varied in strength according to ONI values, with the strongest El Niño events occurring in 1982–1983, 1997–1998, 2015–2016 and the strongest La Niña event occurring in 1988–1989. Three El Niño years and five La Niña years are classified as weak events, while the majority of ENSO events are classified as moderate strength. Furthermore, the majority of El Niño events (6 events) directly transitioned to a La Niña episode the following year. However, between 2003–2007, three separate El Niño events occurred without a complete La Niña event in between. There were four occurrences in which a La Niña episode was directly followed by a second episode (Table 2.1). Both a strong and weak event for El Niño and La Niña was selected to explore the influence of ENSO strength on Agulhas leakage, as represented in Figure 2.4, Figure 2.5, Figure 2.6 and Figure 2.7. First and foremost, we analyze whether the individual ENSO events follow the same patterns of SST and SSS signal expression and propagation that was found in Section 2.3A for the average of all El Niño and La Niña events.

Beginning with the SST signal, we expect to see basin-wide warming (cooling) during the peak of El Niño (La Niña) that propagates westward the following year to surround Madagascar and east of Madagascar between 15°–35°S. Ultimately, two years
after the peak of El Niño (La Niña) Agulhas leakage responds by releasing anomalously warm (cool) water. The SST signals of all four individual ENSO events during the peak year show the basin-wide temperature trend that can also be identified the following year near the coast of Madagascar (Figure 2.4a,c, Figure 2.5a,c, Figure 2.6a,c and Figure 2.7a,c). A response in Agulhas leakage two years after the peak of ENSO is evident in both strong events as well as the weak El Niño (Figure 2.4e, Figure 2.5e, and Figure 2.7e). Note, warm waters from the strong El Niño event are seen in the Agulhas leakage region as early as one year after the peak (Figure 2.5c). The weak La Niña, however, shows a mix of both warm and cool waters in 2003, two years after the peak of La Niña. The expected cool waters dominate the leakage box itself, but an evident warm pool has formed off the southern tip of Africa moving into the Atlantic (Figure 2.6e).

Moving on to the SSS signal, we expect that during the peak of an El Niño (La Niña) the Indian Ocean basin should be anomalously fresh (saline) in the north-west and saline (fresh) in the south-east i.e., express the primary and secondary SSS signal respectively. The following year, the dual pattern of primary and secondary SSS signals should persist, but shifted to the west so that the primary fresh (saline) waters surround Madagascar with the secondary saline (fresh) waters to the east moving westward. Finally, two years following the peak of El Niño (La Niña) the Agulhas leakage region should initially express the primary fresh (saline) waters and later transition to the secondary saline (fresh) waters. The dual SSS signals of the Indian Ocean basin is evident in the strong El Niño (Figure 2.5b) and to a lesser extent in the weak El Niño (Figure 2.7b) but the strong and weak La Niña express only a single saline or fresh signal respectively (Figure 2.4b and Figure 2.6b). Surrounding or approaching the Madagascar
coast a year after the peak of ENSO, we see the expected primary saline signal for La Niña and primary fresh signal for El Niño for all events (Figure 2.4d, Figure 2.5d, Figure 2.6d, and Figure 2.7d). Finally, two years following the peak of ENSO, the strong La Niña shows anomalously fresh SSS because the expected primary saline signal is still near the Madagascan coast. It is important to note that this observed fresh signal is not indicative of the expected secondary signal due to the original dominant saline response in the Indian Ocean basin (Figure 2.4f). The weak La Niña, however, does show isolated areas of the expected primary saline leakage in 2003 with the secondary fresh signal observed surrounding Madagascar at the same time (Figure 2.6f). In comparison, the strong El Niño event expresses the expected primary fresh SSS signal as early as 1999 (Figure 2.5d). By the year 2000, the secondary saline signal is released in Agulhas leakage and continues to surround Madagascar (Figure 2.5f). The Agulhas leakage two years after the weak El Niño is a mix of the expected primary fresh SSS with some high-salinity waters. The expected high-saline secondary SSS signal is propagating toward Madagascar at this time (Figure 2.7f).

In addition, Figure 2.8 and Figure 2.9, showing the weak ENSO anomalies subtracted from the strong ENSO anomalies, support the observed differences between the strong and weak events and highlight other important variations. Positive (red) regions in these figures indicate that the stronger event expressed warmer SST or more saline SSS relative to the corresponding weak event. Negative (blue) values in these figures are indicative of cooler SST or fresher SSS anomalies during the strong event with respect to the corresponding weak event. The most noticeable difference between the strong and weak SST signal is the positive SST values in Figure 2.9c and negative
SSS values in Figure 2.9d of the Agulhas leakage region. Furthermore, two years after the peak El Niño, the Agulhas leakage of a strong El Niño is warmer than that of the weak El Niño excluding a small region where an anomalously warm core eddy was present in leakage during the weak event (Figure 2.9d). The intensity of the SST anomalies of Agulhas leakage is also greater during a strong La Niña than the weak La Niña, as shown by the negative anomalies in Figure 2.8e. The same can be said for the primary saline SSS signal during La Niña (Figure 2.8f). In general, the SSS during the strong La Niña event is more saline across the entire Indian Ocean than the weak event (Figure 2.8b), and the strong El Niño more strongly expresses the dual SSS signal (saline in the south-east and fresh in the north-west) compared to the weak El Niño event (Figure 2.9b).

C. Temporal Variability of ENSO Signal

A time series of box-averaged SST and SSS anomalies in the Agulhas leakage region is shown in Figure 2.10. We used this time series to evaluate the changes in the SST and SSS of Agulhas leakage in response to all ENSO events that have occurred between 1981–2016. From the previous sections, we have defined the type of SST and SSS response observed for La Niña events compared to El Niño. In this section, we are primarily interested in further identifying the lag between the peak of an ENSO event and the SST and SSS response of Agulhas leakage. A lead-lag correlation analysis for both SST and SSS to the ONI index for ENSO was performed, and the results are presented in Figure 2.11. This figure serves as a quantitative analysis of the following trends from the time series.
There are a few seasonal and decadal trends of Agulhas leakage that should be mentioned first. First and foremost, there is a natural yearly high to low fluctuation in SST and SSS. Additionally, after 2005 the SST and SSS show an increasing trend in which the anomalies rarely drop below zero. In general, the time series for SST and SSS closely mimic each other in shape, meaning that for observed peaks and dips in the SST time series there are corresponding peaks and dips in the SSS time series. A correlation analysis quantifies this association as having a correlation of 0.243. While this may seem low, it is important to notice that the SSS anomalies have a smaller range than SST anomalies, from $-0.4$ to $0.4$ and $-1.5$ to $1.5$, respectively. Also, the SSS trend line is shifted slightly right when compared to SST, thus explaining the low calculated correlation compared to what is observed in Figure 2.10. In the next paragraph, when we isolate trends with respect to ENSO events, it will become evident that SSS response shows the primary and secondary signal response, explaining why corresponding SSS response occurs later than that of SST.

When evaluating the time series with respect to ENSO events, we identify the anomalous SST and SSS values two years after the marked ENSO years. For all El Niño events, the SST trend line is strongly positive at this time and for all La Niña events, the SST trend line is strongly negative. Additionally, extreme values of SST are found to correspond to the strongest ENSO events. In particular in 2000, 2 years after a strong El Niño, the SST increases to nearly $1.2 \, ^\circ C$. With respect to SSS, the same patterns emerge but, as previously noted, the corresponding positive (negative) peaks (dip) occur slightly after the two-year mark of El Niño (La Niña) because these are related to the secondary SSS signal. At the two-year mark itself, the opposite primary negative (positive) SSS
signal is evident. Notably, more than two years after a strong El Niño event (1982–1983) an extreme SSS dip of nearly −0.2 is observed.

An additional lead-lag correlation analysis of the SST and SSS to the ONI ENSO index is included in order to analyze the time series with more precise quantitative measurement of the delay in response between the peak of ENSO and Agulhas leakage response. A positive correlation indicates that as the ENSO index strengthens, the anomalous SST and SSS is also increasing, meaning the Agulhas leakage is anomalously warm and saline. The opposite can be said for a negative correlation, as ENSO strength increases the SST and SSS are decreasing, meaning the Agulhas leakage is anomalously cool and fresh. During a La Niña event, it is expected that SST should have a negative correlation and the SSS should first show a positive correlation followed by a negative correlation, indicative of its primary and secondary SSS signal. Figure 2.11 indicates that the La Niña SST of Agulhas leakage has a positive correlation with the ONI index until 24 months after the peak of La Niña. A decrease in correlation begins as early as 20 months and continues on until the greatest negative correlation at 30 months after the peak of La Niña events. The corresponding SSS signal during La Niña is also dominantly positive, with the strongest positive correlation at a 20-month lag. After this peak, the correlation drastically decreases until the greatest negative correlation at a 26-month lag continuing to a 30-month lag. The same monthly lags apply to the El Niño SSS correlation but with the opposite sign: a negative correlation transitioning to a positive correlation. The SST correlation with El Niño is also opposite to that observed during La Niña. Most importantly, an increasing correlation is present at a 24-month lag for El Niño SST, which peaks with the strongest positive correlation at about a 34-month lag.
2.5 Discussion

A. SST and SSS Signal Response to El Niño and La Niña

According to Putrasahan et al. [2016] and others, changes to circulation patterns coupled with Rossby wave propagation and wind-stress curl carry an ENSO signal from the Pacific, across the Indian Ocean, to alter Agulhas leakage. Putrasahan et al. [2016] proved this connection by correlating warmer waters in the Agulhas leakage region to El Niño. We use this established connection to discuss the differences in the SST and SSS signal with respect to El Niño events compared to La Niña events, as presented in Section 2.3A.

The observed SST signal of basin-wide warming (cooling) during El Niño (La Niña) from Figure 2.2a (Figure 2.1a) is consistent with the findings of Kug and Kang [2006] and Kilpatrick et al. [2001] corresponding to fluctuations in Walker Circulation and easterly (westerly) wind anomalies over Indonesia during the boreal winter/spring. The observed regions of positive and negative SSS in Figure 2.1b and Figure 2.2b can be attributed to the influence of anomalous ENSO conditions as well as coincident positive (negative) Indian Ocean Dipole (IOD) with El Niño (La Niña). Primarily, easterly (westerly) winds drive upwelling (downwelling) along the Sumatra coast, explaining the observed secondary signal of positive (negative) SSS anomalies further enhanced by reduced (increased) rainfall created from the atmospheric circulation patterns of El Niño (La Niña). The negative primary SSS signal observed in the equatorial Indian Ocean during El Niño is explained by horizontal advection of low salinity waters from the Bay
of Bengal, while the primary positive SSS in the equatorial Indian Ocean during La Niña is produced by eastward-flowing Wyrtki jets [Grunseich et al., 2011].

A zero-lag SST and SSS response of waters near the tip of Africa is most likely related to changes in southern African rainfall associated with ENSO-driven SST patterns in the Pacific rather than ENSO SST and SSS signal transmission. Most of the severe droughts have happened during the mature phase of El Niño and the wettest summers during La Niña [Richard et al., 2000]. Decreased (increased) rainfall could explain the observed salinization (freshening) along the coast during El Niño (La Niña). Additionally, weaker (stronger) upwelling favorable winds are present during El Niño (La Niña), and this ultimately creates conditions in which SST is anomalously warm (cool) during El Niño (La Niña). This positive correlation between ENSO and SST and SSS properties applies only to the south coast of Africa, while a negative correlation exists with the Agulhas Current system south of 36°S [Rouault et al., 2010]. In other words, it is highly unlikely that ENSO influences the SST or SSS signal of Agulhas leakage during the peak of the ENSO event. Instead, it is possible that atmospheric-related weather patterns associated with ENSO alter the SST and SSS conditions near the southern tip of Africa, explaining the observed changes to that region in Figure 2.1a,b and Figure 2.2a,b.

One year after the peak of ENSO, both the dominant SST signal and the dual SSS signal have shifted westward. The previous basin-wide trend in SST is isolated near the region east of Madagascar at ~15°–35°S. Note, this is the latitude where the SEC is found [Palastanga et al., 2006], supporting the idea that the SEC is involved in signal transmission. Grunseich et al. [2011] attributes the westward movement of the SSS signal
to Rossby waves associated with the westward flowing SEC. Most importantly, the SST signal and primary SSS signal surround Madagascar to interact with the source currents, which has the potential to influence eddy formation of the EMC and MC, thus continuing on to impact Agulhas leakage. This impact is initially seen two years after the peak of ENSO, as expected by the Putrasahan et al. [2016] study. However, Putrasahan et al. [2016] did not identify the continuation of this impact occurring for nearly 3 years after the peak of an El Niño (La Niña). During this time, the SST signal is consistently positive (negative) but the original primary fresh (saline) SSS signal is replaced by the secondary saline (fresh) SSS signal. Further evidence supporting the lag in response of Agulhas leakage is discussed in Section 2.4C. From Figure 2.1, Figure 2.2 and Figure 2.3, representing the average response of SST and SSS to ENSO events, we have established that both the SST and SSS signal of Agulhas leakage have a contrasting response to an El Niño versus a La Niña event. A single opposite SST signal occurs two years after the peak of El Niño as compared to La Niña, warming and cooling respectively. The SSS response is composed of the initial primary signal followed by the opposite secondary signal. First, the SSS of Agulhas leakage is anomalously fresh (saline) two years after the peak of El Niño (La Niña). In the following months, this anomalously fresh (saline) signal is replaced by the secondary saline (fresh) SSS signal in Agulhas leakage. Furthermore, these figures provide a general understanding of the transmission of an ENSO signal. The signal originates in the Pacific Ocean and during the peak of an ENSO event (December–March) it moves into the Indian Ocean basin, changing SST and SSS properties. The following year, the SST and SSS signals propagate westward across the Indian Ocean basin to surround Madagascar and begin to influence the Agulhas Current.
Strong changes to Agulhas leakage are observed two years following an ENSO event and continue for nearly three years after ENSO. This process is consistent with the circulation, Rossby wave, eddy process, and wind curl explained in the Introduction. The next section explores how the strength of an ENSO event alters this signal formation and transmission.

B. Variability of Agulhas Leakage in Response to Strength of ENSO Events

Figure 2.4, Figure 2.5, Figure 2.6 and Figure 2.7, showing individual ENSO events of either strong or weak strength, were analyzed in Section 2.3B for any deviations from the established SST and SSS trends identified in Section 2.3A. Deviations from this established trend may be indicative of the interaction of ENSO strength on SST and SSS expression. With respect to the SST signal, the only deviation in signal propagation occurred near the Agulhas leakage region. During the strong El Niño episode, warm waters appeared a year earlier than expected and during the weak La Niña episode an evident warm pool formed off the southern tip of Africa contrasting the cool waters in the Agulhas leakage region. This warm pool occurred two years after the peak of the weak La Niña event in 2003. That year was also the peak of the 2002–2003 El Niño. In Section 2.4A, we explained that atmospheric circulation associated with ENSO is known to cause warming near the tip of Africa, thus explaining this mixed signal during the weak La Niña.

There were several deviations from the established trend in the SSS signal. In particular, during the peak of La Niña for both the strong and weak event, there was only a saline or fresh signal, respectively, instead of the expected dual primary and secondary
signals evident in both the El Niño episodes. The peak of the strong La Niña event, 1989, is also a negative IOD year that peaks in July [De Ruijter et al., 2004], which may explain the strongly negative SSS signal. Furthermore, the clear dual SSS signal of the strong El Niño can partially be attributed to the positive IOD that peaked in November of 1998 [De Ruijter et al., 2004]. The lack of any IOD influence may have inhibited the strong expression of an anomalous negative SSS in the north-western region during the weak La Niña. Regardless, the westward propagation of the SSS signal occurred as expected in all events. However, the influence of the primary SSS signal on Agulhas leakage, expected to occur two years following the peak ENSO event, was not consistent in all events. The primary signal was delayed in the strong La Niña event and appeared nearly a year early in the strong El Niño event. Interestingly, the primary signal was present in the Agulhas leakage two years after both the weak El Niño and La Niña. The mix of low salinity waters with the expected primary saline signal in Agulhas leakage two years after the weak El Niño may be the result of weak signal strength. While the primary fresh signal was present in the north-western Indian Ocean basin during the peak of this El Niño, it was not strong relative to the secondary saline signal, which may explain the corresponding weak expression in Agulhas leakage.

Trends identified in Figure 2.8 and Figure 2.9, highlight important differences between the strong and weak events and provide further support for the signal transmission discussed. The warm fresh Agulhas leakage signal was identified previously as occurring nearly a year earlier during a strong El Niño. This is further supported by the positive and negative SSS values identified in the Agulhas leakage region (Figure 2.9c,d). The stronger anomalies identified in the Agulhas leakage region with respect to strong
ENSO events indicate that ENSO strength is proportional to signal strength. Lastly, the trends referring to the expression of SSS in the Indian Ocean are most likely attributed to the IOD influence previously mentioned rather than differences in ENSO strength.

In conclusion, the established SST and SSS signal response to El Niño and La Niña is consistent for all events of varying ENSO strength, but the strength appears to influence the intensity of the signal and the time of its transmission, thereby explaining any variations from the established trends. In general, increasing ENSO strength increases the extremes of the resulting anomalous signal and impacts the Agulhas leakage region earlier during El Niño and slightly later during La Niña. As previously discussed, weakened trade winds in the Pacific and resultant strengthened trade winds in the tropical Indian ocean create a zonal band of positive wind-stress curl over the tropics which Putrasahan et al. [2016] correlated to the Agulhas leakage response. Knowing this, we can support this observed variation in time of signal propagation with ENSO phase and strength to a corresponding change in the strength of wind-stress curl [Feng and Meyers, 2005]. As trade winds strengthen in the tropical Indian Ocean during stronger El Niño events, a corresponding increase in wind-stress curl would be expected across the tropical Indian Ocean, providing increased propagation of the SSS and SST signals. The opposite can be said for stronger La Nina events which correspond to further weakening of trade winds in the tropical Indian Ocean and a corresponding decrease in wind-stress curl slowing propagation of the SSS and SST signals. This temporal perspective is further explored in the next section.
C. Temporal Variability of ENSO Signal

In Section 2.3C, we used the time series (Figure 2.10) to evaluate changes in the SST and SSS of Agulhas leakage for all ENSO events between 1981–2016. We also conducted a quantitative analysis of the trends from the time series using the lead–lag correlation analysis in Figure 2.11. Explaining the seasonal trends in the time series helps to better understand how the Agulhas leakage SST and SSS time series is changing with respect to ENSO. The naturally annual fluctuations in SST and SSS are likely attributed to a seasonal signal related to changes in current speed [Krug and Tournadre, 2012]. The increasing trend in the time series after 2005 could be indicative of a decadal warming trend observed in the Agulhas Current region [Rouault et al., 2009] and an increase in leakage in response to shifting Southern Hemisphere westerlies [Biastoch et al., 2009].

When evaluating the time series with respect to ENSO events, we evaluated the anomalous SST and SSS values two years after the marked ENSO years, because the time series represents a box average of Agulhas leakage and in the previous sections the initial response of Agulhas leakage to the ENSO signal was found at this time. The trends in the time series at this time support the temporal perspective of both the primary and secondary SSS signal and the single dominant but lasting SST signal observed in the Agulhas leakage region.

The time series in Figure 2.10 only serves to provide a general qualitative analysis of the trends found in the previous sections and the time during which they are taking place. The lead–lag correlation analysis of the SST and SSS to the ONI ENSO index in Figure 2.11 supports this analysis with a more precise quantitative measure of the
delay in response between the peak of ENSO and the Agulhas leakage response. The trends identified in Figure 2.11 support the existence of a single SST response of Agulhas leakage to ENSO, and this response has an average lag of ~20 months that persists and strengthens until a lag of nearly 30 months. Additionally, the dual primary and secondary signal response of the SSS of Agulhas leakage to ENSO is supported in Figure 2.11. The primary SSS signal has an average lag of ~20 months followed by the opposite secondary SSS signal at a lag of ~26 months.

2.6 Conclusions

Thus far, we have explored yearly fluctuations in Agulhas leakage using anomalous SST from AVHRR and SSS from SODA reanalysis. Figure 2.1 and Figure 2.2 show that the response of Agulhas leakage to an El Niño event is opposite to that of a La Niña event for both SST and SSS. The single dominant SST response of Agulhas leakage occurs around 20 months and continues for nearly 30 months after the peak of ENSO and is anomalously high for El Niño and anomalously low for La Niña. At the same time, the corresponding SSS signal is anomalously saline for La Niña and fresh for El Niño. However, the SSS signal is composed of this initial primary signal, which reaches the region first, followed by the secondary signal that reaches Agulhas leakage about 26 months after the peak of ENSO. The secondary signal is fresh for La Niña and saline for El Niño. Additionally, Figure 2.3, Figure 2.4, Figure 2.5, Figure 2.6, Figure 2.7, Figure 2.8, Figure 2.9 and Figure 2.10 suggest ENSO strength influences the intensity of both the signal and the time of its transmission. In general, increasing ENSO strength increases the extremes of the resulting anomalous signal and impacts the Agulhas leakage region earlier during El Niño and slightly later during La Niña.
Correlation observations from Figure 2.11 support the Putrasahan et al. [2016] proposed 2-year period for an ENSO signal to influence Agulhas leakage and also establishes the lags for the primary and secondary SSS signal response of Agulhas leakage.

The aim of this study was only to highlight that a relationship between ENSO and Agulhas leakage exists and define this relationship using SST and SSS, as well as to identify the time in which this response lags an ENSO event. We also explored the effect of ENSO strength on this relationship. Most notably, this study evaluates this process from start to finish to not only show that ENSO-generated SST and SSS signals influence Agulhas leakage, but also where these signals originate and how they propagate, providing a visual and qualitative representation of the connection between the Pacific, Atlantic, and Indian Ocean. Further investigation is required to understand the dynamics of the various systems involved in this relationship and signal propagation. Suggestions for future work include addressing how the eastern and central modes of El Niño may change this relationship. Furthermore, the depth signal of this described trend is another important parameter worth considering. This paper relied primarily on AVHRR SST and SODA SSS. Both data sets have been used in countless previous studies to explore the Indian Ocean basin or Agulhas current system and have been proven reliable for doing so [Grunseich et al., 2011; Rouault et al., 2010]. However, it is important to note some issues with these data sets that may have influenced the results. Specifically, when conditions deviate from the mean atmosphere and ocean conditions, errors arise in AVHRR SST retrieval [Kilpatrick et al., 2001]. Therefore, AVHRR is unable to perform properly under cloudy conditions and direct sunlight, and we mentioned earlier that rainfall events are an expected response to La Niña events. The full intensity of SST
readings may, therefore, be compromised due to interpolation to account for missed readings due to cloud or direct sunlight interactions. Future studies may benefit from using another data source for SST and compare the findings. Additionally, SSS from SODA is reanalysis-based. Observational comparisons would be beneficial to further support the findings in this paper.

We include an additional figure, Figure 2.12, to show that recent salinity missions will be valuable resources for future work in this field. Figure 2.12 highlights the SSS signal from SMOS of the most recent El Niño event (2015–2016). SMOS is able to provide a more accurate representation than previously available models. Also, recently launched (launch date: 31 January 2015 and data availability since April 2015) Soil Moisture Active Passive (SMAP) derived salinity will be useful in ENSO studies.
Table 2.1: El Niño Southern Oscillation (ENSO) phase years between 1981–2015.

<table>
<thead>
<tr>
<th>El Niño</th>
<th>La Niña</th>
<th>Neutral</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015–2016 ¹</td>
<td></td>
<td>2001</td>
</tr>
</tbody>
</table>

¹ Strong ENSO event; ² weak ENSO event.
Figure 2.1: Composite mean for all La Niña events listed in Table 2.1 from January–March for both Advanced Very High Resolution Radiometer (AVHRR) sea surface temperature (SST) anomalies (left column) and Simple Ocean Data Assimilation (SODA) sea surface salinity (SSS) anomalies (right column) during the peak (a,b), the following year (c,d), and two years after (e,f). The boxes represent the established leakage region (37°–45°S, 10°–20°E).
Figure 2.2: Same as Figure 2.1 except for all El Niño events listed in Table 2.1 during the peak (a,b), the following year (c,d), and two years after (e,f).
Figure 2.3: Composite mean of SODA SSS anomalies for all La Niña events (left column) and for all El Niño events (right column) listed in Table 2.1 two years after the peak for April–June (a,b), July–September (c,d), October–December (e,f), and three years after the peak for January–March (g,h). The boxes represent the established leakage region (37°–45°S, 10°–20°E).
Figure 2.4: Composite mean for strong 1988–1989 La Niña event from January-March for both AVHRR SST anomalies (left column) and SODA SSS anomalies (right column) during the peak (a,b), the following year (c,d), and two years after (e,f). The boxes represent the established leakage region (37–45°S, 10–20°E).
Figure 2.5: Same as Figure 2.4 except in reference to the strong 1997–1998 El Niño event during the peak (a,b), the following year (c,d), and two years after (e,f).
Figure 2.6: Same as Figure 2.4 except in reference to the weak 2000–2001 La Niña event during the peak (a,b), the following year (c,d), and two years after (e,f).
Figure 2.7: Same as Figure 2.4 except in reference to the weak 2004–2005 El Niño event during the peak (a,b), the following year (c,d), and two years after (e,f).
Figure 2.8: Composite mean for strong 1988–1989 La Niña minus the weak 2000–2001 La Niña from January–March for both AVHRR SST anomalies (right column) and SODA SSS anomalies (left column) during the peak (a,b), the following year (c,d), and two years after (e,f). The boxes represent the established leakage region (37°–45°S, 10°–20°E).
Figure 2.9: Same as Figure 2.8 except in reference to the strong 1997–1998 El Niño minus the weak 2004–2005 El Niño during the peak (a,b), the following year (c,d), and two years after (e,f).
Figure 2.10: Time series from 1981–2016 for monthly box-averaged (37°–45°S, 10°–20°E) AVHRR SST (solid line) and SODA SSS (dashed line) anomalies. ENSO events are represented during their peak (January–March) by vertical shaded bars (red for El Niño and blue for La Niña).
Figure 2.11: Correlation analysis between absolute values of Oceanic Niño Index (ONI) index and box-averaged AVHRR SST anomalies (solid line) and SODA SSS anomalies (dashed line) at monthly lag intervals for El Niño years in red and La Niña years in blue.
Figure 2.12: Composite mean of Soil Moisture Ocean Salinity (SMOS) SSS anomalies from January–April (first column), May–August (middle column) and September–December (last column) during the most recent El Niño event starting and stopping in 2014 (top row), restarting in 2015 (middle row), and reaching its peak in 2016 (bottom row).
CHAPTER 3

Propagation of ENSO Signal Across the Indian Ocean to the Agulhas Current System

3.1 Abstract

This study explores the complex connection between El Niño Southern Oscillation (ENSO) that originates in the Pacific Ocean and the response of the Indian Ocean to influence Agulhas leakage. In particular we use sea surface salinity (SSS) from Simple Ocean Data Assimilation (SODA) reanalysis and sea surface temperature (SST) from the Advanced Very High Resolution Radiometer (AVHRR) to analyze the surface response in the Indian Ocean basin during the peak of an ENSO event and two years later near the Agulhas retroflection region for an expected response in the Agulhas leakage. The subsurface response is studied using Argo float data. In addition, sea surface height (SSH) data from AVISO is used to examine the propagation of ENSO signal across the Indian Ocean to the Agulhas leakage region. Of particular interest in this paper is exploring how the subsurface temperature and salinity anomalies are influenced by the propagation of ENSO signal in the Indian Ocean basin and ultimately Agulhas leakage. The results indicate that during the peak of an ENSO event the Indian Ocean basin is anomalously warm at the surface to a depth of 500 meters in response to El Niño but anomalously cool and of comparable magnitude in response to La Niña. The SSS is anomalously fresh for both events in the eastern and western Indian Ocean basin but the underlying subsurface salinity signal during El Niño is anomalously saline to about 150 meters in both basins. The basin wide trends persist in the subsurface longer than those at the surface, for about a year after the peak of ENSO in the in the eastern Indian Ocean basin and nearly two years after the peak of ENSO in the western Indian Ocean basin. Hovmöller diagrams at 12°S and 25°S indicate the westward propagation of high (low) SSH anomalies across the Indian Ocean basin during El Niño (La Niña). It takes two
years for the initial signal from Rossby waves propagating at 12°S to reach Agulhas leakage region after the peak of an ENSO event. This signal is anomalously warm two years after El Niño and anomalously cool two years after La Niña. Once again, this signal is also reflected in the subsurface of the Agulhas leakage region.

3.2 Introduction

El Niño Southern Oscillation (ENSO) originates in the equatorial Pacific Ocean but its influence reaches far beyond the Pacific Ocean’s boundaries. Air-sea interactions involved in the formation of El Niño and La Niña conditions have been linked to both temperature and salinity anomalies in the Indian Ocean [Kug and Kang, 2005; Grunseich et al., 2011]. In particular, fluctuations to Walker Circulation during an ENSO event alter the wind variability over the eastern Indian Ocean in turn changing sea surface temperature (SST) in the Indian Ocean basin [Kug and Kang, 2005]. A dominant basin wide warming (cooling) response during El Niño (La Niña) is observed in the boreal winter-spring [Bernal et al., 2001] due to the persistence of easterly (westerly) surface winds over the eastern Indian Ocean that suppress (enhance) convective activity increasing (decreasing) the underlying temperatures ultimately causing basin wide temperature patterns [Tokinaga and Tanimoto, 2004]. At the same time, these anomalous easterly (westerly) winds promote upwelling (downwelling) along the Sumatra coast bringing cool (trapping warm) waters to the surface. These anomalous winds force a westward downwelling (upwelling) Rossby wave that deepens (shallows) the thermocline in the western Indian Ocean. As a result, in boreal autumn previously basin-wide patterns of SST changes to a dipole like pattern in which the eastern Indian Ocean basin is anomalously cool (warm) and the western Indian Ocean basin is anomalously warm
A similar response in sea surface salinity (SSS) is seen in which during El Niño (La Niña) large freshening (salting) occurs in the southwestern Indian Ocean with a coincident salting (freshening) off the southern Sumatra coast [Grunseich et al., 2011].

The Indian Ocean is also linked to the Pacific Ocean by two major physical pathways north and south of Australia via the Indonesian Throughflow (ITF) and Tasman leakage (TL) [Durgadoo et al., 2017]. Both of which are also considered source waters for Agulhas leakage contributing about 12.6 Sv (1 Sv = 10⁶ m³s⁻¹) to Agulhas leakage including recirculation from frontal regions of the Southern Ocean. Nearly half of this contribution, about 6.1 Sv, comes from the ITF. The ITF is composed of relatively fresh surface waters and saltier intermediate waters with a wide temperature range [Gordon et al., 1997] that feed into the South Equatorial Current (SEC). These waters are primarily concentrated in the top 600 m between the island of Java and 13°S with an estimated total transport range of 10.7 to 18.7 Sv into the Indian Ocean [Sprintall et al., 2009]. Evidence by Le Bars et al. [2013] shows a co-dependency between ITF transport and Agulhas Leakage. An increase in Agulhas leakage, or an increased number of eddies released into the Atlantic Ocean, is linked to an increase in ITF. Furthermore, the transport of the ITF has been found to change in response to ENSO. The ITF transport is enhanced in response to the La Niña phase and decreased in response to the El Niño phase [Meyers, 1996] with the ITF lagging the ENSO cycle by 8-9 months [England et al., 2005]. The contribution to Agulhas leakage from the second pathway, TL, is much less at about 1.4 Sv. In general, the westward transport of TL into the Indian Ocean to feed the south
Indian sub-tropical gyre occurs at intermediate depths of 500 to 1000 meters between Australia and 40°S and contributes about 16 Sv [Durgadoo et al., 2017].

It is evident that both air-sea interactions and physical connections between the Pacific Ocean and Indian Ocean change the properties of the Indian Ocean in response to ENSO. It is also clear that Rossby waves link the circulation of the south Indian Ocean to Agulhas leakage. A study by Schouten et al. [2002] identified two bands of enhanced variability east of Madagascar at 12°S and 25°S marking the preferred routes along which ENSO generated anomalies propagate westward as baroclinic Rossby waves. As previously mentioned, easterly (westerly) wind anomalies produced during El Niño (La Niña) generate westward propagating Rossby waves [Feng and Meyers, 2003] thus explaining the SSH variability at 12°S. The SSH variability at 25°S is explained by the existence of the subtropical North Pacific Pathway. By this pathway, North Pacific Rossby waves associated with ENSO impinge on the east coast of Australia moving equatorward as coastally trapped Kelvin waves where they are finally released into the Indian Ocean as the secondary set of ENSO associated Rossby waves at 25°S [Cai et al., 2005].

This paper explores changes in temperature and salinity in the water column of the Indian Ocean basin in response to ENSO events and how these changes at depth are further propagated across the Indian Ocean basin to influence the Agulhas Current and ultimately alter Agulhas leakage dynamics. Agulhas leakage occurs at the southern tip of Africa where the Agulhas Current retroflects releasing warm, saline waters from the Indian Ocean into the Atlantic in the form of Agulhas rings, eddies, and filaments [Beal et al., 2011]. This is the only connection between the Indian Ocean and Atlantic Ocean
and this Agulhas leakage continues to feed the upper arm of the Atlantic Meridional
Overturning Circulation. Understanding changes in leakage dynamics is important to
understanding the continuing impact to the strength of overturning cell sequentially
altering climate patterns.

3.3 Data and Methods

A. Satellite Data

We have used the NOAA’s National Climatic Data Center provided version 2 of
the Advanced Very High Resolution Radiometer (AVHRR) SST data from October 1981
to December 2015 at daily intervals with a 4 km resolution (http://iridl.ldeo.columbia.edu/SOURCES/.NOAA/.NCDC/.OISST/.version2/.AVHRR/.sst/). We have used the AVISO Version 1 sea level anomalies data from 1993 to 2015,
which are Ssalto/Duacs altimeter products produced and distributed by the Copernicus
Marine and Environment Monitoring Service (CMEMS) (http://www.marine.copernicus.eu). The sea level anomalies represent variations of the
SSH relative to the mean sea surface over a 20 year reference period from 1993-2012.
These values were provided daily from a gridded data set at 0.25° x 0.25° resolution. For
the purposes of our study, monthly averages of both SST and SSH anomalies were
computed from the daily files.

B. Simple Oceana Data Assimilation (SODA) Reanalysis

The Simple Ocean Data Assimilation (SODA) reanalysis is an ocean reanalysis
system. The version 3.3.1 monthly averaged salinity data spans from January 1980 to
December 2015 at 0.25° x 0.25 spatial resolution and a 40 level depth resolution from 5
to 2,000 meters depth. Like Argo, the top-most SODA salinity measurement is at 5 meter depth. *Carton and Giese* [2008] provides a comprehensive description of the SODA reanalysis product, but a brief summary is provided here. This SODA product is a combination of an ocean model based on the Parallel Ocean Program (POP) and data assimilation [*Giese and Ray*, 2011]. The POP model includes relaxations to climatological SSS on a 3-month timescale. It is important to note that the data assimilation uses salinity profiles obtained through the World Ocean Database, which includes Argo floats. For comparisons with Argo, the spatial resolution is reduced to a 1°x1°. SSS anomalies are calculated by removing the monthly means averaged from January 1980 to December 2015.

*C. In-situ Observations of Argo Temperature and Salinity*

Temperature and salinity profile data are provided by Argo floats and this data was downloaded from the Asia Pacific Data Research Center (APDRC), University of Hawaii. This data is available at monthly intervals with 1°x1° horizontal resolution from January 2005 through December 2014 at 29 depth levels up to a maximum depth of 2000 meters (http://apdrc.soest.hawaii.edu/datadoc/Argo_iprc.php).

*D. Oceanic Niño Index*

ENSO events are determined using the Oceanic Niño Index (ONI) from the National Weather Service and Climate Prediction website (http://www.cpc.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml). ONI calculates ERSST.v4 SST anomalies in the Niño 3.4 region (5°N-5°S, 120-170°W) with an applied 3-month running mean and is based on a centered 30-year base period updated
every 5 years. El Niño events are classified as having ONI value at or exceeding +0.5°C anomaly threshold for 3 consecutive months and La Niña events as having an ONI value at or below -0.5°C anomaly for 3 consecutive months. This classification process is consistent with that used by NOAA’s Climate Prediction Center (http://www.cpc.ncep.noaa.gov/).

E. Methods

The monthly SST interannual anomalies used throughout the study are obtained by computing the average monthly SST from the full AVHRR data set (1981-2015) and subtracting them from the monthly average of a given year to remove the seasonal SST climatology from the monthly SST data. The same process is used for SSS anomalies except using SODA reanalysis for the period 1980-2015. Additionally, Argo salinity and temperature anomalies over the depth from surface to 500 m are obtained by the same process, except calculated for each depth range over the full time-series for the period 2005-2014.

We define the Agulhas leakage region based on the location in which prevalent transport of warm, saline waters is observed. This region spans from the tip of the African continental shelf to the oceanic subtropical front (37°S-45°S) [Ruijter et al., 1999] and has a western limit established by the Good Hope transect [Swart et al., 2008] and an eastern limit at the point of retroflection (10°E-20°E) [Biastach et al., 2015]. Note Dencausse et al. [2010] defines the retroflection region as having an average position at 18°E, within our defined box average. However, the results are not observed as being largely skewed by retroflection signal because the position of this area is highly variable.
and the average mitigates the influence of extreme values that may come from retroflection interaction. Furthermore, box regions are also considered in the eastern and western Indian Ocean region. The eastern Indian Ocean box spans from 90°-105°E to 0°-20°S while the western Indian Ocean box spans from 60°-80°E to 10°-30°W. The eastern box is placed at such a position so to capture where ENSO signal response originates and also interaction of the Indonesian Throughflow. The position of the western box is designed to capture signal propagation as it approaches the source currents while avoiding interaction with the East Madagascar Current retroflection. This box includes both the South Equatorial Current and region of Rossby wave propagation. The box averaged salinity and temperature of these regions were obtained to create a time-series at depth from Argo data.

3.4 Results and Discussion

A. Penetration of Surface Signal in Subsurface Depths

For the purpose of this paper, the years 2007-08 and 2009-10 have been chosen for La Niña and El Niño events respectively. Records from NOAA’s National Centers for Environmental Information State of the Climate (https://www.ncdc.noaa.gov/sotc/enso/200813) state that the La Niña episode developed during September of 2007 but did not peak until February 2008, corresponding to the coldest SST anomalies in the Niño 3.4 region (5°S-5°N and 170°-120°W), and it lasted until March 2008. This is consistent with the ONI, showing anomalous SST values at or below -0.5°C during this time with minimum value of -1.6°C. The El Niño episode developed early May 2009 and reached its peak in late December 2009 before breaking
down and returning to neutral conditions by April 2010. Once again, this timeline is supported by the ONI with values at or greater than 0.5°C during this period and as high as 1.6°C at its peak. These years were evaluated for SSH, salinity, and temperature changes in the Indian Ocean basin associated with the propagation of ENSO signal. Furthermore, the SSH, salinity, and temperature conditions were analyzed two years following the peak of these ENSO events to determine whether ENSO signals further affected the Agulhas Current and ultimately Agulhas leakage.

Figure 3.1 represents the La Niña episode and Figure 3.2 represents the El Niño episode. Both figures show the anomalies of SSH, SSS, and SST averaged over the January to March period during ENSO and 2 years after the peak ENSO event. Therefore, what these figures actually represent is the variation in the response of the Indian Ocean to La Niña (Figures 3.1a-c) as compared to El Niño (Figures 3.2g-i). Additionally, the January to March period averaged panels of two years after the ENSO event represent the propagation of this signal to the area of primary concern, Agulhas leakage (Figures 3.1d-f and Figures 3.2j-l).

Beginning with the patterns of anomalous SST (Figures 3.1b,e and Figures 3.2h,k), an opposite response is associated with La Niña as compared to El Niño. Figure 3.1b shows anomalously cooler SST in both box regions of the Indian Ocean basin (box b1 and box b2) while Figure 3.2h shows anomalously warmer SST predominant in the western Indian Ocean basin (box h2). This anomalous signal stays consistent in box e1 (Figure 3.1e) as well as in box k1 (Figure 3.2k) representing the Agulhas leakage region. These figures support the predicted basin wide warming and cooling trends observed by Tokinaga and Tanimoto [2004] in response to El Niño and La Niña respectively.
However, it appears that the basin wide warming in response to El Niño (Figure 3.2h) has already begun to transition to the dipole like pattern where warming is concentrated in the western Indian Ocean basin.

The SSS does not show an opposite response. Instead, both El Niño and La Niña indicate a sea surface freshening response but the spatial patterns varies between the events (Figures 3.1c,f and Figures 3.2i,l). Figure 3.1c shows this freshening in and around box c1 of the eastern Indian Ocean basin, while Figure 3.2i shows a dominantly freshening signal in box i2 of the western Indian Ocean basin. This distribution pattern is most likely attributed to upwelling along the Sumatra coast during El Niño and downwelling during La Niña resulting in the salting and freshening respectively observed off the Sumatra coast by Grenseich et al. [2011] study. The fresh surface waters of the ITF may also contribute to the fresher waters observed during La Niña because La Niña episodes enhance the ITF transport [Meyers, 1996]. Regardless of the spatial variation, two years after the peak of ENSO, freshening is seen in both Figure 3.1f and Figure 3.2l but it is more widespread in box f1 than on box l1 in the Agulhas leakage region. La Niña appears to result in a stronger freshening SSS signal of Agulhas leakage.

The anomalous SSH signal can be evaluated using Figures 3.1a,d and Figures 3.2g,j. In the context of signal propagation we are primarily focused on the latitudes 12°S and 25°S indicated respectively by lines a1 and g1 and the lines a2 and g2 (Figure 3.1a and Figure 3.2g). Warm fresh waters are associated with anomalously positive SSH while cold saline waters are associated with anomalously negative SSH. In Figure 3.1a there is a widespread and strongly negative SSH signal along line a1 at 12°S. This signal appears along line a2 as well but as several smaller isolated regions. This is the same region
previously identified as displaying a basin wide cooling trend. The anomalously low SSH is also seen at the eastern extent of line g2 but isolated near the northern coastline of Australia and near the ITF region rather than the Indian Ocean basin (Figure 3.2g). It should be noted at this same position in Figure 3.2h, a strongly negative SST is present and to a lesser extent negative SSS in Figure 3.2i. Furthermore, in both the Figures 3.1d and 3.2j alternating regions of anomalously high and low SSH are found in the Agulhas current and near the retroflection region suggesting eddy propagation at this time (line d1 and j1 respectively).

To better understand SSH in the context of signal propagation Hovmöller diagrams were constructed at 12°S and 25°S showing anomalous SSH across the Indian Ocean basin from 50°E to 110°E with time from January 2007 to January 2012 (Figure 3.3). In each diagram, alternating bands of positive and negative SSH suggest the westward propagation of Rossby waves. Estimates of the theoretical speed of Rossby waves at 12°S and 25°S, based on Killworth et al. [1997] numerical calculations, are about 15 cm/sec and 5 cm/sec respectively. The steep diagonal bands of connected negative or positive SSH at 25°S compared to the more shallow bands at 12°S indicate faster speed at 12°S than at 25°S, as expected. The propagation speed at 12°S calculated from line a1 and g2 (Figure 3.3) is 15.57 cm/sec, comparable to the theoretical value of 15 cm/sec. The propagation speed calculated from line a2 at 25°S is 6.92 cm/sec which is also similar to the theoretical value of 5 cm/sec.

It should be noted that Figure 3.3 also isolates the Rossby wave SSH signal trigged by La Niña and El Niño as indicted by line a1, a2 and g1, g2 respectively. At both 12°S and 25°S, lines a1 and a2 correspond to the movement of a low band of SSH across
the Indian Ocean. In comparison, lines g1 and g2 correspond to an oppositely high band of SSH moving across the Indian Ocean. In other words, the Hovmöller diagrams provide a visual representation of the transport of cold waters across the Indian Ocean basin during La Niña and warm waters during El Niño. The arrival of this low and opposite high SSH signal to near the coast of Madagascar, 50°E, occurs around March of 2009 (line a1) and February of 2011 (line a2) respectively in reference to 12°S. At 25°S the arrival of the same low signal does not occur until nearly a year and a half later in October 2010 (line a2). The initiation of isolated Rossby waves begins around November 2007 and October 2009 for both latitudes, slightly before the peak of La Niña and El Niño respectively. In the context of Agulhas leakage, these results suggest that Rossby waves at 12°S, moving at the calculated 15.57 cm/sec, initiate changes to Agulhas leakage because they are faster transporting water across the Indian Ocean basin to impact the source currents within a year after the peak of ENSO. Changes to Agulhas leakage should be seen in the following months as the Agulhas Current carries the temperature and salinity signal of ENSO to the Agulhas leakage region. As previously mentioned, figure 3.1e and 3.2k show proof of this signal transmission at a lag of two years after the peak of ENSO. The Rossby waves at 25°S, moving at the calculated 6.92 cm/sec, are more likely responsible for the continuing impact to the Agulhas leakage over time because they will not reach the source currents nor Agulhas Current until nearly 36 months after the peak of an ENSO event.

Figure 3.4 represents the latitude-time variations of anomalous SSH crossing the Agulhas leakage region (15°E, -37° to -45°S) from January 2007 to January 2013. This figure indicates possible eddies moving through the Agulhas leakage region. In
particular, box d1 and box j1 indicate SSH anomalies propagating through the region two years after the peak of La Niña (2010) and El Niño (2012) respectively. Compared to box d1, box j1 shows a larger region of anomalously high SSH in Agulhas leakage region at the start of January 2012 followed by smaller isolated regions of SSH later that year. This region of high SSH may suggest that eddies propagation increased two years after the El Niño event but stalled two years after the La Niña event.

B. Subsurface Variability in Salinity and Temperature Anomalies

Using Argo in-situ observations, we are able to compare the temperature and salinity anomalies with depth in the upper 500 meters to those previously identified at the surface. At the peak of an ENSO event during January-March at the surface we identified anomalously low SST across the Indian Ocean basin during La Niña and oppositely high SST anomalies predominately in the western Indian Ocean basin during El Niño. At this time the SSS anomalies are low for both ENSO events, but more widespread during the La Niña event. Figure 3.5 and Figure 3.6 represent the temperature (salinity) from box b1, box h1 (box c1, box i1) for the eastern Indian Ocean basin and box b2, box h2 (box c2, box i2) for the western Indian Ocean basin. These figures clearly depict the subsurface temperature (salinity) anomalies are consistent with those previously identified at the surface in Figure 3.1 and Figure 3.2.

When evaluating the boxes (b1, b2, c1, c2) corresponding to the peak of La Niña, obvious negative temperature and salinity anomalies are noted for both the eastern and western basins. The anomalously low temperature in the eastern box begins as early as mid-2007 reaching about 150 meters depth and continues in both the surface and
subsurface deepening to past 500 meters until about mid-2008 when the surface signal is replaced by anomalously warm waters. The subsurface anomalously cold signal persists between 50 to 150 meters for much longer until about June of 2009. Near the end of 2009 the warm surface signal dominates, reaching a depth of about 100 meters by March 2010. The salinity during this same time period is consistently strongly negative in both the surface and up to 150 meters depth. The downward propagation with time is more evident in both temperature and salinity anomalies in the western Indian Ocean box (Figure 3.6), but with lesser magnitude of anomalies. The cold, fresh anomalies of the La Niña event (2008) continues with depth for the next two-year period in the western Indian Ocean box (Figure 3.6). The cool signal is longer lasting than the eastern signal at the surface. It does not reverse to a warm signal until after the start of 2009. A similar pattern is evident between salinity and temperature in the western box averaged region. The only difference is that instead of a signal reversal at the start of 2009, a shallow region of high salinity only develops for approximately 3 months before returning to anomalously fresh.

In the context of a La Niña event, the patterns in these figures suggest that the cold fresh signal response develops around the start of La Niña (previously noted beginning September 2007) in both the eastern and western Indian Ocean basin. The signal is stronger in the eastern Indian Ocean basin because this is where the signal originates. At the peak of the event (February 2008), the cold fresh signal has penetrated to a depth of 150 meters in the eastern basin and over 500 meters in the western basin. This surface and subsurface signal persists for longer in the western basin than the eastern basin because waters from the eastern basin are transported to the western basin by Rossby waves. Furthermore, basin wide cold patterns are expected to transition to a
dipole like pattern in which the eastern basin is anomalously warm [Bernal et al., 2001; Tokinaga and Tanimoto, 2004] as represented by the warm surface waters introduced in mid-2008. It should be noted that this dipole response only influences the surface.

An evaluation of the boxes (h1, h2, i1, i2) corresponding to the peak of El Niño is also performed. A consistent anomalously positive trend is present in all four boxes (Figure 3.5 and 3.6). In other words, the initial response of both the eastern and western box averaged regions during the peak of El Niño is anomalously warm and saline. This trend begins as early as 2009 in the western Indian Ocean basin but is isolated to the top 100 meters. Over the next year, the anomalously warm signal persists and deepens to past 500 meters in the western basin. A few months into 2010 the warm signal is replaced at the surface by a cool signal but at depth these anomalously warm temperatures continue until 2012. Over the same time period in the box averaged eastern Indian Ocean region, a primary warm signal transitions to a secondary cool signal. The warm signal is greatest in the top 150 meters but extends beyond 500 meters. This signal develops in early 2009 but only lasts until about April of 2010 when it is replaced in both the surface and subsurface by an anomalously cold signal. A similar pattern is observed in the salinity of the eastern basin but the saline signal lasts slightly longer, prior to the end of 2011. The salinity of the western Indian Ocean basin is saline at the surface at the start of 2010 and similar to temperature propagates past a depth of 500 meters throughout the year. Midway though 2012 the saline surface signal is replaced by a fresh signal at the surface but high salinity persists at a high magnitude below 150 meters. It is important to note that this anomalously high salinity signal did not appear in our primary evaluation of the corresponding surface salinity from SODA. This previously unrecognized subsurface
saline signal could attribute to the salinity differences noted in Agulhas leakage two years after the peak of El Niño as compared to La Niña.

The timeline of signal propagation in the context of the El Niño event in both the eastern and western Indian Ocean basin is similar to that of the previously evaluated La Niña. In particular, the warm saline response develops during the start of the El Niño episode (May 2009). At the peak of El Niño, this signal has penetrated to beyond 500 meters in both the eastern and western basin. Once again, the anomalous signal is greater in the eastern basin compared to the western basin but the subsurface signal persists longer in western basin. Similar to La Niña, the basin wide pattern transitions to the expected dipole like pattern with anomalously cold waters in the eastern basin. However, unlike La Niña, this transition also influences the subsurface.

The depth-time sections of temperature and salinity anomalies are shown for the box averaged Agulhas leakage region (Figure 3.7). In this figure, boxes e1 and f1 correspond to two years after the peak La Niña event and boxes in Figure 3.1 while box k1 and l1 correspond to boxes in Figure 3.2 for two years after the peak El Niño event. These depth-time sections are interesting because the Agulhas leakage region is observed as being anomalously cool and fresh from 2008 to mid-2010 for the entire depth profile. Notice this time period includes box e1 and f1, two years after the peak of La Niña. The temperature profile shows a surface-warming signal briefly in mid-2010 that penetrates up to 500 meters with time until the end of 2012. Notice, this is also two years after the peak of El Niño. The low salinity anomalies occupy the top 200 meters at the beginning of 2008 and continue to propagate over time with depth, lasting over 4 years until early 2012.
We previously noted anomalously cold surface waters in box e1 (Figure 3.1) and anomalously warm surface waters in box k1 (Figure 3.2) representing the Agulhas leakage region to La Niña and El Niño respectively. The trends described in the previous paragraphs support that this same response occurs in the subsurface. It also appears that the subsurface influence in the Agulhas leakage region is longer lasting than that of the surface. This would imply that changes could be longer lasting the originally assumed by studies of only the surface signal. In addition, Argo data indicates an anomalously saline signal in Agulhas leakage two years after El Niño that was not represented in the SODA SSS values.

3.5 Conclusions

The results indicate that during the peak of an ENSO event the southern tropical Indian Ocean basin is anomalously warm in response to El Niño and anomalously cool in response to La Niña, but with prevailing anomalously fresh waters during both the events. This is relatively consistent with previous studies that looked at the response of the surface signal in the Indian Ocean to ENSO. The novel findings of this particular study are that this trend is also true in the subsurface signals in the eastern and western Indian Ocean basin. Around the start of an ENSO event, the Indian Ocean basin exhibits the respective anomalous signal and this signal penetrates beyond 500 meters by the peak of the event. After this time, the eastern basin transitions to the respective opposing signal believed to be apart of the dipole like pattern response to ENSO. This transition is only at the surface for La Niña but also at depth for El Niño. In the western Indian Ocean basin, the subsurface signal of both ENSO events persists for nearly two years after the peak of the ENSO event. Furthermore, we hypothesized that Rossby waves triggered by ENSO
associated systems were responsible for the propagation of this signal. Hovmöller diagrams identified and also quantified this propagation. Hovmöller diagrams of SSH anomalies at 12°S indicate the propagation of high (low) SSH anomalies across the Indian Ocean basin from the peak El Niño (La Niña) event, reaching the coast of Madagascar approximately a year later. The same signal is observed in the surface and depth profiles of Agulhas leakage two years after the peak of an ENSO event. This signal indicates that the intensity of Agulhas leakage is affected by ENSO events. Anomalously cold waters in the Agulhas leakage region two years after the La Niña event would suggest Agulhas leakage weakens in response to a La Niña episode. In contrast, anomalously warm waters in the Agulhas leakage region two years after the El Niño event would suggest Agulhas leakage strengthens in response to an El Niño episode. The westward propagation of Rossby waves at 25°S is slow and the signal reaches the coast of Madagascar in 36 (or 48) months.
Figure 3.1: AVISO SSH (a,d), AVHRR SST (b,e), and SODA SSS (c,f) anomalies averaged from January-March during the peak of the 2007-08 La Niña Event (a,b,c) and two years following (d,e,f). Line (a1) at [12°S, 50°-120°E], line (a2) at [25°S,50°-115°E], box (b1) and (c1) at [0°-20°S,90°-105°E], box (b2) and (c2) at [10°-30°S,60°-80°E], line (d1) at [37°-45°S,15°E], and box (e1) and (f1) at [37°-45°S,10°-20°E] represent areas of interest in signal propagation corresponding to subsequent figures.
Figure 3.2: Same as Figure 3.1 except in reference to the peak of the 2009-10 El Niño event (g,h,i) and two years following (j,k,l). The defined regions from Figure 3.1 are also the same for this figure except with labels corresponding to these years.
**Figure 3.3:** Hovmöller diagrams from AVISO SSH anomalies at 12°S (left) and 25°S (right) form January 2007 to January 2012. Lines (a1) and (a2) correspond to Figure 3.1a and lines (g1) and (g2) correspond to Figure 3.2a. These lines follow the westward propagating Rossby waves produced during the La Niña and El Niño event respectively.
Figure 3.4: Latitude-time variations of AVISO SSH anomalies crossing the longitude of 15°E from -37-45°S from January 2007 to January 2013. Box d1 and j1 correspond to Figure 3.1d and Figure 3.2j respectively representing the time two years after the peak of El Niño event in 2008 and La Niña event in 2010.
Figure 3.5: Depth-time sections of box averaged Argo temperature anomalies (top panel) and Argo salinity anomalies (lower panel) from January 2007 to January 2013 for the box b1 and box c1 (as shown in Figures 3.1b and 3.1c) in the Eastern Indian Ocean Basin [0°-20°S, 90°-105°E] for the peak La Niña year and for the box h1 and box i1 (as show in Figures 3.2h and 3.2i) for the peak El Niño year.
Figure 3.6: Depth-time sections of box averaged Argo temperature anomalies (top panel) and Argo salinity anomalies (lower panel) from January 2007 to January 2013 for the box b2 and box c2 (as shown in Figures 3.1b, 3.1c) in the Central Indian Ocean Basin [10°-30°S, 60°-80°E] for the peak La Niña year and for the box h2 and box i2 (as shown in Figures 3.2h, 3.2i) for the peak El Niño year.
Figure 3.7: Depth-time sections of box averaged Argo temperature anomalies (top panel) and Argo salinity anomalies (lower panel) from January 2007 to January 2013 for the box e1 and box f1 (as shown in Figures 3.1e, 3.1f) in the Agulhas Leakage region [37°-45°S, 10°-20°E] showing the signal two years after the peak La Niña year and for the box k1 and box l1 (as shown in Figures 3.2k, 3.2l) showing the signal two years after the peak El Niño year.
CHAPTER 4

CONCLUSIONS AND FUTURE WORK

4.1 CONCLUSIONS

The chapters of this thesis work together to trace the influence of an ENSO event originating in the Pacific Ocean traveling across the Indian Ocean to ultimately impact the Agulhas leakage region. This thesis first presents relevant studies that identify the circulation patterns associated with the Agulhas Current and the equatorial Indian Ocean as well as several studies that have initially instigated the connection between ENSO and the Agulhas Current system. Specifically, chapter two utilizes previous research to state the various mechanisms involved in signal propagation such as Rossby waves, wind anomalies, wind stress, circulation patterns, and eddy formation. The second chapter then builds upon this previously established connection to identify the response of the SST and SSS signal of the Agulhas leakage region to an ENSO event and quantify the time lag of this response. Chapter three further defines this relationship by evaluating the subsurface signal and analyzing the proposed signal interaction with Rossby waves. Overall, this thesis utilizes previous research to support the validity of the novel conclusions drawn from this extensive research to seamlessly connect previously isolated studies providing a comprehensive understanding of the influence of ENSO on the Agulhas leakage region.
In particular, there are several novel findings presented throughout this thesis that are imperative to acknowledge because they represent the fundamental contributions provided by this research. First and foremost, chapter two highlights the response of the Agulhas leakage region to an El Niño event is opposite of the response to a La Niña event and occurs at a lag of 20 months continuing for nearly 26 months after the peak of ENSO. It is found that Agulhas leakage is anomalously warm in response to El Niño and anomalously cool in response to La Niña. The corresponding SSS signal shows both a primary and a secondary signal response. At first, the SSS signal of Agulhas leakage is anomalously fresh in response to El Niño, but this primary signal is replaced by a secondary anomalously saline signal. In response to La Niña, the primary SSS signal is anomalously saline, while the secondary SSS signal is anomalously fresh. Additionally, chapter two also finds that increasing ENSO strength increases the extremes of resulting anomalous SST and SSS signal and impacts the Agulhas leakage region earlier during El Niño and slightly later during La Niña. Prior to this work, the relationship between Agulhas leakage and ENSO was largely unexplored especially with regards to SSS. Chapter two clarifies the expected SST signal response of Agulhas leakage previously proposed by Putrasahan et al. [2016] to include El Niño and La Niña as well as the response to varying ENSO strength. Most importantly, chapter two also proposes the existence of a SSS response in Agulhas leakage to ENSO.

Chapter three validates the findings of chapter two by identifying the same SST and SSS signal response of Agulhas leakage to ENSO while further determining this surface signal penetrates into the subsurface to a depth of over 500 meters and persists for longer than that at the surface. Additionally, chapter three also isolates the same salinity
and temperature signal in the Indian Ocean basin prior to the response of the Agulhas leakage region. Signal interaction in the Indian Ocean was found to occur during the peak of an ENSO event and once again persists longer at depth, nearly a year to two years after the peak of ENSO. Finally, the third chapter also identifies Rossby waves at 12°S and 25°S are associated with the westward propagation of high and low SSH anomalies during an El Niño and La Niña event respectively. This work not only confirms the results from chapter two but also evaluates a novel parameter, the subsurface signal. Chapter three is the first research of its kind that begins to explain the connection between ENSO and Agulhas leakage at depth. The subsurface signal interaction is a key parameter in the transmission of heat and salt content from the Pacific through the Indian Ocean into the Agulhas Current feeding into the Atlantic Ocean. The lasting subsurface signal combined with Rossby wave propagation rationalizes the complex mechanisms that transmit ENSO signal at the observed lag between an ENSO event and Agulhas leakage response.

4.2 Future Work

Any accomplished research produces as many questions as it answers. It is a fundamental part of the scientific process. Therefore, this thesis provides numerous opportunities for future investigations. The results thus far highlighting signal response in the Agulhas leakage region suggest Agulhas leakage weakens in response to La Niña but strengthens in response to El Niño. However, by definition, Agulhas leakage is not just the region south of the tip of Africa but rather a dynamic system of eddies, cyclones, and filaments released during the retroflection of the Agulhas Current. Future research could benefit by specifically identifying individual eddies of Agulhas leakage and explaining
how these eddies are responsible for the observed changes in temperature and salinity in the Agulhas leakage region. Eddies are distinguishable by their highly saline and warm properties. Therefore, it could be hypothesized that the warm signal identified by this thesis in response to El Niño would be associated with the release of more mesoscale eddies and the cool signal identified in response to La Niña would indicate a decrease in mesoscale eddy production. Such a hypothesis is precisely what should be tested in future work. Programs such as AVISO are best for tracing the pathways of specific eddies. Additionally, newly launched Soil Moisture and Ocean Salinity (SMOS) and Soil Moisture Active Passive (SMAP) missions provide some of the first satellite-derived direct SSS measurements.

Furthermore, the practical applications of the connection between the Indian Ocean and the Atlantic Ocean by Agulhas leakage are essential for both global and regional processes. Benguela upwelling is one such regional process requiring future evaluations. The Benguela Current is a broad northward flowing current along the southeastern coast of Africa and is of particular interest because the Indian Ocean via the Agulhas Current is a major water source [Gordon et al., 1992]. Ship and satellite data have revealed numerous large eddies of Agulhas water embedded in the Benguela Current [Gordon and Haxby, 1990]. This region is known to support biological productivity due to a prevalent upwelling presence along the coast driven by prevailing southerly and southeasterly winds. Interactions between changes to the Agulhas leakage region and Benguela upwelling could have an important impact on the fisheries dependent on this biologically productive ecosystem.
Preliminary results evaluating the interaction between ENSO related changes to Agulhas leakage and Benguela upwelling response are presented in Figure 4.1. The Agulhas leakage region and Benguela upwelling region are identified by a box placed at 37°–45°S, 10°–20°E and 27°–35°S, 15°–20°E respectively. Figure 4.1 uses anomalous values of Chlorophyll-a, SST, and SSS to represent upwelling and these values are averaged during December to February of the indicated year because this is during the peak in seasonal intensity in upwelling [Tim et al., 2015]. A study by Chen et al. [2012] can be consulted to compare the validity of Chlorophyll-a, SST, and SSS as a proxy for upwelling as well as the strengths and weakness of each parameter. For the purposes of Figure 4.1, it should be assumed that anomalously low SST, anomalously high Chlorophyll-a concentrations, and anomalously high SSS are indicative of anomalously high upwelling events. Three years were isolated in Figure 4.1 with reference to ENSO events: 2007-08 is the peak of a La Niña, 2009-10 is the peak of an El Niño event and two years after the La Niña, 2011-12 is two years after the El Niño. Both 2009-10 and 2011-12 indicate a visible decrease in upwelling but an isolated region of increased upwelling is present at the tip of Africa in 2009-10. This isolated region also appears in 2007-08, along with more widespread anomalously high upwelling in the Benguela upwelling box.

These observed trends indicate there is a connection between changes in Agulhas leakage and Benguela upwelling further caused by changes in ENSO signal. Specifically, La Niña related cooling of the Agulhas leakage region appears to strengthen upwelling events while El Niño related warming of the Agulhas leakage region appears to weaken upwelling events. However, these results lack the ability to determine the mechanisms
triggering the observed fluctuations to upwelling. A study by Tim et al. [2015] proposes a correlation between wind stress and ENSO in which El Niño events producing stronger than normal easterly winds may be a potential factor. A second study by Rouault et al. [2010], found a positive correlation between changes in SST in the Agulhas Current system and Benguela upwelling.
Figure 4.1: Composite mean from December to January for MODIS Chlorophyll-a concentrations anomalies (left column), AVHRR SST anomalies (middle column), and SODA SSS anomalies (right column) during the peak of the 2007-08 La Niña (top row), the peak of the 2009-10 El Niño as well as two years after La Niña (middle row), and 2011-12 two years after El Niño (bottom row). The boxes represent the established leakage region (37°–45°S, 10°–20°E) and Benguela upwelling region (27°–35°S, 15°–20°E).
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APPENDIX A

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A.1 CHAPTER TWO COPYRIGHT PERMISSIONS

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