The variability of retention in St Helena Bay

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A minor dissertation

submitted in partial fulfilment

of the requirements for the degree of

Master of Science in Applied Ocean Sciences

of the

University of Cape Town

Department of Oceanography

Faculty of Science

Submitted February 2020

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Abstract

The circulation in St Helena Bay and the variability of the retention of the Bay are investigated using seasonal climatologies of the Regional Ocean Modelling System (ROMS). While retention has been studied biologically, the seasonality of the hydrodynamics contributing to the retention have received less attention. In this study we explore how the sea temperature, atmospheric forcing and currents contribute to the seasonal recirculation dynamics in St Helena Bay. Ichthyop, a lagrangian particle tracking method is used to study the spatial variations of local retention rates, with the particles released from the Bay.

The circulation on the shelf of the west coast is dominated by upwelling dynamics with the equatorward boundary current, the Benguela Current located just off the shelf. St Helena Bay is protected from the direct impact of the Benguela current by coastal geographical features. A cyclonic circulation pattern is observed in the bay especially in autumn and winter. However, the results suggest that the recirculation patterns are prominent in summer and spring due to the intensification of the Benguela Jet and the nearshore southward current flows along the coast. Similar cyclonic features are observed at 100 m depth in the water column. An analysis of the particle tracking reveals that more drifters are retained in winter than in summer, supported by what is observed in the circulation patterns. Moreover, more drifters are retained in the surface waters than the deep waters.

Acknowledgements

I would like to express my deepest gratitude to my supervisors Dr Jennifer Jackson-Veitch and A/Prof Mathieu Rouault for their knowledge, guidance and assistance during the research and writing of this thesis. I would also like to acknowledge Dr Laura Brady for her invaluable helping with MATLAB and the writing process. Thank you to Drs Gildas Cambon and Steven Herbette for running the ROMS simulation. To DEFF, I would like to thank them for providing the in situ dataset used in this thesis.

Lastly, a special and huge thanks to my family and friends for their unwavering support. Thank you for believing in my dreams. You all are real Gs!

Contents

Chapter 1

Introduction

This introductory chapter gives an overview of the Benguela region and St Helena Bay in two sections. The first section provides a global context of the Benguela region including its importance and outlining its location. The second section briefly summarizes the location of St Helena Bay and why it is of interest.

The Benguela Current Large Marine Ecosystem (BCLME), one of the four major eastern boundary currents, is located in southern Africa on the west coast (figure 1.1). Commencing approximately at 14 °S in Angola through the entire Namibian coast to approximately 34°S off the southern tip of Africa, it ranges along the South Africa south coast to about 27 °E, the Agulhas bank eastern edge (Shannon & Nelson, 1996). The BCLME is a region where upwelling continuously takes place throughout the whole year at approximately 15 °S -30 °S and seasonally at approximately 30 °S -34 °S like the regions of North West Africa, California and Peru (Hutchings et al., 2009). Generally, the currents on the surface are equatorward with strong upwelling cells. Additionally, a narrow and strong shelf edge jet that is equatorward and a poleward undercurrent exists along the bottom of the shelf.

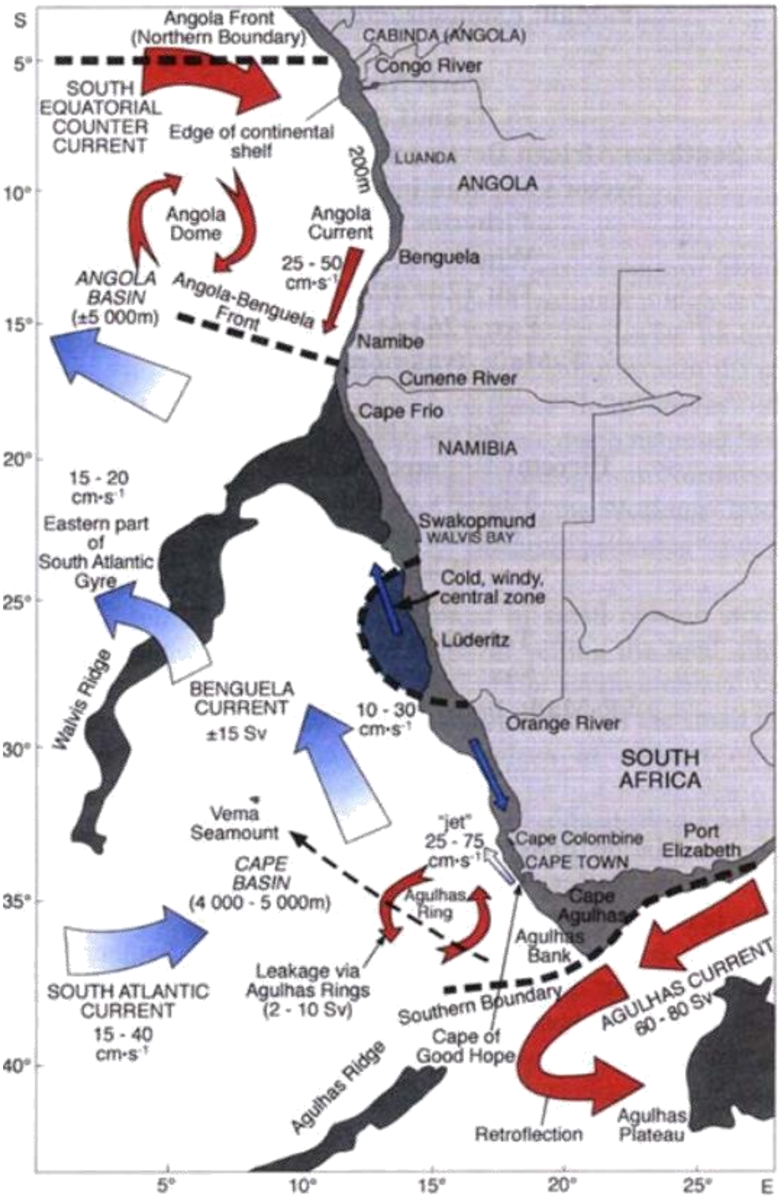


Figure 1.1 The BCLME (Hutchings *et al.*, 2009)

The equatorward and poleward ends are both bounded by regimes of warm water. This is a unique feature of the Benguela. A great deal of oceanographic research that has come about the Benguela has been directed toward biological research connected with fisheries in the southern Africa west coast. It is one of 64 large marine ecosystems. Globally, it is one of the most productive marine areas, supporting high biomass of species that are commercially important (FAO, 2018). The Agulhas bank region is vital for the pelagic reproduction of fish which after spawning the eggs and larvae drift northward until recruitment of the juvenile fish takes place in St Helena Bay (Penven et al., 2008).

St Helena Bay (32 °S), situated in the southern Benguela, is an upwelling regime and a retention zone important for fish nursery (Monteiro and Roychoudhury, 2005). The retentive characteristic of St Helena Bay is important for the effective anchovies and sardines recruitment that are exploited by the South African fishing industry (Shelton and Hutchings, 1982). It is important to the fishing industry, making it one of the most productive regions in the Benguela Current. It has been the research focus of the pelagic fishing industry. The fishing industry is supported by the abundant food source that is phytoplankton that thrives due to the nutrient rich upwelled waters. The upwelling in the area is driven by Ekman transport offshore which drives the warmer waters offshore allowing the colder upwelled waters to come to the surface. This will be further discussed at length in the literature review.

Previous studies have focused on the biology and how it is affected by the retention leaving the physical dynamics poorly understood. The oceanic circulation is important to the recruitment of anchovies as emphasised by Penven et al., (2001) and Veitch et al., (2010) using hydrodynamic modelling. The purpose of this study is to understand the seasonality of retention and the mechanisms responsible for it. Further, the aim is to investigate how the retention changes at differing depths through the water column using high resolution numerical modelling and lagrangian particle tracking to quantify. The benefit of using a high-resolution model is that it can resolve more oceanographic details, such as the nearshore poleward current, than coarse models. The study area, St Helena Bay, is immediately north of Cape Columbine, the shallow shelf region extending 200 km cross-shore and 300 km alongshore.

Chapter 2 is consisting of the literature review of the Benguela Upwelling System focusing on the atmospheric setting, the large-scale circulation features and coastal upwelling. A brief overview of the circulation patterns in St Helena Bay are also presented here. Chapter 3 describes the ROMS model used, the different datasets, proves a model evaluation for the model and the methods used to produce the results shown and discussed in chapter 4. The Lagrangian particle tracking is described in chapter 5. The details about the tool and experiment are described here. The results and discussion of the particle tracking are also in chapter 5. Concluding remarks are then presented in chapter 6.

Chapter 2

Literature Review

In this chapter, 4 major sections are discussed with regards to the BCLME. The first is the atmospheric setting of the region followed by the large-scale features. A brief look at the upwelling coastal dynamics follows and St Helena Bay, the region of interest, is examined more closely.

2.1 Atmospheric setting

In the Benguela region, winds are influenced by three factors. These factors are the seasonal low-pressure field over the subcontinent, the South Atlantic Pressure system, and the easterly mid latitude cyclones generated south of the subcontinent. These mid latitude cyclones lead to an intermittent decline along the coast of south-easterly winds with the flow becoming more westerly (Andrews and Hutchings, 1980). The south easterly winds drive the upwelling regime. The upwelling regime is further discussed in a later section.

Part of a disjointed high-pressure systems belt that surrounds the subtropical hemisphere, the South Atlantic High Pressure is sustained throughout the year in intensity and varies seasonally in terms of position. Conversely, it is located at approximately 25°S, 15°W varying latitudinally by 6 degrees reaching a southern extremity in February and a northern extremity in May (Hastenrath, 1976). The westward extremity is reached in August and it has a longitudinal variation of 14 degrees (Reboita et al., 2019). Moreover, the high pressure contributes to southerly wind stress adjacent to the southern Africa west coast.

One of the fundamental forcing agents acting on the sea surface for dynamic ocean processes is wind stress curl (Bang and Andrews, 1974). It is an important oceanic dynamic as it is a source of vorticity and controls Ekman pumping (Smith, 1968). Furthermore, the wind stress curl is linked to vertical advection of direct coastal boundary effects in regions that are toward the sea (Yoshida, 1995a). Also, it plays an important role in shaping upwelling. This is further discussed later in the literature review.

Seasonality in the pressure gradients over the continent are established as a result of the latitudinal shifting of the Continental Heat Low and the Inter Tropical Convergence Zone (ITCZ). Throughout the western South Africa, heat low pressures develop. These low-pressure systems enhance the zonal pressure gradient. This leads to southerly wind stress intensification off the west coast (Shillington *et al.*, 2006). The atmospheric pressures continually change from matured lows throughout summer to weak highs in the winter months. The comparatively strong interior thermal barrier steers the curved anticyclonic movement related with the South Atlantic High (Shillington *et al.*, 2006).

In addition to the changes that take place seasonally in the low-level winds, significant mesoscale and synoptic variability occurs at inter-annual and longer time scales. Mesoscale features such as berg winds also perturb the anticyclonic equatorward wind flow. Occasionally following the berg winds are coastal lows which have a tendency to greatly disturb the coastal wind fields (Reason and Jury 1990). More common in the winter months, are cold fronts. Contrastingly, cut off lows can transpire in any season but show a tendency of being more common in autumn and spring. West coast troughs south of 10 °S may affect the whole coast however they are more prevalent during summer in the south and winter in the north (Shillington *et al.*, 2006).

The regional wind patterns in St Helena Bay are important as they have a major influence on the surface current dynamics. A case study by Jury (1985) found that over St Helena Bay, impacting the surface winds and currents is the disjointedness of the topography. The offshore component of the jet results in the clockwise circulation observed in St Helena Bay driven by sea level variations and cyclonic wind stress curl (Jury, 1985). The headland of Cape Columbine blocks the bay from receiving some winds creating a sheltering effect. Simultaneously, the atmospheric Benguela Jet is created by the topographic effects just off the cape. The cyclonic turning of the wind assists in creating the clockwise circulation with land-sea breeze cycle controlling the inertial oscillations (Jury, 1985).

2.2 Large-scale circulation features

2.2.1 Benguela Current, Jet and poleward undercurrent

The currents on the surface over most of the shelf area in the Benguela are impacted by prevailing winds. The general current direction on the surface along the west coast is equatorward as shown in figure 2.1. They bend to the northwest and become isolated from the coast at around 30 °S while quickly broadening (Peterson and Stramma, 1991). The South Atlantic current (southern part of the subtropical gyre), the Antarctic Circumpolar Current and the Agulhas current feed into the Benguela Current.

At the shelf edge at depths ranging between 500-800 m, the poleward undercurrent is the dominant characteristic (Shannon, 2001). Thus the undercurrent net poleward flow ranges from 5-6 cm/s (Shannon, 2001) Additionally,-the depth range of the current at 250-1000 m (Nelson, 1989).

The Benguela Jet, also known as the Good hope Jet, lies over the poleward undercurrent. Following the shelf, it flows northward alongside the west coast of South Africa between Cape Point and Cape Columbine. The Jet splits into two with one branch funnelling into the west coast into St Helena Bay with recorded speeds of 0.5 m/s (Bang and Andrews, 1974). The other branch veers offshore. Moreover, the Benguela Jet is associated with upwelling fronts in Cape

Point and Cape Columbine. The current is narrow, approximately 20 km in width that varies in intensity and position, responding swiftly to wind stress magnitude and direction (Ragoasha et al., 2019). The jet current is responsible in facilitating the transportation of pelagic fish eggs and larvae from the Agulhas Bank in the spawning grounds to the recruitment areas on the West Coast (Shelton and Hutchings, 1982). Following the seasonal cycle of upwelling, it strengthens in summer due to the reinforcement of across-shore density gradient through the upwelling of coastal cold water (Veitch and Penven, 2017). The across-shore density gradient declines in winter due to the reversal in wind direction however it still perseveres because of the warm Agulhas Current water contribution from the south (Twatwa et al., 2005).

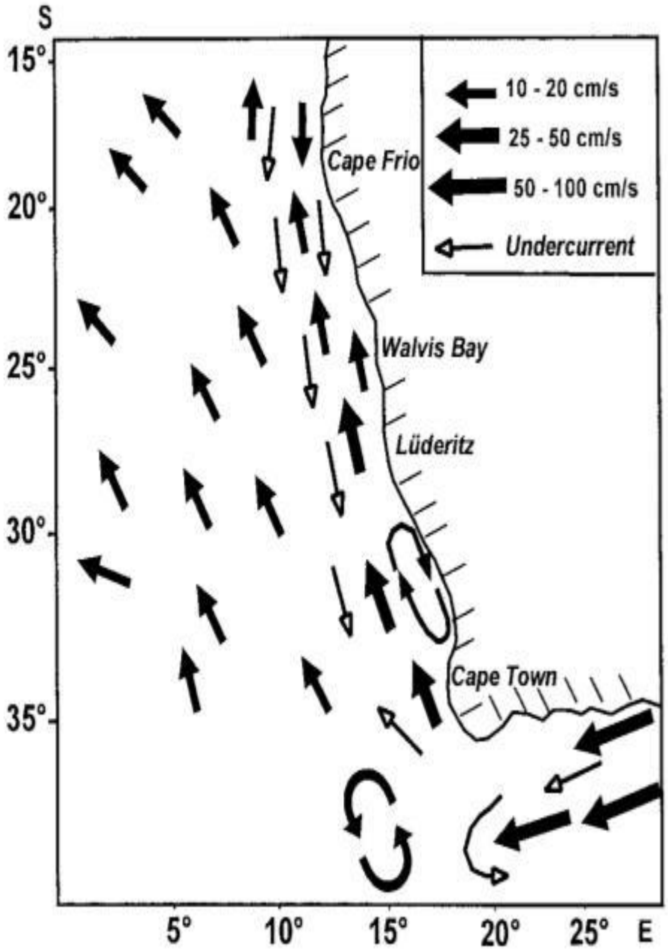


Figure 2.1 A redrawn diagram of the surface and undercurrent in the Benguela region. (Nelson and Hutchings, 1983; Shannon, 1985); Shannon and Nelson 1996).

2.2.2 Agulhas influx (Cape Basin)

The Atlantic Ocean receives additional energy from the Agulhas current that combine with the Benguela Current and move into the Atlantic (Van Ballegooyen, Grundlingh and Lutjeharms, 1994). This additional energy comes in the form of eddies, rings and filaments shed at the Agulhas retroflection. The eddy fluxes of the Agulhas eddies contribute a great amount of the energy of the south-eastern region of the Cape Basin and the Benguela current (Matano and Beier, 2003). This process is exceptional to the BCLME and does not take place in any other key eastern boundary currents (Shillington et al., 2006). Additionally, to the energy influx, the eddy fluxes also inputs heat and salt, which is believed to be vital in maintaining the global overturning of the ocean (Duncombe Rae, 1991). The influx of heat aids in the intensification and modulation of the Benguela Jet (Strub *et al*., 1998). The south-eastern region of the Cape Basin has thus been dubbed “Cape Cauldron” by Boebel et al., (2003). This is because it is characteristically high in energy due to the interaction of the Agulhas rings, eddies, filaments and shelf edge upwelling fronts associated with mesoscale features.

In the literature, there is no consensus as to how much water in the Atlantic Ocean originates from the Indian Ocean. The Agulhas Current has an enormous impact on the Benguela Current. This is seen through the large differences in the transport estimates. Peterson and Stramma, (1991) estimates that across 30°S, the Benguela Current transport is approximately 20-25 Sv. However, the Benguela Sources and Transport (BEST) monitoring campaign propositions that it is the Agulhas Rings’ presence that results in the high estimation of the transport. The Benguela Current transport yearly average is closer to 16 Sv according to Garzoli et al., (1996).

2.2.3 Water masses

The water masses found in the Benguela area are subtropical surface (SSW) and tropical (TSW) waters, thermocline waters (also known as central water), Antarctic Intermediate Water (AAIW), Antarctic Bottom Water (AAIW) and North Atlantic Deep Water (NADW). Inclusive of the thermal waters is South Indian Central Waters (SICW), South Atlantic Central Water (TACW) and Tropical Atlantic Central Waters (TACW). In the Benguela region, the intermediate, surface and central waters are characterized as being warmer and more saline if originating from the tropics and if influenced by the sub Antarctic or Antarctic waters, the water is cooler.

Central water is distinguished by temperature ranging from 6°C– 16°C and salinity ranging from 34.5 psu to 35.5 psu. It is the central water that is upwelled along the coast to the surface and accordingly comprises the Benguela shelf waters that are frequently substantially modified (Wefer *et al.*, 1996). Gordon et al., (1992) used chlorofluoromethanes as tracers to differentiate between water masses. This was done due to the SICW and SACW being similar in salinity and temperature structures. The study determined that as much as two thirds of the thermocline waters in the Benguela Current originate out of the Indian Ocean. Nevertheless Kamstra (1985) cautions that this statistic may be inflated. Through investigating the thermocline water mass of the whole Atlantic Ocean, Poole and Tomczak (1999) found that the waters of the south Atlantic central waters can be differentiated to Western South Atlantic Central Water (WSACW) and Eastern South Atlantic Central Water (ESACW). The former results from the Brazil/Malvinas Confluence and the latter from Indian central water through the Agulhas Current. Noted by Mohrholz et al., (2001), ESACW is dominant in the Cape Basin while SACW is prevalent in the thermocline waters of the Angola basin north and south of 16°S respectively.

In St Helena Bay Monitoring Line (SHBML) several water masses have been identified. Saline Oceanic Surface Water (OSW) at the top of the water column was noted further offshore, different from the Modified Upwelled Water (MUW) observed across the shelf (Lamont et al., 2015). Beneath the MUW far offshore, the Light South Atlantic Central Water (LSACW) was found as a slim layer from September to January at a depth of approximately 80 m. Far offshore the South Atlantic Subtropical Mode Water (SASTMW) was observed perennially with bigger vertical extent in spring and summer at depths between 81 m and 201 m. Sub Antarctic Mode Water (SAMW) occupies the bulk of the water in the SHML with salinities ranging between 34.78–35.49 g kg^{-1} and temperatures of 6.32°C and 13.18°C (Lamont et al., 2015). At the continental slope and shelf break below the SAMW is the AAIW. The AAIW core is at approximately 750 m in the south-east Atlantic according to Shannon and Hunter (1988).

Finally, the Upper Circumpolar Deep Water (UCDW) was discovered below the AAIW in the furthest offshore station of the SHBML transect (Lamont et al., 2015).

2.3 Coastal upwelling dynamics

Dominating the oceanography in the BCLME region is the upwelling system that is strongly driven by the pressure gradient between the pressure system over neighbouring subtropical region of southern Africa, the South Atlantic High Pressure (Estrada and Marrasé, 1987), the topography and the impact of the Agulhas Current (Shannon, 1985). Figure 2.2 illustrates the coastal upwelling and associated atmospheric forcing.

The associated winds over the southern BCLME region are mainly southerly or south easterly in summer and westerly in winter. There are two mechanisms responsible for wind driven upwelling; equatorward winds at the coast causing coastal divergence on the surface and curl of the wind stress driving Ekman pumping (Jacox and Edwards, 2012). Coastal divergence takes place adjacent to the coast in a narrow band. In contrast, the upwelling driven by wind stress curl can extend more offshore. The main mechanism of the upper ocean circulation in eastern boundary currents is the alongshore wind stress curl consequently forcing the SST distribution (Fennel et al., 2012).

Upwelling occurs along the west coast of southern Africa with seven upwelling cells that have been recognized (Lutjeharms and Meeuwis 1987). The cells are influenced by coastline orientation changes and located in wind stress curl enhanced areas (Shannon and Nelson 1996). The cells are named Cunene, Namibia, Walvis Bay, Lüderitz, Cape Peninsula, Namaqua, Cape Columbine and cells according to the naming convention of Lutjeharms and Meeuwis (1987). The southern Benguela cells; the Cape Peninsula, Cape Columbine and Namaqua cells are controlled by the topographical variations in the coastline that bring about distinct upwelling (Nelson and Hutchings, 1983). Significantly, the most intense cell, the Lüderitz, is a powerful upwelling cell located 26 °S with elevated offshore advection, intense winds and strong turbulent mixing, partly separating the southern and northern Benguela regions into sub systems.

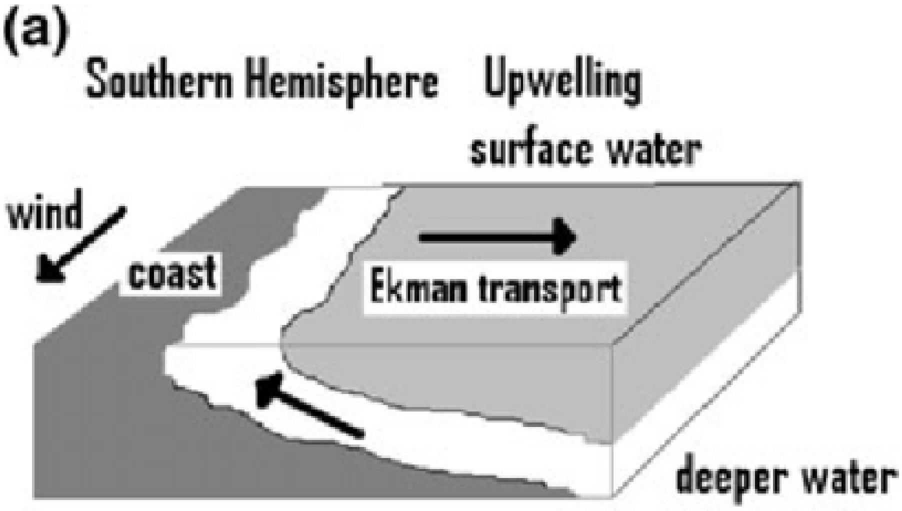


Figure 2.2 The structure of coastal upwelling and associated circulation (Ribeiro et al., 2011).

2.3.1 Columbine upwelling cell and plume

Identified as the main upwelling centre in the southern BCLME is Cape Columbine (Monteiro and Roychoudhury, 2005). The irregular topography in the form of the cape induces cyclonic wind stress curl that produces the formation of a plume through upwelling. Specifically, the orientation of the plume is thought to be influenced by the cyclonic curving of the northward winds in the coastline side of Cape Columbine (Jury, 1985).

The warm Agulhas Current water's proximity to the system wields substantial impact. The northward movement of the Agulhas Current waters during upwelling seasons around Cape Columbine strengthens the horizontal gradients around the upwelling centres (Armstrong et al., 1987). Therefore, the northward flow that dominates during the upwelling season forms the equatorward coastal jet off Cape Columbine where the shelf is steep as well as thin resulting in a plume of cold water (Penven *et al.*, 2000). The plume extends from Cape Columbine northwards, separating the jet from the coast to the north of the headland where the influence of the bathymetry decreases as the slopes become gentle (Fawcett et al., 2007). Naturally the upwelling plume then has a tendency to separate the inshore from the offshore environment, thus stimulating retention on the coastal side of the plume (Penven *et al.*, 2000). A dynamic boundary is created between the onshore and offshore environment from the northward wind that produces a cyclonic eddy on the coastline side of Cape Columbine (Fawcett et al., 2007).

2.3.2 Cape and coastal current interactions

The interactions between coastal currents and headlands are intricate and although they have been studied in various ways these interactions remain poorly understood. Crepon et al., (1984) analytically solved a linear upwelling two-layer model around a quadrilateral headland. Their study showed that barotropic and baroclinic Kelvin waves, which originated at the corner of the promontory and propagated poleward can result to upwelling variations autonomous of local wind. Further Crepon et al., (1984) relate the difference in phase speeds between the barotropic and baroclinic waves to the poleward undercurrent. Near Cape Blanco, located on the coast of southwestern Oregon in the United States, the split of an upwelling coastal jet was observed using a Conductivity, Temperature, and Depth (CTD) sensor and a shipboard acoustic Doppler current profiler (ADCP) (Barth, et al., 2000) .

Doglioli et al., (2004) conducted a study to investigate the winter circulation around Promontorio of Portofino in Italy. The current meters used to gather the data shows that the inbound current on to the shelf flows in north-western direction and behind the cape southward recirculation is observed, signifying the presence of an accompanying anticyclonic eddy. A study by Scherbina & Gawarkiewicz (2008) which used both a numerical model and observations, examined the joint result of abating and wind driven buoyancy flux on the coastal current east of Cape Cod situated in Massachusetts United States. They found that wind driven buoyancy flux is a vital driving force on the continental shelf.

2.4 Circulation features in St Helena Bay

Numerous studies have been done in St Helena Bay. Andrew and Hutchings (1980) found that longshore, episodic northward winds are the principal controlling mechanism of the southern Benguela system. Through the winds, cold nutrient rich SACW are upwelled into the euphotic zone, generating a front (Lamont *et al.*, 2015).

One of the foremost environmental processes influencing fish reproductive strategies are the retention processes that let pelagic fish eggs and larvae to be kept within nursery grounds (Bakun, 1996). These retention processes are the Cape Columbine upwelling plume, the Benguela Jet and the recirculation feature in the Bay. Fish usually avoid reproducing during periods of active upwelling or in upwelling centres to circumvent loss of their reproductive material offshore (Parrish et al., 1983). The spatial structure in certain zones of upwelling allows a positive coupling with retention of water (Bakun, 1996). Numerous studies have demonstrated that a contributing factor to providing retention are upwelling plumes and that fish reproduction is frequently linked with such structures (Graham and Largier, 1997; Roy 1998).

The presence of an eddy in the region supports the development of two diverse circulation patterns. First, the flow is mainly alongshore in the offshore region. Secondly in the coastal area, the circulation is driven by the associated recirculation pattern and a clockwise eddy (Penven *et al.*, 2000). The enlargement of the extent of the eddy results from the wind forcing intensity increasing (Penven *et al.*, 2000). The offshore and nearshore environment are isolated from one another due to the eddy induced recirculation (Penven *et al.*, 2000). Moreover, the eddy confines the cross-shelf swap over of water and keeps the water particles within the coastal area consequently supplying a retention mechanism. In this coastal region retention is strongly linked to cyclonic patterns that are wind induced.

2.4.1 Response to upwelling relaxation events

The reversal or reduction of the winds favouring upwelling leads to the relaxation of an upwelling system. The shelf waters warm after the relaxation described as cross-shelf advection of heat. Wind decay events take place through the austral spring and summer season. The southerly wind reversal during these seasons is due to the weakening of the South Atlantic High pressure system (Nelson and Hutchings 1983). Other systems during summer that can contribute to the wind relaxation are coastal lows and west coast troughs (Risien et al., 2004). The upwelling-favourable winds weaken near the end of summer and autumn resulting in longer periods of wind relaxation. Equally, the wind relaxation is linked to the development of a nearshore counter current resulting in the southward movement of dinoflagellate blooms (Fawcett et al., 2007). During upwelling relaxation periods, the upwelling front moves inshore, responding to the changes in wind direction and stress (Armstrong et al., 1987). Inner shelf in-situ observations in the California region suggest that interludes of wind relaxation produce inner shelf circulation that are characterized by strong poleward flows (Cudaback, Washburn and Dever, 2005). The wind reversals are lagged with the near-surface current resulting in the implication that a poleward current exists in the absence of wind (Fawcett et al., 2007). Further contributing to the retention observed in the bay is the inshore poleward current that is controlled by the negative pressure gradient created by the division from the Cape Columbine coast of the equatorward jet (Fawcett et al., 2007).

Chapter 3

Modelling strategy and evaluation

This chapter provides details about the model used in the study, ROMS, specifying the model description and configuration. The different datasets used are also described here. The model is then evaluated using sea surface temperature and vertical temperature.

3.1 The Regional Ocean Modelling System (ROMS)

3.1.1 Model description

The Regional Ocean Modelling System (ROMS) (Shchepetkin and McWilliams, 2005) solves with a free surface the hydrostatic, incompressible, primitive equation of fluid dynamics. Based on the assumption that the buoyancy force is balanced by the vertical pressure gradient, ROMS solves incompressible primitive equations combined with diffusion or advection schemes for salinity, potential temperature and an equation of state that is nonlinear. The vertical coordinates follow the topography or bathymetry while the horizontal coordinates are curvilinear. The material properties are salinity and temperature while surface elevation, baroclinic and barotropic horizontal velocity components are the analytical variables.

3.1.2 Model configuration

Herein this thesis, the ROMS numerical model is applied to the South West Atlantic Ocean with the objective being to investigate the seasonal variability of retention in St Helena Bay. The model domain ranges from 22 °S to 38 °S and zonally from 8 °E to 21 °E (figure 3.1). The model has 75 vertical levels. The horizontal grid spacing is 1/36°, producing daily averages from the timeframe between 1991 and 2011. The model was run by Gildas Cambon and Steven Herbette from Institute of Research for Development. The GEBCO_1 global elevation database was used to extract the bottom bathymetry at 1 arc-minute spatial resolution (http://www.gebco.net).

The wind stress was computed from NCEP Climate Forecasting System Reanalysis (CFSR) (Saha, 2010) using bulk formulae with a spatial resolution of 0.34° and a 6-hourly sampling. A monthly seasonal climatology was derived from Simple Data Ocean Assimilation (SODA) 2.3.4 reanalysis for the conditions of temperature, horizontal velocity, salinity and sea level at the lateral boundary (Carton & Giese, 2008). In a general circulation model, the reanalysis product assimilates observational data based on the Parallel Ocean Program (Smith, et al., 1992). The average horizontal resolution is 0.4° in latitude is 0.25° in longitude with 40 vertical levels with a 10m near the surface spacing. Using ROMS tools, the forcing, initial and boundary conditions were linearly interpolated on ROMS grid (Penven, et al., 2008).

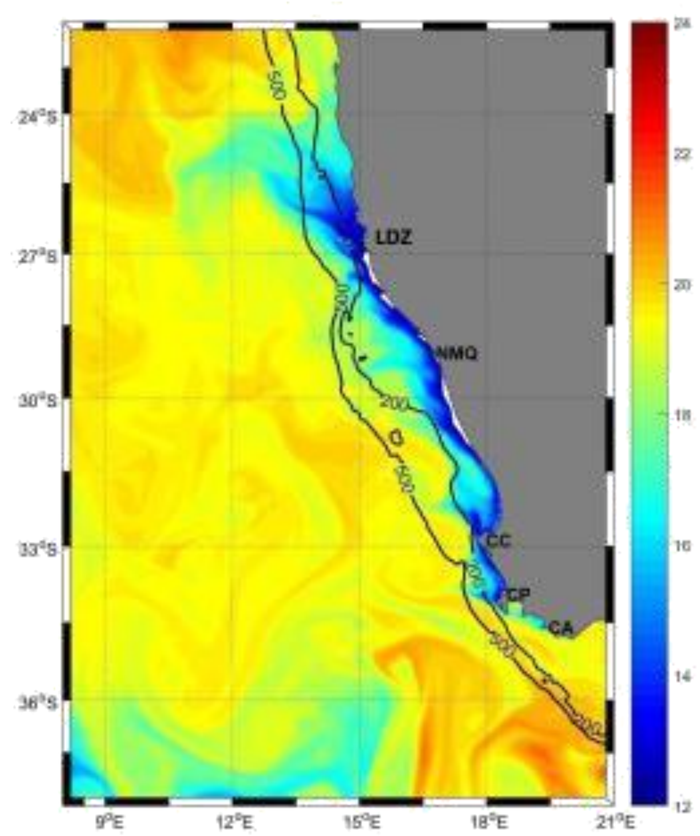


Figure 3.1: January 1991 average snapshot of SST for the model domain. The domain encompasses the region from 22 °S to 38 °S and 8 °E to 21 °E. The upwelling cells are indicated; LDZ is Luderitz (25°S), NMQ is Namaqua (29°S), CC is Cape Columbine (33°S), CP is Cape Peninsula (34°S) and CA is Cape Agulhas (35°S).

3.2 Data sources

3.2.1 Climate Change Initiative Satellite

The Climate Change Initiative (CCI) satellite data version 1.1 was used in the model evaluation to compute a seasonal bias for sea surface temperature (SST). The product spans over a time period from 1991-2010 on a regular latitude-longitude grid with spatial resolution of 0.05 ° and is available from http://www.neodc.rl.ac.uk. The daily analysis product input fields are the 20 cm SST from the SST CCI Along-Track Scanning Radiometer (ATSR) and Advanced Very High-Resolution Radiometer (AVHRR) datasets.

3.2.2 In situ data

The St Helena Bay Monitoring Line (SHBML) transect data was used to assess the thermal stratification of the numerical model. Containing 12 stations, the most inshore located off Elands Bay at 32.30◦ S, 18.31◦ E and the furthest station located at 32.78◦ S, 16.43◦ E, a Conductivity-Temperature-Depth (CTD) was used to measure various parameters. These parameters are temperature, salinity and dissolved oxygen, measured from the surface to a depth maximum of 1466 m offshore. The data was acquired from the Department of Environmental, Fisheries and Forestry (DEFF) cruises. The data was collected monthly from April 2000 to December 2011.

3.3 Model evaluation

3.3.1 Sea Surface temperature

Figure 3.2 shows a comparison between the satellite observations and the model. The bias was determined by subtracting the CCI SST from the ROMS SST. A mean warm bias is observed over the St Helena Bay region in all four seasons. The summer season are the months January to March, April to June are the autumn months, July to September are the winter months and spring are the months October to December. The seasons were allocated this way as it has been determined that January to March is the time when the SST maximum occurs and June to August is the time when the SST minimum takes place.

The bias is warmer in summer when upwelling is strongest and is lower in winter. This means that ROMS is overestimating the temperature due to variations in upwelling. The SST overestimation in summer and spring along the coast can also lead to a stronger density gradient producing stronger jets. The reason for the warm bias may be a dynamic response to too much of a nearshore poleward flow that brings in warmer waters from the north of Cape Columbine cell transporting the water southward.

Around the Columbine (33°S) upwelling cell is a cold bias in summer and spring, higher in summer. This cold bias extends to the Cape Peninsula upwelling cell (not shown here). The dynamic response of too much of the nearshore poleward flow bringing in warmer waters could be the reason for this. The winter bias plot shows a warm bias within St Helena Bay and a cool bias offshore. This decreases the negative gradient and can potentially produce a positive gradient that would result in the reduction of the speed of the Benguela Jet.

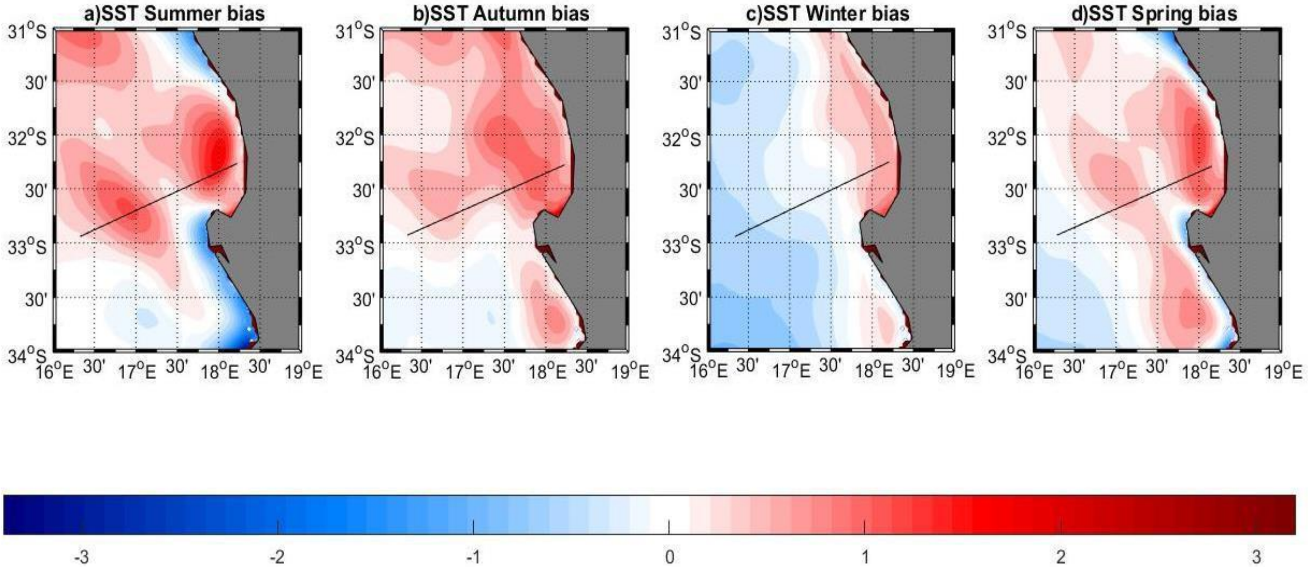


Figure 3.2: The difference between the model and the satellite SST (℃). Positive (red) values indicated the regions where the model overestimates the SST and the negative (blue) values show the regions where the model underestimates the SST values. The white regions show areas where there is zero difference. The black line indicates the SHBML. A) shows the summer SST bias, (b) autumn SST bias, (c) winter SST bias and (d) spring SST bias.

3.3.2 Vertical temperature profile

The vertical thermal structure of the model compared to the in-situ data of the SHBML is shown in Figure 3.3. The model and the in-situ data show similarities in that lower temperatures are observed in both ROMS and the in-situ data nearer to the coast indicative of the upwelling taking place in the region. The surface temperatures are warmer offshore than onshore for both the model and in-situ data.

At the surface, the ROMS is higher than the in-situ data. Offshore, the 11 ℃*and* 9℃ isotherms are deeper in the SHBML than the ROMS indicating that ROMS temperature are lower than the SHBML at depth. These two isotherms curve upwards more on the ROMS than the SHBML and then tilt downwards more especially in summer and spring. Since in the upper layers of the water column density is primarily determined by density, the slope of isotherms show the direction of the current. The downward tilt in the ROMS indicates the direction of the current which is flowing poleward. This is indication of the poleward undercurrent observed between the oceanic current and coastal current. The SHBML isotherms similarly show a downward tilt, albeit weaker, in the nearshore region, during autumn, winter and spring. In summer, the isotherms do not appear tilt downwards. This shows that the model nearshore is warmer compared to the in-situ data. The fact that the downward tilt at the coast is more extreme in the model sections shows that the model nearshore is warmer and experiences a more intense poleward flow in comparison to the in-situ data, further supporting why the St Helena Bay region has a warm coastal bias in the SST plots (figure 3.2) .

The upward tilt of the isotherms in the top 100 m in the ROMS model and the SHBML data near the coast is characteristic of upwelling. The close isotherms in summer and spring ~~of the~~ show the fast-flowing nature of the current closer to the coast.

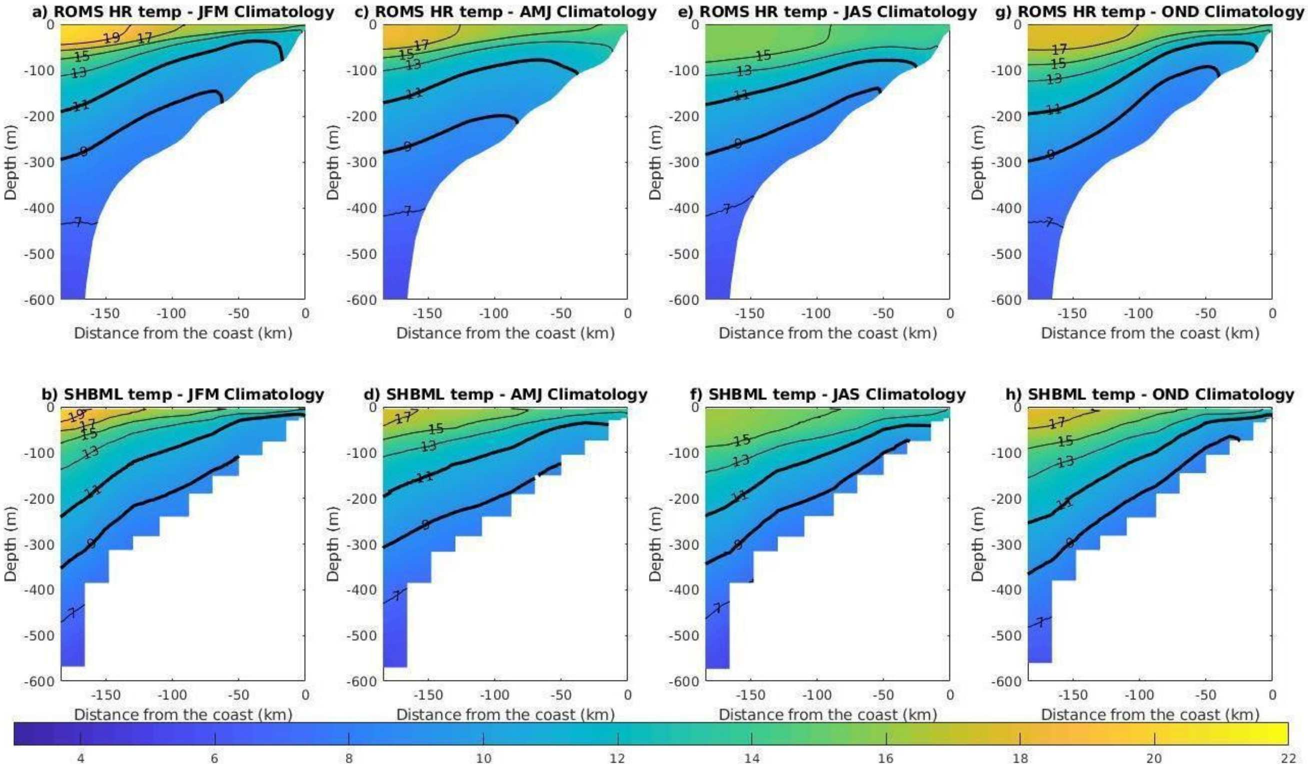


Figure 3.3: Seasonal temperature vertical structure (℃) for a, c, e, g ROMS model and b, d, f, h for the SHBML. The 11°C and 9°C isotherm highlighted for comparison.

Chapter 4

Seasonality of Circulation within St Helena Bay

The goal of this chapter is to describe the seasonal circulation taking place in St Helena Bay. The atmospheric forcing used in the model is examined first. The temperature and currents are investigated at the surface and the depth of 100 m. The alongshore and cross-shore velocities are also computed. A better conception of the seasonal dynamics is vital because it provides an improved understanding of the retentive nature experienced of the Bay.

4.1 Atmospheric setting

4.1.1 Wind stress

The seasonality of the wind stress is evident in figure 4.1. The wind stress in summer and spring is southerly, favourable for upwelling and shifting the upwelling front offshore. This wind regime generates offshore Ekman transport. The surface waters drift offshore and are replaced by the cold upwelled waters (Salam, 2012) as seen in figure 4.3 below. The wind stress is the same direction as wind, proportional to the square of the wind speed and more related to upwelling than wind itself. The equatorward winds result in a strong alongshore coastal jet, The Benguela Jet, that is geostrophically balanced with the isopycnals that are upwelled (Castelao and Barth, 2007).

In autumn and winter the wind stress is weaker with more westerly component, shifting the upwelling front inshore as the winds are not favourable for upwelling. In magnitude, it is also strongest in the summer and spring seasons. This strong wind stress occurs offshore, obeying the outline of the bathymetry. The weakest wind stress in all the seasons is along the coastline corresponding to the cyclonic wind stress curl in figure 4.2. The rotation of the wind stress appears to be anticlockwise offshore as characteristic of an eastern boundary current (Bakun and Nelson, 1991).

The wind conditions in summer and spring favour upwelling which could possibly decrease the retention as the conditions transport water offshore. In autumn and winter, the winds are more onshore, increasing the retention potential of the region.

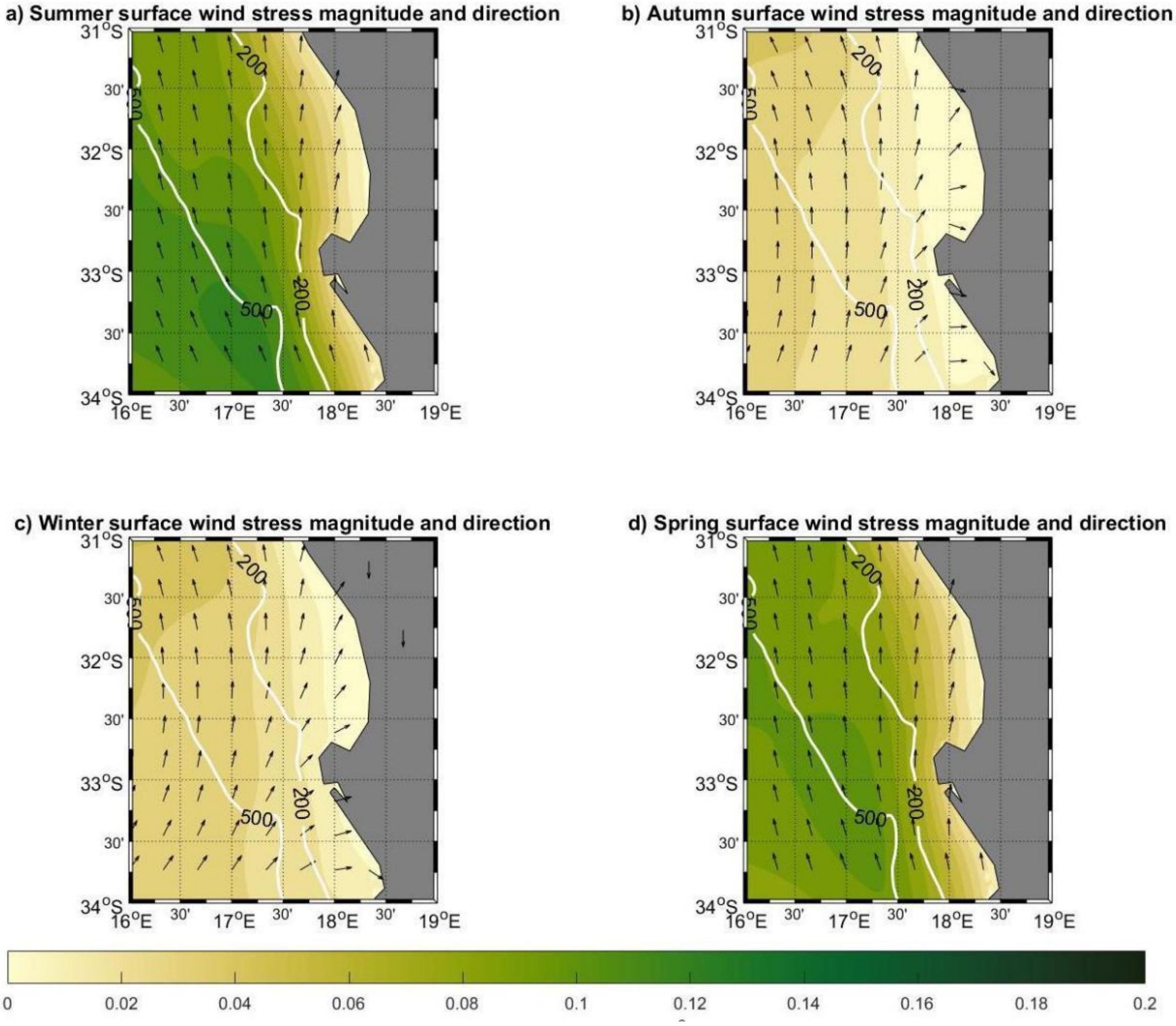


Figure 4.1: Climatology of seasonal surface wind stress magnitude in N/m^2 and direction. The 200 m and 500 m isobaths are shown in white. Figure (a) is the summer surface wind stress magnitude and direction, (b) autumn surface wind stress

magnitude and direction, (c) winter surface wind stress magnitude and direction and (d) spring surface wind stress magnitude and direction

4.1.2 Wind stress curl

Figure 4.2 shows the wind stress curl which shows a strong seasonal variability. Along the coast and most of the continental shelf, the wind stress curl is negative all year round. It is most negative in the summer and spring seasons than autumn and winter around Cape Columbine and southward. With this strong intensification of wind stress curl, the currents offshore and downstream of Cape Columbine are intensified. The offshore region experiences alongshore divergence facilitating the process of the separation of the Jet (Castelao and Barth, 2007).

Offshore, in all the seasons, the wind stress curl is positive indicative of Ekman downwelling. This is because of the changes in wind direction during these ~~two~~ seasons as observed in figure 4.1. This cyclonic wind stress curl around the cape has been related to the generation of the upwelling plume by Kamstra (1985). Negative wind stress curl results in positive Ekman pumping and upwelling. The negative wind stress curl is induced by the coastal wind drop-off in the nearshore band between the 200 m isobath and the coast. Offshore, the wind stress curl is positive resulting in the water being pushed down resulting in downwelling offshore.

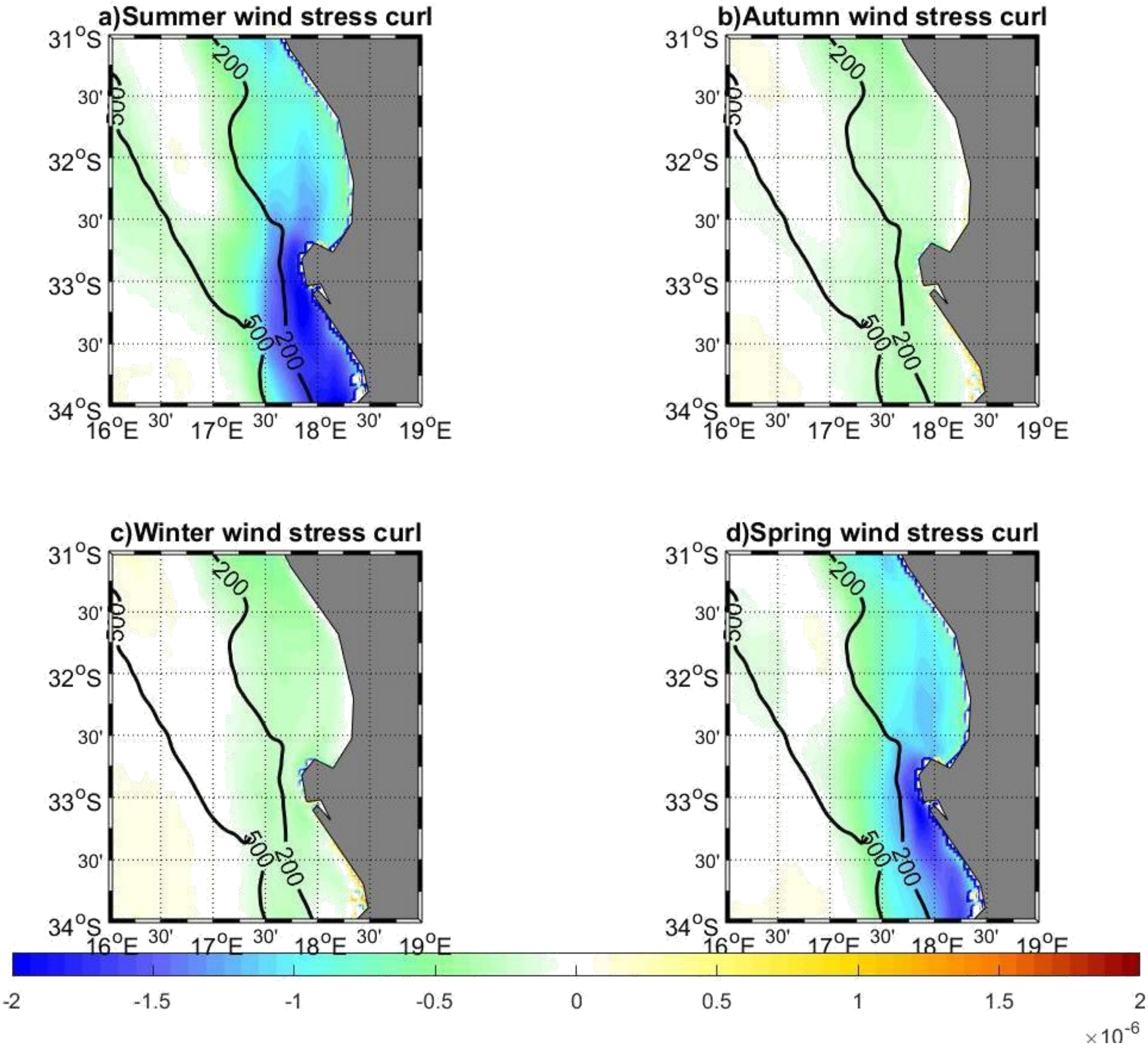


Figure 4.2 Seasonal wind stress curl climatologies. The 200 m and 500 m isobaths are shown in black. Figure (a) is summer surface wind stress curl magnitude, (b) autumn surface wind stress curl magnitude, (c) winter surface wind stress curl magnitude (d) spring surface wind stress curl magnitude.

4.2 Temperature

4.2.1 Sea Surface temperature

Figure 4.3 shows the seasonal sea surface temperatures (SSTs). Throughout all the seasons, a cold band of water extends along the coastline. The presence of the Columbine (33°S) upwelling cell is evident with the associated upwelling plume. The plume is visible in summer and spring. Note that this is the region with the most negative wind stress curl in summer and spring. From the coast to the offshore region, the SSTs increase in all seasons. Summer has the highest SSTs offshore, reaching a maximum of up to 21 °C while winter has the lowest, reaching a maximum of up to 16 °C.

In summer and spring, there are temperature differences between the 200 m and 500 m isobath with the water cooler inshore and warmer offshore as seen in figure 3.2. The cooler water inshore is a result of upwelling. This results in a sharp positive cross-shore density gradient that creates the Benguela Jet. The Jet is strongest in summer and spring due to the stronger density gradient. Although weaker, the positive density gradient persists in autumn and winter because of the influx of warm Agulhas waters offshore. The different densities of the offshore and onshore water masses inhibit mixing of these water bodies.

East of the 200 m isobath, there is a warm tongue of water intruding toward the coast most visible in summer. In spring, the same feature is visible although not as strong. Due to this, the warm tongue intruding toward the coast isn’t as strong. The warm tongue gives rise to a negative density gradient which is suggestive of a poleward current flowing nearshore.

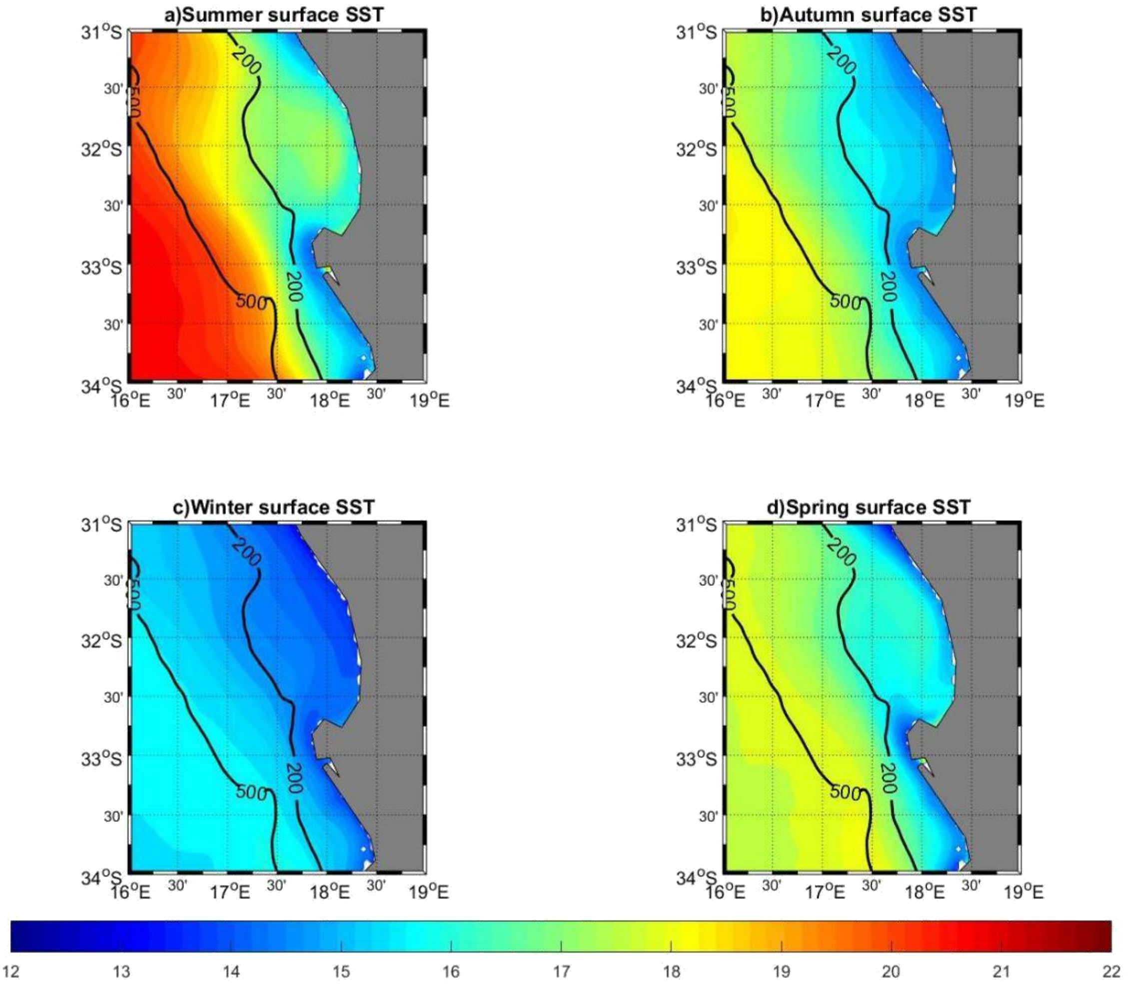


Figure 4.3 Surface seasonal SST (°C) climatologies. Isobaths of bathymetry are displayed at 200 m and 500 m in black. Figure (a) is summer SST, (b) autumn SST, (c) winter SST and (d) spring SST

4.1.2 Temperature at 100 m depth

At the 100 m depth, the warmer water is offshore while the cooler water is nearshore. The purpose of showing the temperature at depth is to assess how the circulation patterns compare to the surface and how the circulation patterns induce retention. In summer, the temperature gradient is still present between the 200 m and 500 m isobaths however it is not as distinct as it is on the surface. This shows that the Benguela Jet extends to this depth however not as fast as the surface as the density gradient is reduced. This is the same for spring. In autumn and winter the reversal of what happens nearshore in summer and spring occurs. A temperature gradient is created nearshore by the warmer water followed by cold water. This is suggestive of the poleward flow near the shoreline.

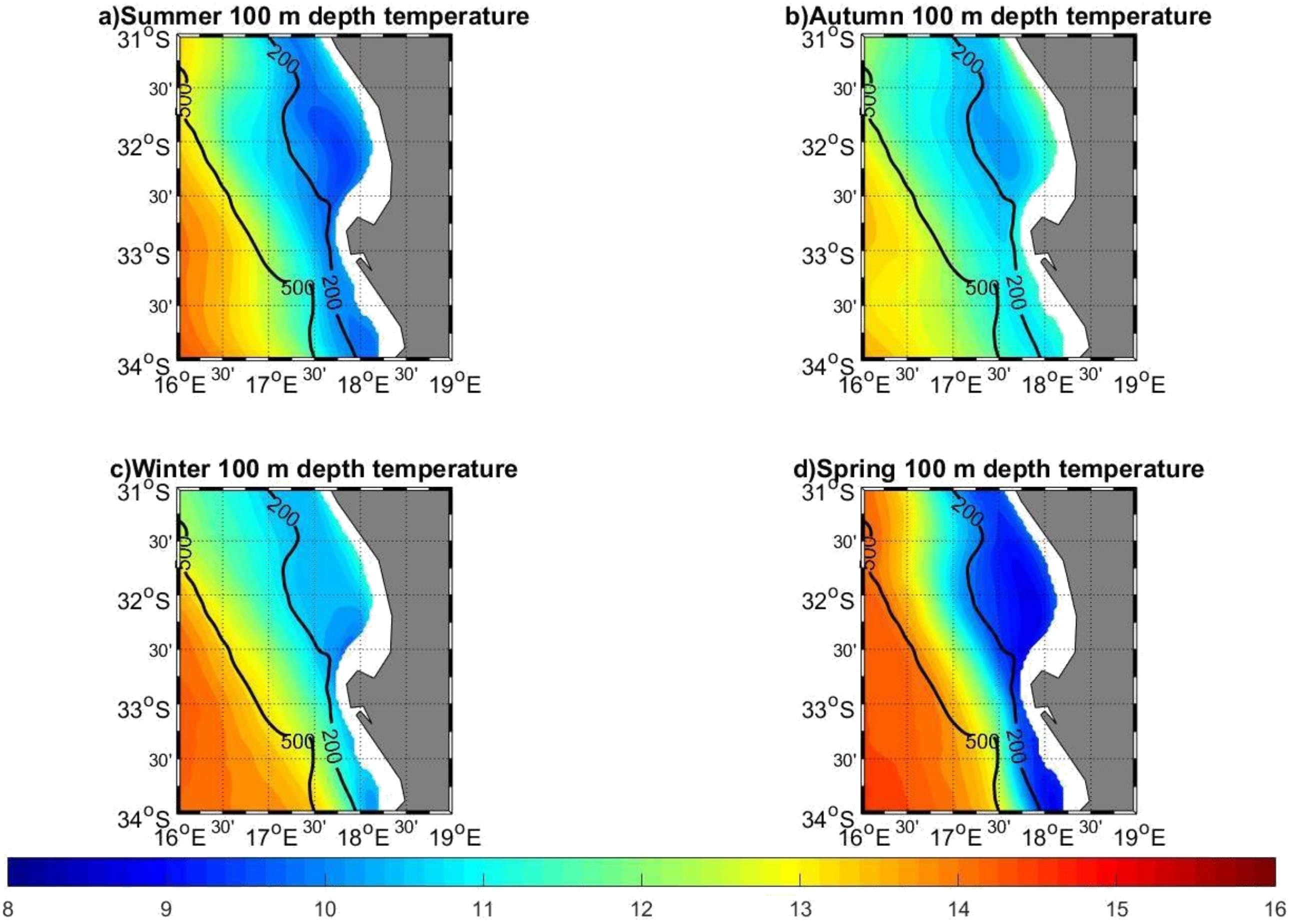


Figure 4.2 100 m depth seasonal SST (°C) climatologies with isobaths of bathymetry are displayed at 200 m and 500 m in black. Figure (a) is summer temperature at 100 m depth, (b) autumn temperature at 100 m depth, (c) winter temperature at 100 m depth and (d) spring temperature at 100 m depth.

4.3 Circulation

4.3.1 Surface currents

The seasonal climatology of the surface current speeds is shown in figure 4.3 with the arrows indicating the direction of the flow. The main feature that stands out is the Benguela Jet that is geostrophic balanced along the shelf-edge, between the 200 m and 500 m isobath consistent with Veitch et al., (2017) findings. It is most prominent in summer and spring seen in the same position as described in figure 4.1. Interestingly, it is strongest in spring with speeds up to 0.4 m/s and weakest in winter with speeds of 0.27 m/s.

The current direction along the coast differs in all four seasons. In summer, near St Helena Bay along the coast it is north westward. It changes in autumn to south westward. In winter the current direction is eastward and southward. In spring, it is north-westward and westward. Between the 200 m and 500 m isobaths, for all seasons, the current direction is mostly north westward. This circulation indicates a cyclonic pattern especially evident in the autumn season when the nearshore poleward current is strongest. This creates the potential for retention in recirculation caused by the cyclonic pattern.

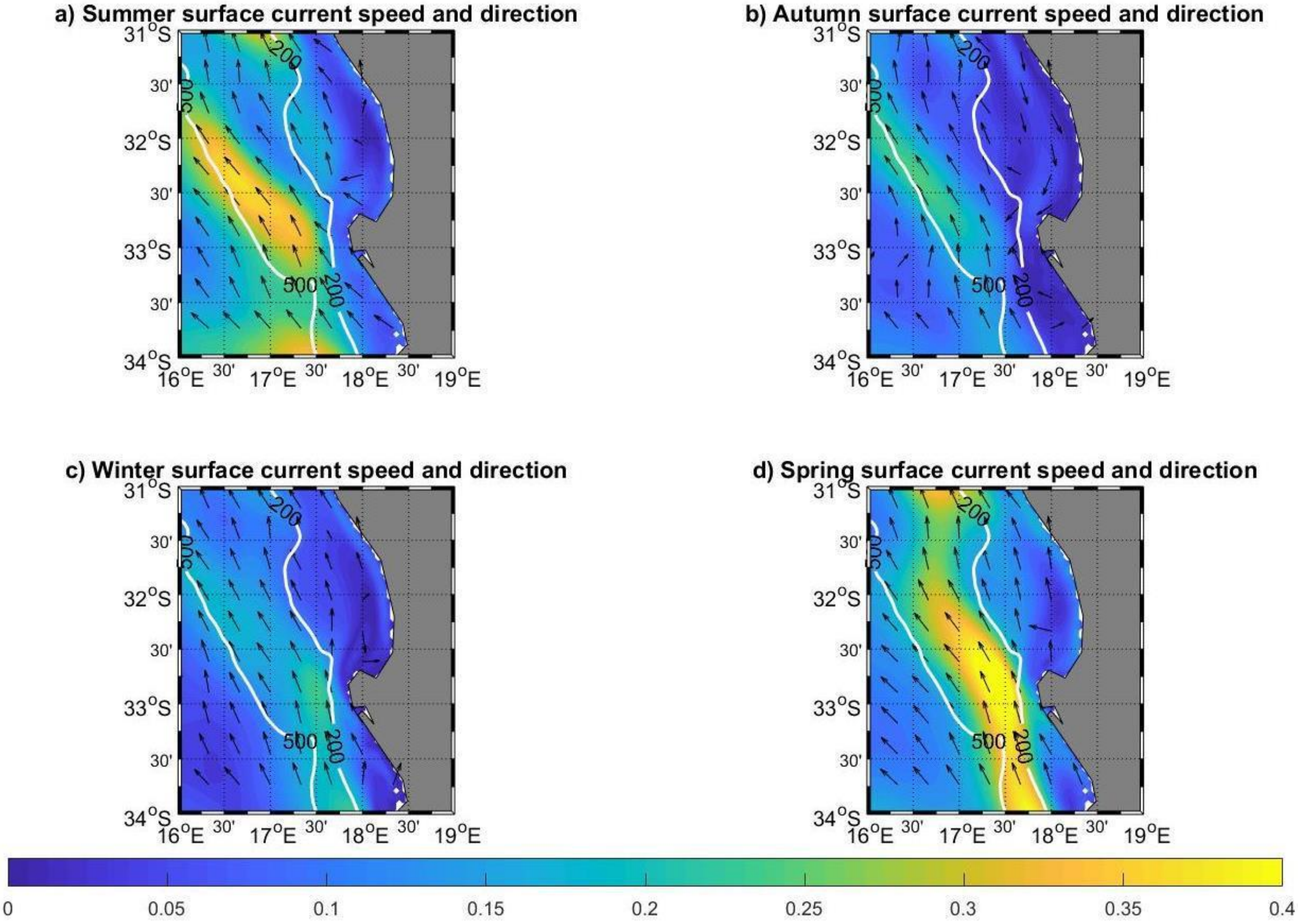


Figure 4.3 Seasonal surface current speed (m/s) and direction climatologies. Isobaths of bathymetry are displayed at 200 m and 500 m in white. Figure (a) is summer surface current and speed, (b) autumn surface current and speed, (c) winter surface current and speed and (d) spring surface current and speed.

4.3.2 Currents at depth of 100 m

Current speeds at 100 m depth are presented on figure 4.4. (figure 4.4). In summer and spring as seen in figure 4.2, the temperature gradient extends to the 100 m depth indicative of the depth of the Benguela Jet. At this depth, the Jet has speeds of up to 0.1 m/s. The speeds at the 100 m depth are lower than at the surface as seen in figure 4.3. In autumn, the Jet appears more offshore and weaker in the higher latitudes (from 33 ° southwards) than the other three seasons. Along the 200 m isobath adjacent to Cape Columbine, is a poleward flow, that flows fastest in summer. In winter, it is not visible. Between the 500 m and 200 m the current direction is north westward turning north eastward in the lower latitudes especially in the summer and autumn seasons.

East of the 200 m isobath, in summer and autumn, the current direction is south-eastward and southward, while in winter it is northward with some indication of a south-eastward flow closer to the coast. The current direction in spring is eastward. The cyclonic circulation in summer moves offshore, extending east of the 200 m isobath. In winter, the cyclonic circulation moves inshore. As above the circulation gives rise to retention at depth. The inshore movement of the eddy may consequently increase the magnitude the retention.

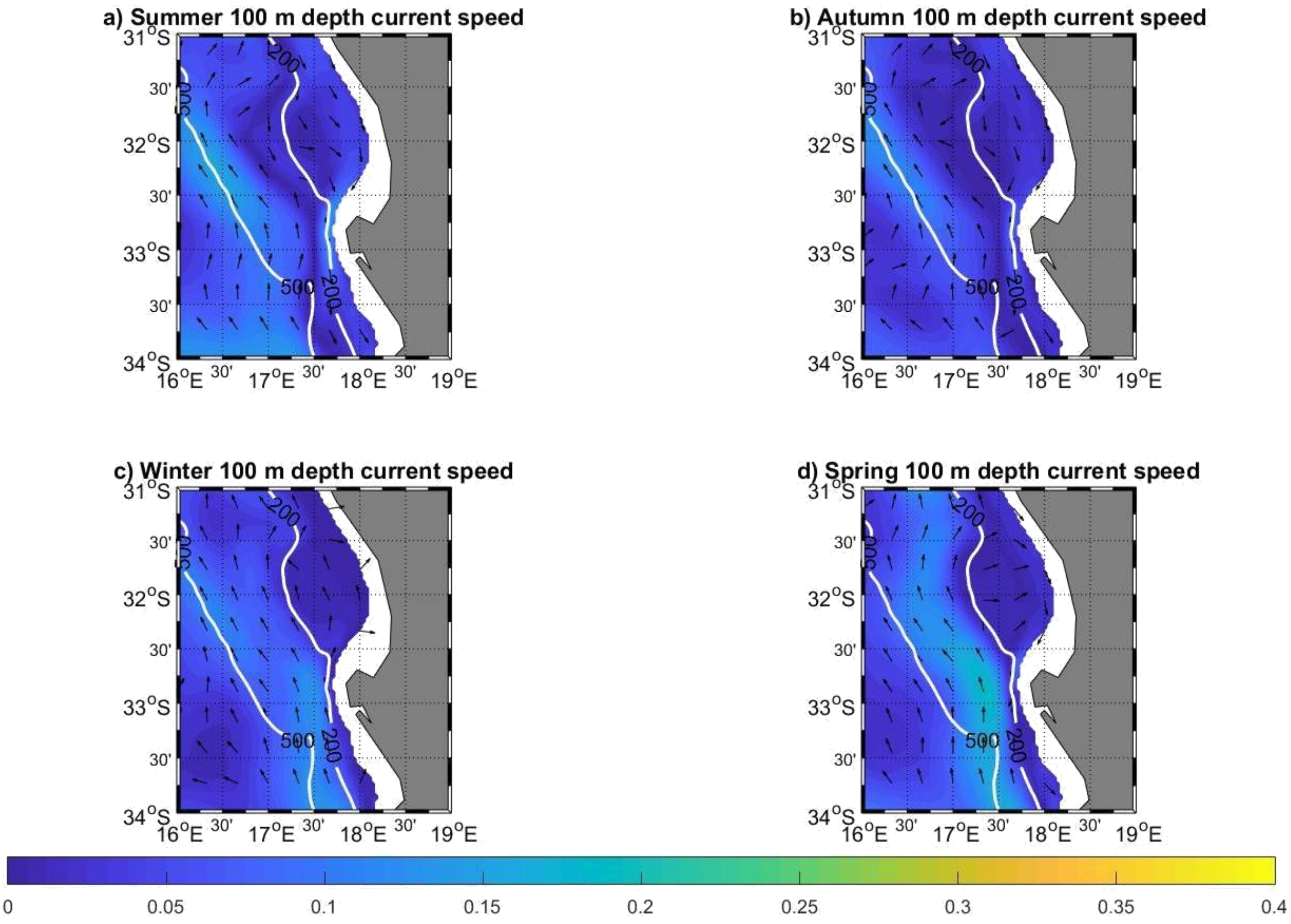


Figure 4.4 Seasonal current speed climatologies at depth of 100 m down the water column. Isobaths of bathymetry are plotted in white at 200 m and 500 m. The white area is the region above 100 m. Figure (a) is summer 100 m depth current and speed, (b) autumn 100 m depth current and speed, (c) winter 100 m depth current and speed and (d) spring 100 m depth current and speed.

4.3.3 Vertical structure

The vertical structure of the seasonal alongshore velocity is examined along with the seasonal cross-shore velocity. The sections were taken over the latitudes corresponding with the SHBML latitudes. Figure 4.10 shows that the offshore northward current is strongest offshore at the shelf edge especially in the summer and spring seasons reaching the depth of 200 m. This is due to the positive density gradient created by the temperature difference between the cool upwelled waters near the coast and the warmer offshore water as seen in figure 4.1. This northward current is the Benguela Jet previously mentioned. This is consistent with the findings in figure 4.3 of the SSTs in terms of location and strength of the Jet. In summer and autumn, it is further offshore. It’s location and direction are suggestive of decreasing the retention potential as it transports water away from St Helena Bay. Right up against the coast, the equatorward current deepest in winter and strongest in spring. It is most prominent and well defined in autumn, winter and spring.

The poleward undercurrent is evident near the bottom at the shelf edge deeper than 300 m, under the Benguela Jet as seen in figure 4.10 most prominent in summer and spring. The nearshore surface counter current poleward flow is evident and is confined to the top 250 m for all seasons which is the entire water column in most places. It is fastest in summer and slowest in winter, also covering the smallest area when compared to the other seasons. In winter, it is confined to 50 km from the coast. In the other seasons, it extends to from about 80 km to 120 km from the coast.

The offshore component of the Benguela Jet and the poleward counter current contribute to the creation of the cyclonic feature seen in the circulation patterns. A strong equatorward jet and a strong poleward current, the cyclonic feature should intensify in the Bay leading to stronger retention. This is the case for the summer season. In winter, both the Jet and the poleward counter current are not as strong resulting in the weakening of the cyclonic circulation in St Helena Bay.

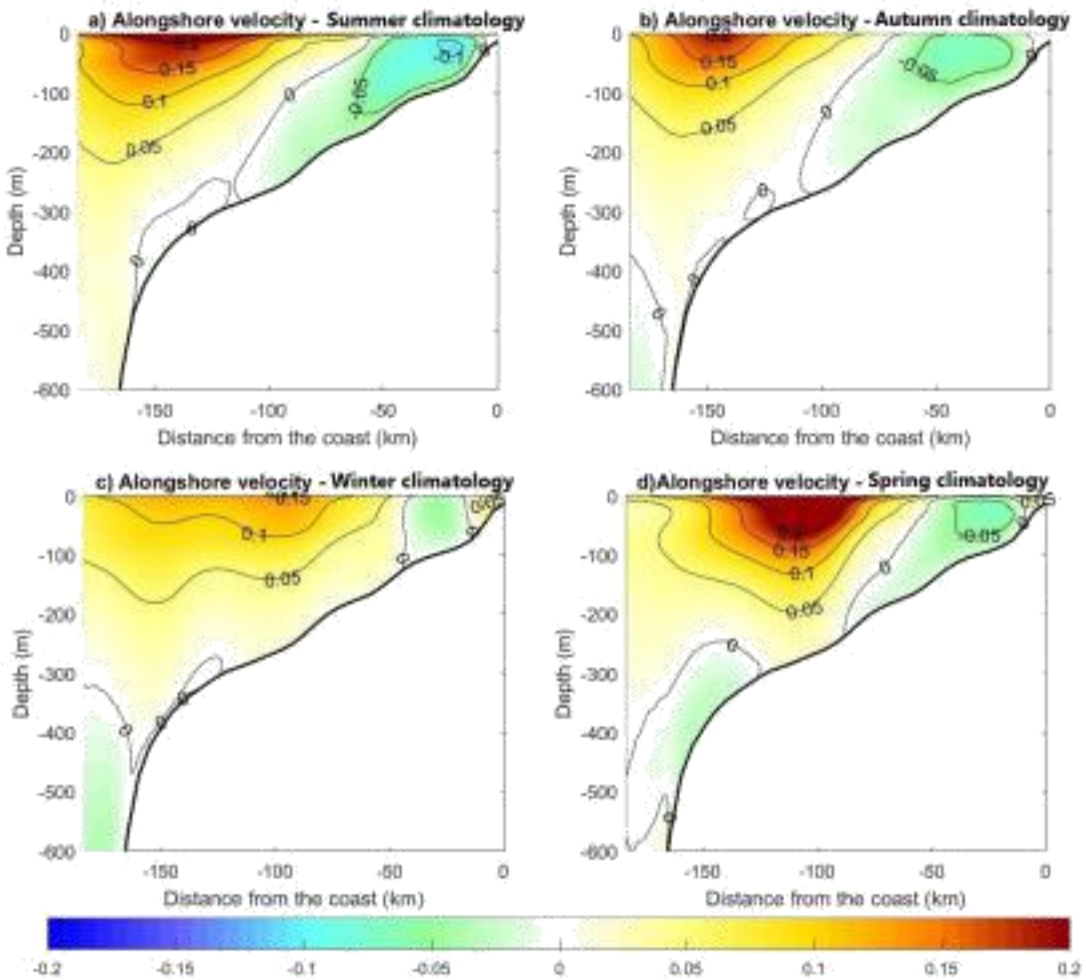


Figure 4.10: Cross section over the latitude 32.3 ◦S - 32.747◦S band alongshore current velocities with 0.05 cm/s contour interval. The positive values indicate equatorward movement of water while the negative values indicate poleward movement of water. Figure (a) is summer alongshore velocities, (b) autumn alongshore velocities, (c) winter alongshore velocities (d) spring alongshore velocities.

The cross-shore current velocities, which are weaker than the alongshore current velocities, show a surface westward flow nearshore within 50 km of the coast in summer and spring. This nearshore westward flow is the Ekman transport related to the prevailing winds that are favourable for upwelling. Adjacent is the eastward undercurrent nearshore present in all seasons (figure 4.11). In summer and spring, it is just beneath the surface, expanding to the bottom of the ocean. In autumn, it starts approximately 100 m from the surface and extends down to the ocean bottom. In winter it shallows and outcrops at the surface. It is weakest in this season. This drives the water in this region toward the coast increasing the potential for retention. A distinctive eastward flow is evident in winter at the shelf edge.

Offshore, the westward flow is fastest in summer and spring due to the westward component of the Benguela Jet. This strong westward flow can potentially affect retention as it transports waters offshore, decreasing the potential for retention. The offshore westward flow is faster than the nearshore westward flow.

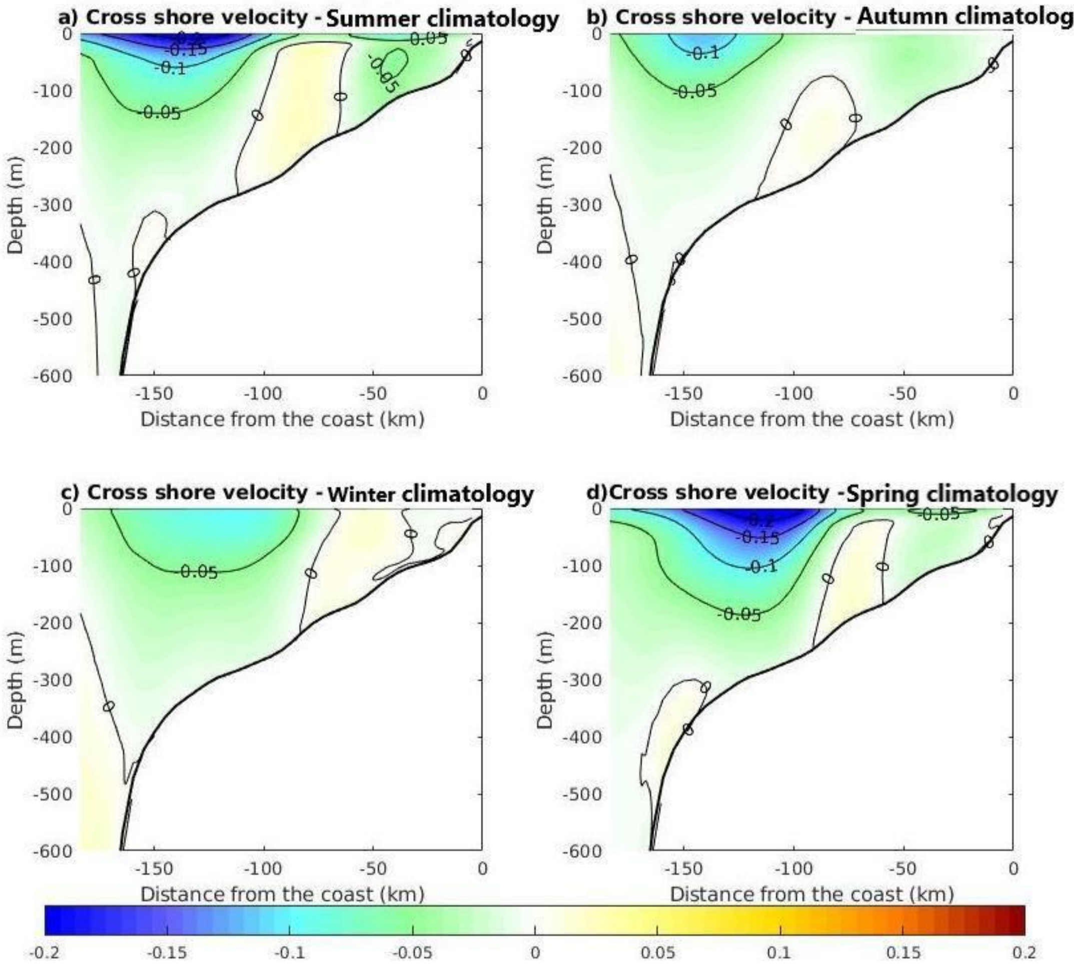


Figure 4.11 Cross section over the latitude 32.3 ◦S - 32.747◦S band cross shore current velocities with 0.05 cm/s contour interval. The positive values indicate eastward movement of water while the negative values indicate westward movement of water. Figure (a) is summer cross shore velocities, (b) autumn cross shore velocities, (c) winter cross shore velocities (d) spring cross shore velocities.

4.4 Seasonal circulation patterns and impact on retention

The objective of this research is to progress the understanding of the variability of retention, to examine the seasonality of the circulation of the ocean and its effect on retention.

Additionally, this study seeks to understand how the retention changes throughout the water column using the ROMS numerical model. Although modelling studies have been done in this region, we are using a higher resolution model (3 km resolution), capable of resolving small scale features. The study relied on the sea temperature, current speed and direction, alongshore and cross-shore velocities, wind stress and wind stress curl derived from the ROMS numerical model to investigate the circulation patterns in St Helena Bay.

Contrastingly to the surface layer, where the seasonal ranges of temperature were considerable (figure 4.3), seasonal variations at the 100 m depth for temperature were greatly reduced (figure 4.4). Different forcing mechanisms are responsible for influencing the sea temperatures in the offshore and inshore environment. Offshore, the solar insolation and Agulhas influx are the dominating forcing mechanisms while inshore it is upwelling dynamics (Lamont *et al.*, 2015).

The SST plot (Figure 4.3) shows a coastal upwelling front created by the temperature gradient. As with Brink, (1987) the front sharpens because of the weakening wind near the coast. The weakening wind results in less mixing sharpening the front. Upwelling fronts are associated with equatorward baroclinic jets (Brink, 1987) as is demonstrated in this study with the Benguela Jet. The Jet aids in retention as it contributes to the cyclonic feature observed in the St Helena Bay. Harmonious with the findings of Nelson and Hutchings (1983), the jet is present in all the seasons. It is strengthened seasonally by the nearshore upwelling regime and moderated by the warm Agulhas influx (Veitch and Penven, 2017). Its intensification leads to the intensification of the cyclonic feature, increasing the potential of retention.

The low wind stress in all the seasons (figure 4.1) near the coast affects retention as coastal currents seen in figure 4.3 and figure 4.4 are driven by the wind stress observed in figure 4.1. The upwelling taking place can be attributed to the coastal divergence associated with the alongshore wind stress and the upward Ekman pumping associated with the cyclonic stress forced by the nearshore reduction in wind stress. The negative wind stress curl near the coast induces the alongshore currents. The equatorward wind stress in summer and spring produce the Benguela Jet, which is stronger and deeper in these seasons as seen in figure 4.3 and figure 4.10 respectively. It also follows the bathymetry. Cape Columbine causes the Jet to split to an onshore and offshore component. The cyclonic wind stress curl around Cape Columbine is produced by the drop off from the alongshore winds near the coast due to frictional effects, more pronounced in summer and spring when the prevailing wind is mostly south easterly. It is the offshore component of the jet, the Cape Columbine upwelling plume and nearshore poleward counter current that contributes to retention as it produces the cyclonic circulation in St Helena Bay. During the autumn and winter season, the equatorward winds relax and change direction to westerly. This results in the shoreward transportation of water leading to the coastal downwelling of waters. The overall displacement of water is shoreward and downwards. This increases the potential of retention in these seasons.

At the 100 m depth, the currents are moving slower closer to the shore, increasing in speed offshore (Figure 4.4). In comparison to the surface, at depth the currents are moving slower. The fastest speeds are between the 200 m and 500 m isobaths, where the Jet extends to this depth increasing the potential of retention at the depth of 100 m. The Jet is still strongest in summer and autumn at the surface. The cyclonic feature observed on the surface persists at depth with the same seasonal variations. However, the reduced current speeds leading to a less intense recirculation pattern in the bay suggest that more retention is experienced in the surface waters than the deep waters.

The poleward counter current evident in figure 4.10. It varies seasonally and it is strongest in summer. This flow contributes to the clockwise circulation taking place in the bay enhancing the retention potential. The warm tongue observed creates the conditions for the negative density gradient to form producing the poleward current. Blanke *et al.*, (2009) suggests that the more negative the winds stress curl, favourable for upwelling, the shallower and more intense the poleward current along the coast. This is consistent with results obtained in this study.

At Cape Columbine upwelling cell cold-water plume forms during summer and spring (figure 4.3). The formation of this plume is due to the negative wind stress curl dominating in that region as seen in figure 4.2 especially prominent in summer and spring. In St Helena bay, warm water is wedged behind a slim ocean front created by the temperature gradient in all the seasons but most evident in summer and spring. The relaxation period, in autumn and winter, the nearshore winds become more westerly, intermittently washing out the bays, creating a recirculation pattern (figure 4.3 and figure 4.4). The spatial structures of the bay allow for the positive coupling between upwelling and retention (Penven et al., 2000) as the plume together with the recirculation patterns provide retention on its coastal side of Cape Columbine as seen in figure 4.3.

Chapter 5

Ichthyop Lagrangian particle tracking

The intention of this chapter is to investigate the retention patterns and quantify the retention experienced in the Bay. The tracking tool description is provided here including the success of retention. The retention patterns for the 21 years are examined for both seasons. Summer and Winter seasons are investigated using January and July as a proxy.

5.1 Ichthyop Lagrangian dispersion tool

5.1.1 The tool

The variability of retention of the study area is assessed using Ichthyop Lagrangian dispersion tool. Ichthyop is an open source java lagrangian tool intended to study the effects of oceanographic fields on ichthyoplankton dynamics produced by models such as ROMS (Lett et al., 2008). It can follow the particle's location and record their ocean properties such as salinity and temperature (Lett et al., 2008). Ichthyop possess the capability of assigning biological behaviours to the particles. For this study, the particles were released as passive drifters. The ocean properties were not recorded.

5.1.2 The experiment set-up

The following are parameters were set in Ichthyop for the experiment: the release region, the distribution of the particles horizontally and vertically, total number of drifters released and the release events frequency. The particles are advected by oceanic currents for a specific timeframe of 30 days. In the study, the ocean currents are the outputs of the ROMS numerical modelling. The release region is in St Helena Bay with a thickness stain of 100 m. 8000 particles were released on the first of every January and July from 1991 to 2011 throughout the entire water column. January is representative for summer while July is representative for winter. None of the biological behaviours were allocated to the particles. They were released in St Helena bay (figure 3.4) at different depths and the simulation ran for 30 days where the drifters were advected by the oceanic currents. The maximum depth was set at 100 m to ensure that the bottom of the bay would have drifters. St Helena Bay is shallower than 100 m.

5.1.3 Retention success

For each of the 8000 particles released monthly, in January and July, the number of particles that remain in the zone defined as the retention zone are counted and recorded at the time, they exited the domain. The retention zone is a box defined in domain 32 °S - 33 °S and 17.5 °E – 18.5 °E. The mean and the standard deviation for each season and water depth were computed.

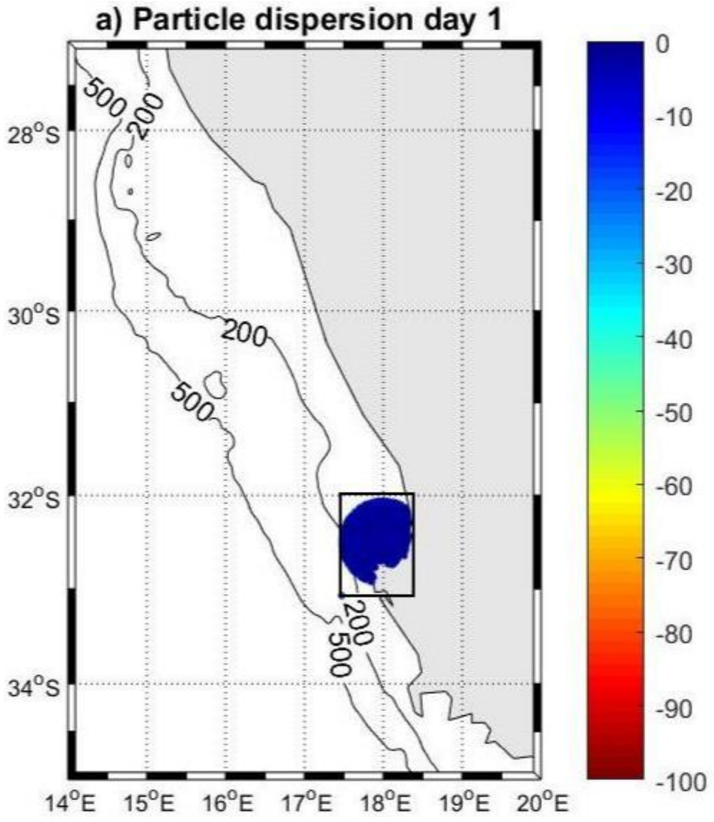


Figure 5.1 Position of the 8000 drifters at the beginning of the simulation. The box over the stain is the retention zone defined above.

In the analysis below, 8000 particles were released on the first of January and July however only 4000 particles are plotted (figure 5.1). The experiment ran for 30 days. Surface water has been defined as the first 30 m of water in the water column while the deep waters are from 31 m to the bottom of the water column.

5.2 Retention patterns

5.2.1 Yearly particle dispersion

In order to get a wide-ranging overview of the drifter trajectories and the dispersion patterns accompanying the trajectories, maps showing the drifter locations are plotted below. The colour bar shows where the particles were initially when released.

Summer particle dispersion

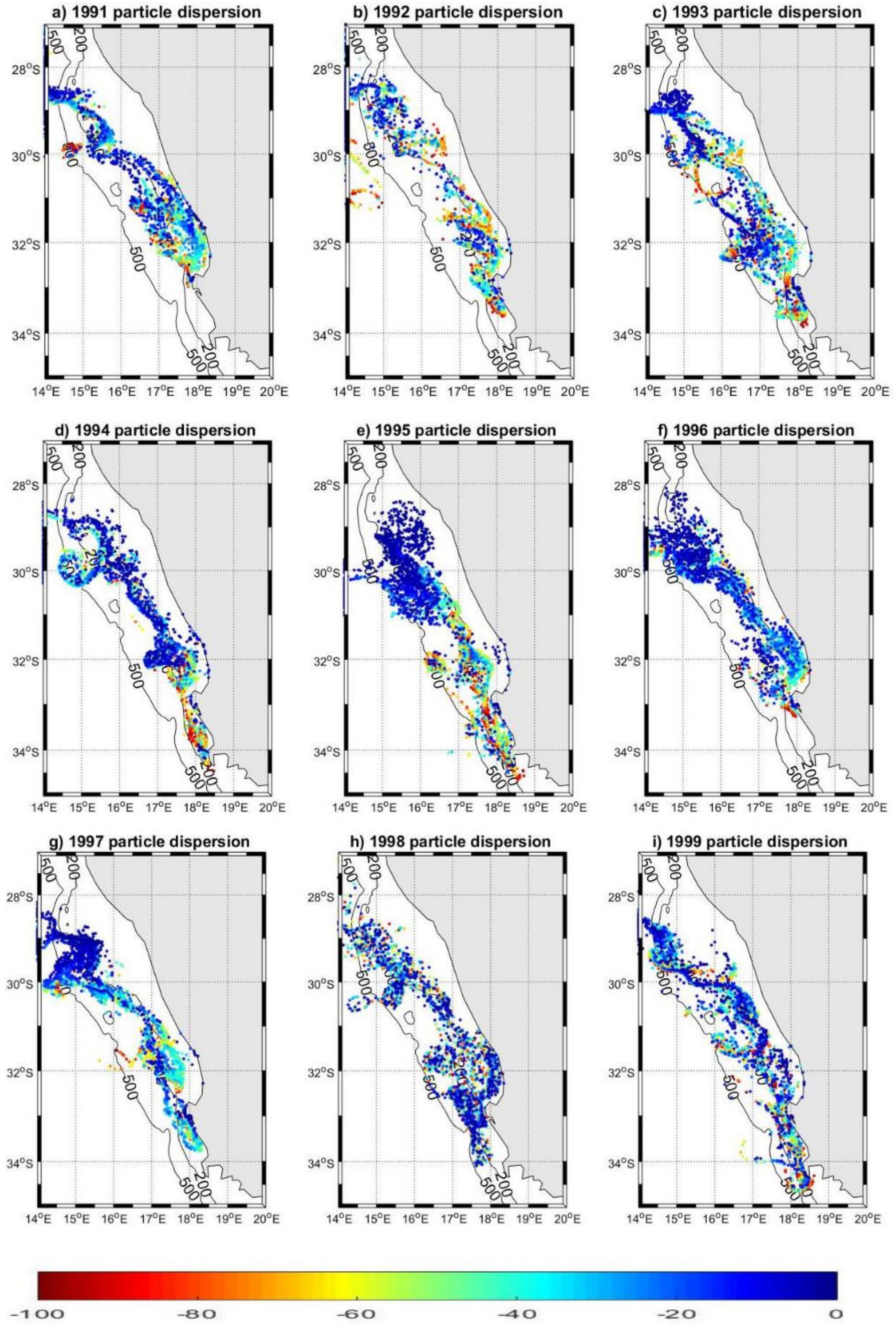


Figure 5.2 1991 to 1999 January particle dispersion at the end of the simulation. The colour of the drifter particles indicates the depth at which the particles started at the beginning of the simulation. The colour bar indicates the depth of the drifters at the start of the simulation.

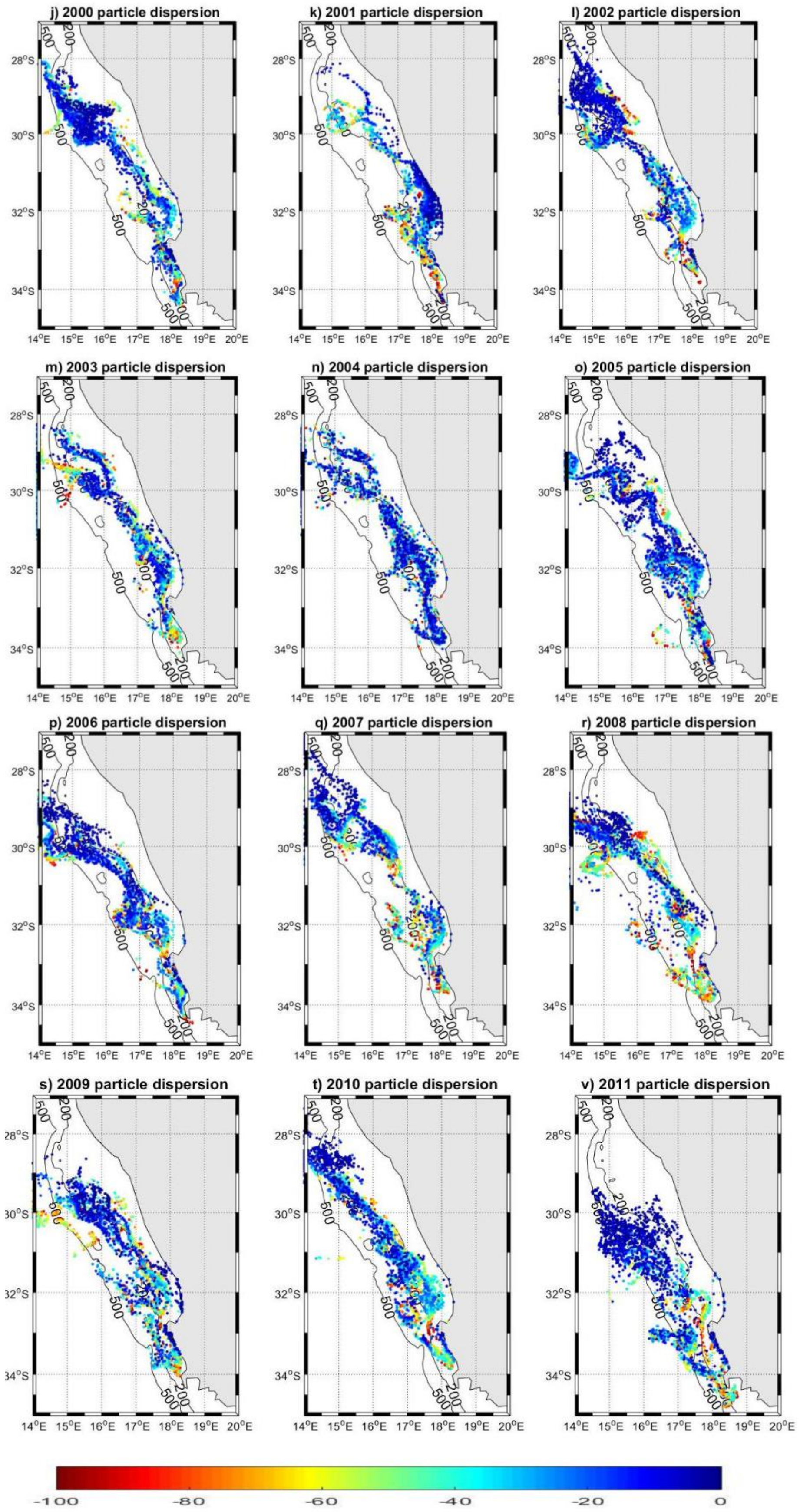


Figure 5.3 2000 to 2011 January particle dispersion at the end of the simulation. The colour of the drifter particles indicates the depth at which the particles started at the beginning of the simulation. The colour bar indicates the depth of the drifters at the start of the simulation.

In figure 5.1 figure 5.2 illustrate the dispersal patterns on the 30th day of the simulation for each year are observed. Due to the current and prevailing winds, the drifters are advected north-westwards, the same direction as the Benguela Jet. 8 of the 21 years (1994, 1995, 1999, 2000, 2001, 2005, 2006, 2011) have drifters that have been advected down to Cape Point. Only 2001 has no particles that cross west of the 500 m isobath. All the other years have drifters that end up west of the 500 m isobath at varying quantities.

Winter particle dispersion

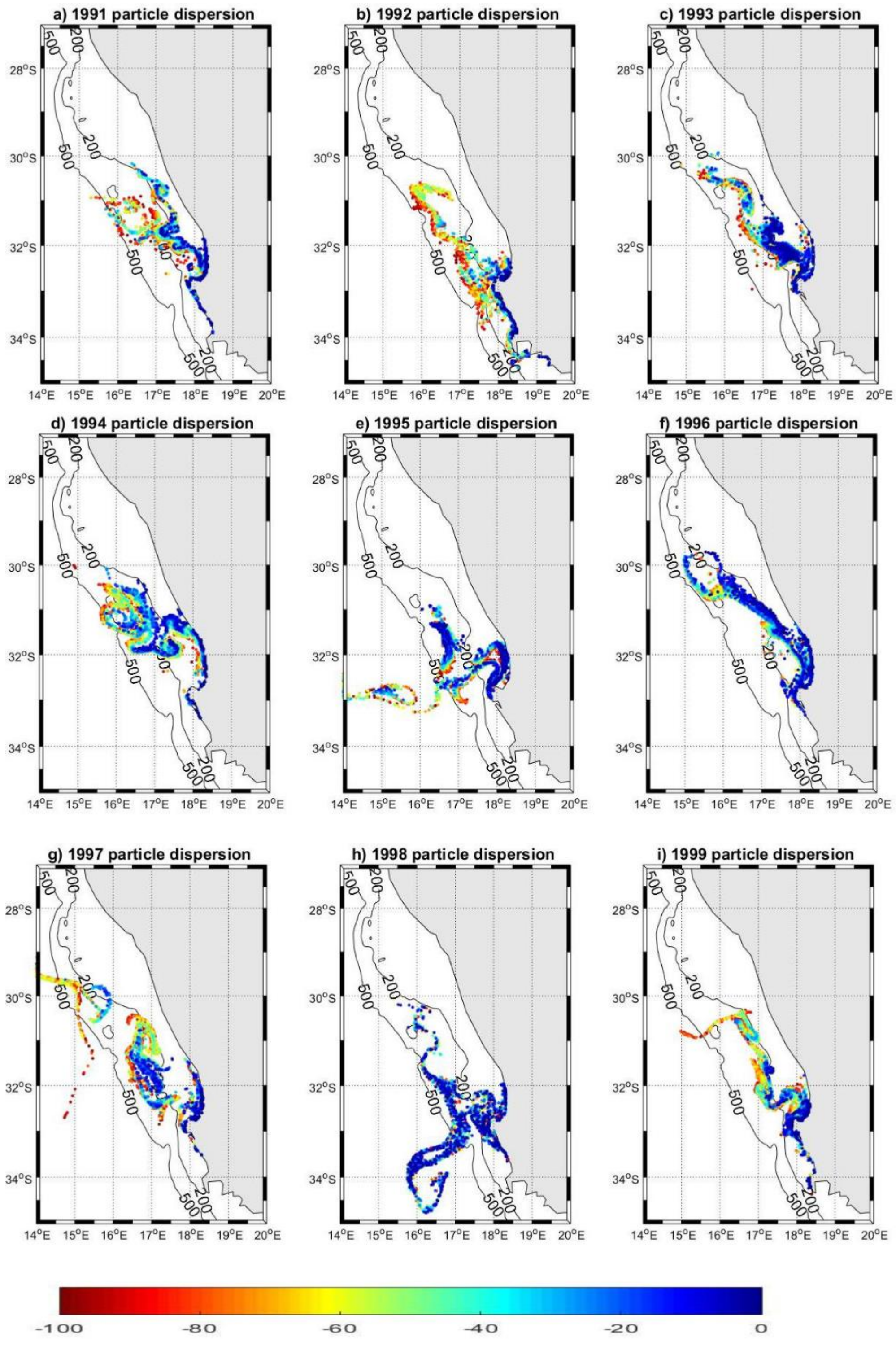


Figure 5.4 1991 to 1999 January particle dispersion at the end of the simulation. The colour of the drifter particles indicates the depth at which the particles started at the beginning of the simulation. The colour bar indicates the depth of the drifters at the start of the simulation.

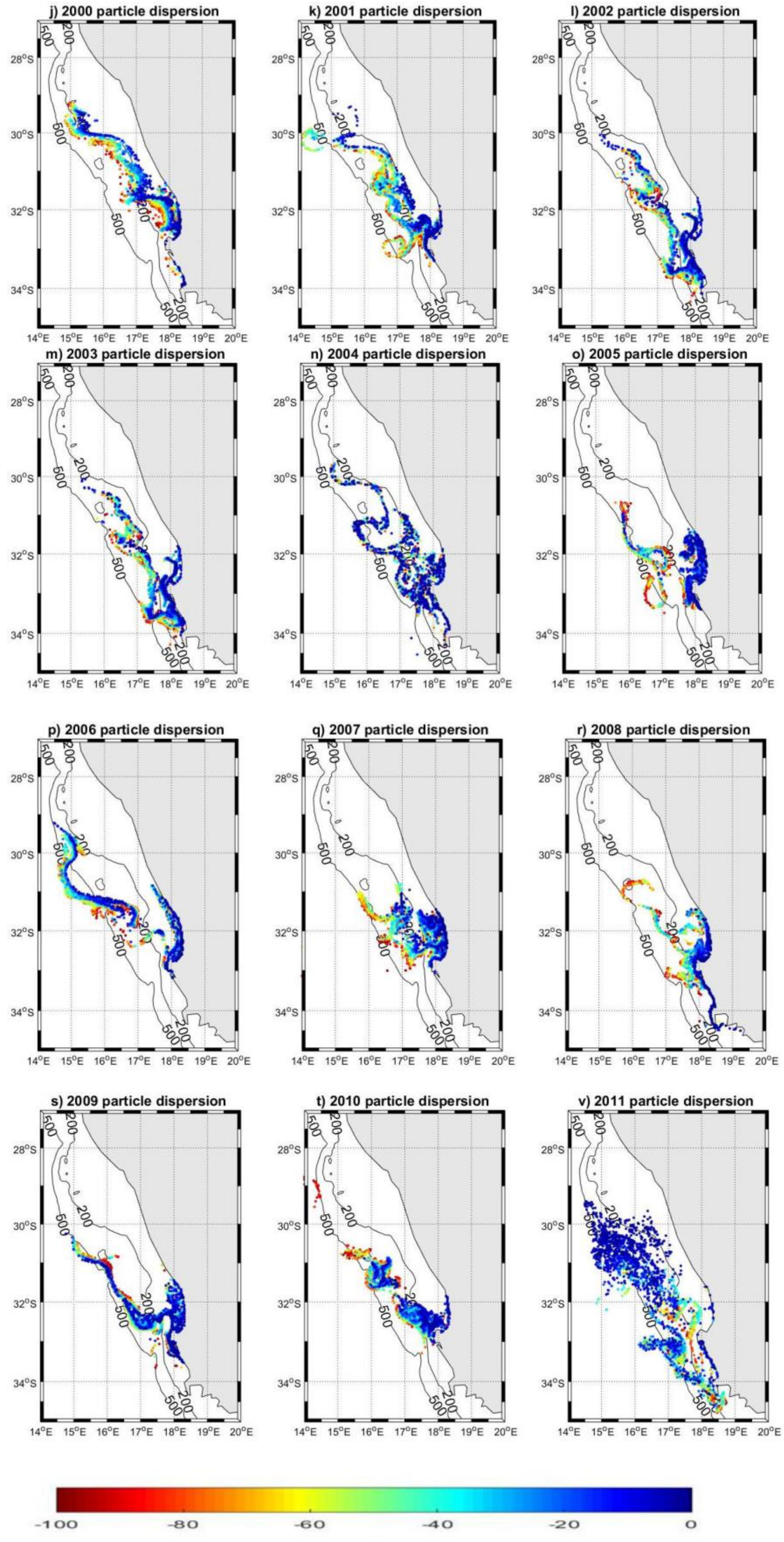
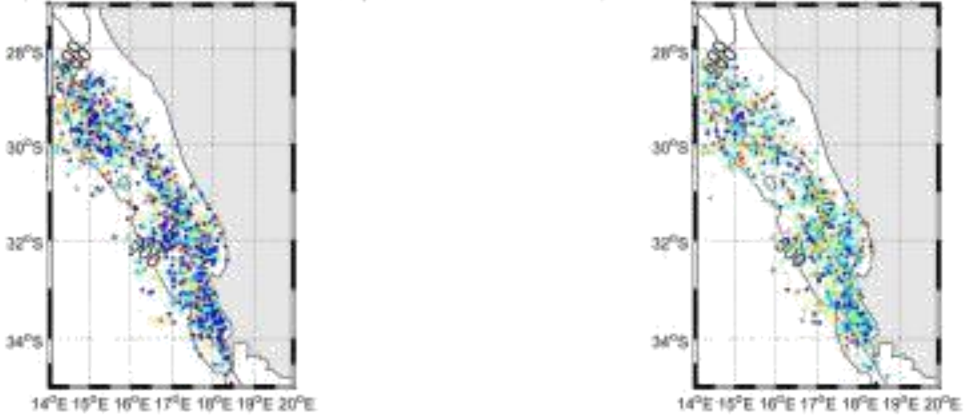


Figure 5.5 2006 to 2011 July particle dispersion at the end of the simulation. The colour of the drifter particles indicates the depth at which the particles started at the beginning of the simulation.

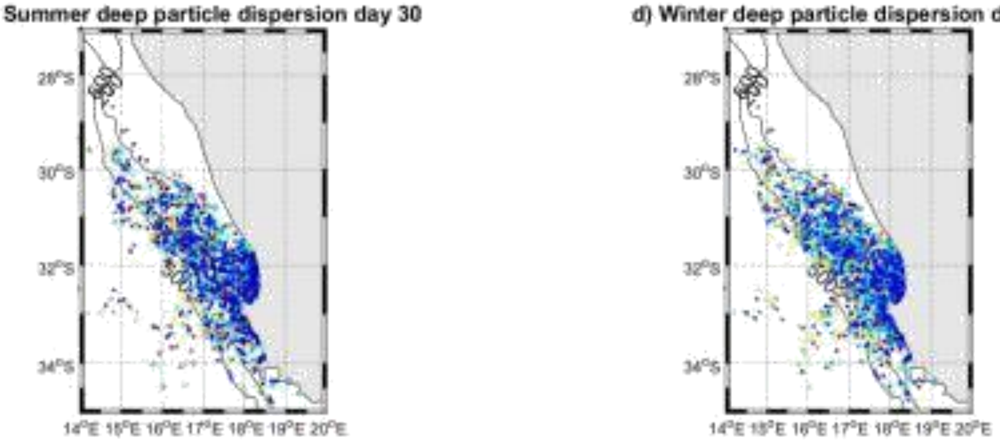
The winter dispersal patterns are shown in figure 5.2. The circulation patterns between the two seasons differ. In summer, the drifters are advected north westward and are more spread out than in winter. In winter, the particles are not advected as north westwards as summer. The drifters are also more clustered closer together. Many drifters are clustered along the coast. Of the 21 years, there are only 4 years (1992, 2002, 2008, 2011) have drifters that reach Cape Point. In the years 1992, 1993, 1996, 2000 and 2008 do not have drifters crossing west of the 500 m isobath.

5.2.2 Seasonal and differing depths particle dispersion

Figure 5.6 shows the different dispersal patterns in the summer and winter seasons in the different water depths, surface and deep water. Of the 8000 particles used in the simulation, only 4000 are plotted below. In all the seasons and different depths, the particles are all advected north westward. The trajectory of the particles follows the same path than of the Benguela Jet. The dispersion in the summer surface and the winter surface waters are similar. Most of these particles are dispersed east of 500 m isobath. Some of the drifters are transported southward, reaching Cape Point. In comparison, the summer surface waters are more dispersed than summer deep water. The same is true for the winter surface and winter deep waters. The summer and winter deep waters are similarly dispersed, remaining closer to St Helena Bay than the surface particles in higher concentrations. Majority of the particles are located east of the 500 m isobath.


a) Summer surface particle dispersion day 30

b) Winter surface particle dispersion day 30


c) Summer deep particle dispersion day 30

d) Winter deep particle dispersion day 30

Figure 5.6 Seasonal particle dispersion separated by the surface and deep waters. The colors are not a representation of any properties. Figure (a) is the summer surface particle dispersion, (b) is the winter surface particle dispersion, (c) the summer deep particle dispersion and (d) winter deep particles dispersion.

5.3 Seasonality in the retention of drifters

Figure 5.3 below shows the percentage of particles that were released in the surface waters in both seasons and their progression through the 30 days of the simulation. The 21 years have been seasonally averaged. At the beginning of the simulation in both seasons, 96 % of the drifters were retained in the surface waters. The majority of the particles in summer are lost in the first 10 days. By the 10th day, only 21 % of the drifters were retained in the summer. In contrast, in winter, 62 % of the particles remained in the retention zone by the 10th day. By day 15, 11% of the particles remained retained in summer and gradually decreased to 6 % retention rate by the end of the simulation. Interesting to note, in winter on the 27th day, the particles decreased to 43 % in the retention zone. On day 28, more drifters returned into the retention zone, increasing the percentage of drifters retained by 1%. Drifters once again exited the retention zone resulting in 43 % of the particles were retained at the end of the simulation. The decrease in retained drifters in summer took place rapidly while in winter the decrease was more gradual over time. The more successful retention seasonally takes place in winter as 37 % more drifters are retained in winter than summer.

Through the water column, the most successful retention takes place at the surface as a higher number of drifters remain in the retention zone on the surface waters than the deep waters.

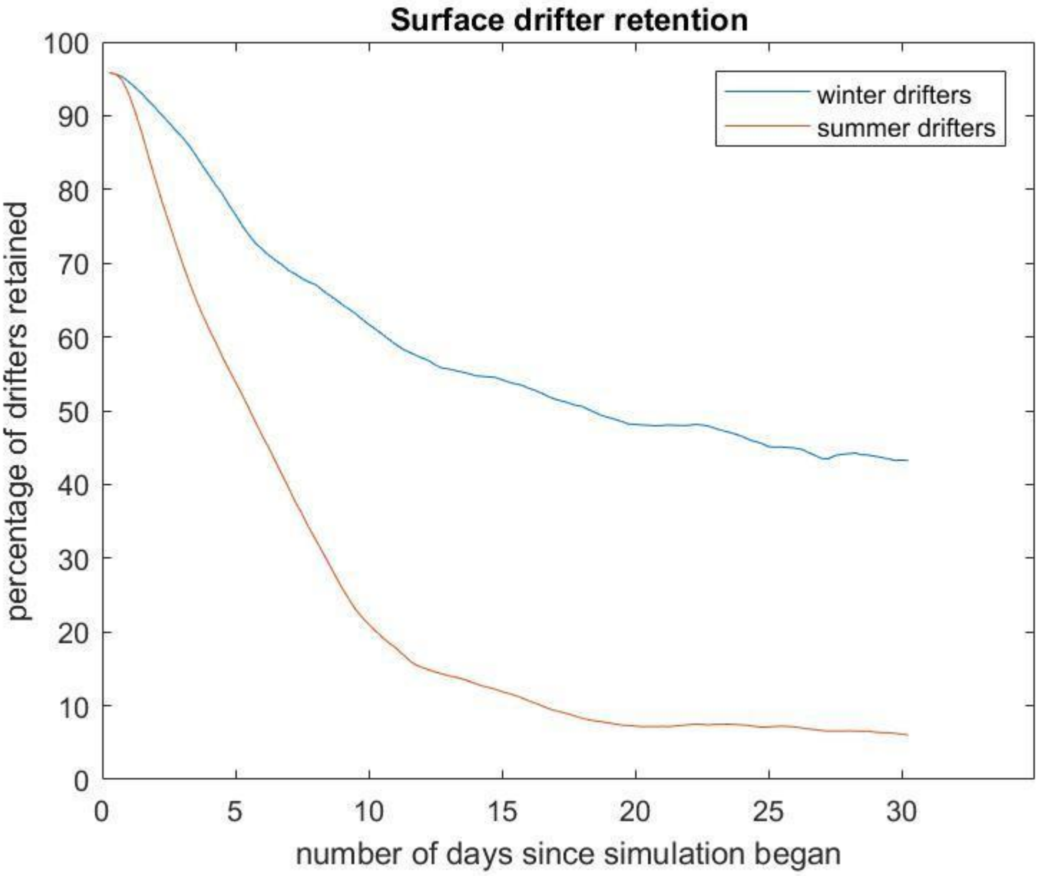


Figure 5.7 Time series of the percentage of particles retained through time in the summer season in the surface and waters

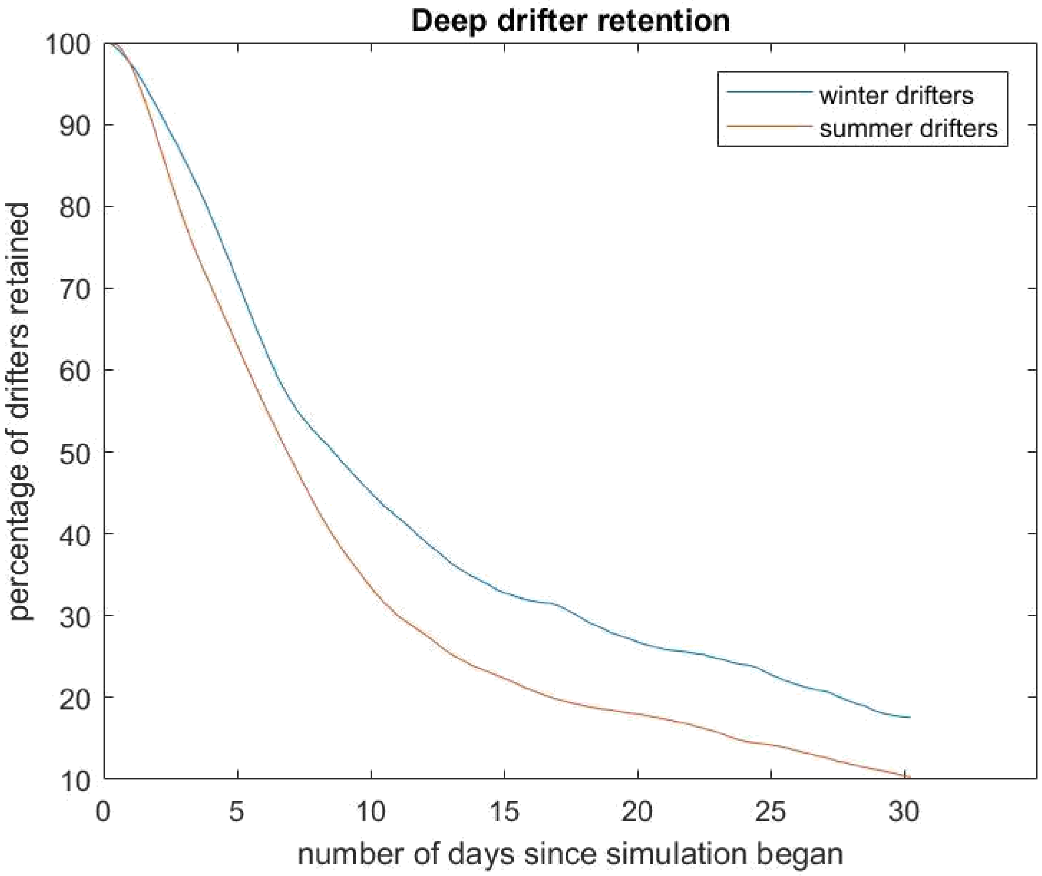


Figure 5.8 Time series of the percentage of particles retained through time in the winter season in the surface waters

The deep water drifters retained is displayed in figure 5.4. When the simulation began, in both seasons 100 % of the particles were retained. Both seasons show similar exponential decrease of retained particles with more drifters remaining retained in the winter than summer. On the 8th day only half of the drifters had not left the retention zone for the winter season. In summer, the 50 % retention of particles mark was reached sooner on day 6. The summer drifters continue to leave the retention zone faster than the winter drifters, with 25 % of the drifters remaining on the 13th day. The winter drifters only reached this mark on day 22. At the end of the simulation, more drifters were retained in the winter season with a percentage of 18 % while in summer only 10 % of the drifters were retained. Both seasons show similar patterns of decreasing exponentially.

Contrasting the surface and deep water drifters, in summer, more particles are retained in the deep water than the surface waters. In winter, the surface particles are retained more than the deep waters.

The mean and standard deviations for the percentage of the particles retained in the different seasons and different water depths for the 30th day for all the study years. The mean of the particles retained was calculated using the following formula:

$$\bar{x} = (\Sigma x_i) / n$$

Where X_i is all the drifters retained at certain time intervals on day 30 and n is the number of the drifters retained on day 30. Thereafter the standard deviation of the retained drifters was calculated. This was done using the following formula using the mean of the 30th day:

$$\text{Standard Deviation} = \sqrt{\frac{\sum_{i=1}^{n}(Xi-\bar{X})^{2}}{N-1}}$$

Where n and x_i is the same as above, $\bar{x}$ is the mean, and N is the number of the drifters retained in the retention zone.

Examining table 1 below, more retention takes place in the surface water than in the deep water. On average, about 25 % of the drifters stay in the retention zone in the surface water while about 14 % remain in the deep water. The high standard deviation in the total surface retention as compared to the total deep water retention reveals that the surface particles values have higher variations of retained drifters than the deep water particles. In total, the summer waters retain less drifters than the winter drifters. The summer waters retain 4 % while the winter waters retain 10 % more in comparison. There is a slightly higher variation in the number of drifters retained in the total winter retention than the total summer retention.

In summer, the surface water retains the least number of drifters when compared to the summer deep water. The deep water drifters in summer more clustered together than the surface water drifters in summer as observed in figure 5.6. Only 6% of the summer surface water drifters stayed in the retention zone.

Comparing the summer surface waters to the winter surface waters maps reveals that the winter surface waters retain far more drifters however the drifter numbers are closer to the mean value in the summer surface waters than the winter surface waters seen through the lower standard deviation percentage.

More drifters are remaining in the retention zone in the winter deep water than in the summer deep water. When contrasting the winter deep water with the winter surface water, the results show that more retention occurs in the surface water (43 % of the drifters are retained compared to the 18 % of the winter deep water). The winter surface waters show more dispersion within the retention zone than the winter deep water.

Table 1: Means and standard deviations for the percentage of the particles retain in the different seasons and water depths for day 30.

Retention index	Mean	Standard deviation
Total retention	25	22
Total Surface water	25	21.8
Total Deep water	14	7.4
Total Summer	4	3.2
Summer surface water	6	3.6
Summer deep water	11	4.8
Total Winter	14	6.0
Winter surface water	43	15.5
Winter deep water	18	7.9

5.4 Linking Lagrangian particle tracking with ocean dynamics

Using the Ichthyop Lagrangian particle tracking, 8 000 passive drifters are released from St Helena Bay and are advected by the ocean currents. Their locations at the end of the experiment on 30-day were plotted and the retention numerically quantified.

Retention is more prominent in winter than in summer as there are more drifters that remain in the retention zone (table 1). This result is confirmed by the particle dispersion plots as the drifters are closer to St Helena bay at the end of the experiment in winter than in summer.

Aiding retention is the position of St Helena Bay in relation to the Benguela current. The Bay is sheltered from the direct impacts of the Benguela current. The prevailing winds in the winter, the westerly, decrease in magnitude the alongshore velocities, increasing the retention rates. The Benguela current appears to function as an impediment to cross-shelf exchanges of drifters as the particles are advected northwards and west of the 500 m isobath in the higher latitudes, there are no drifters advected to that region in summer. The drifters are confined to the continental shelf. In winter, the barrier is not as strong especially in some years (1995, 1998 and 2005) as some drifters are found off the continental shelf.

The seasonality of retention can be associated to the seasonality of the currents. The summer season has lower retention rates because of the acceleration of the Benguela Jet transporting the drifters north westwards and increased upwelling. The increase in speeds of the Jet is caused by the strong density gradient that exists in summer when upwelling is strongest causing the nearshore sea temperatures to be colder than the offshore domain. The upwelling prevailing in summer causes offshore Ekman transport, resulting in more drifters being transported offshore in summer than in winter. In winter, the winds change from the south easterly of the summer to westerly, resulting in onshore Ekman transport and reduced to no upwelling, keeping the drifters trapped closer to the coast.

Although the Benguela Jet is present at depths of 200 m, the speeds at depth are slower than at the surface, increasing the retention rates of the winter deep waters compared to the summer deep waters.

This results in a weaker cyclonic circulation in St Helena Bay. Due to this, more drifters are retained in the surface waters. The drifters on the summer surface waters are lost in the retention zone more when compared to winter surface drifters for the same reasons as above. Additionally, drifters are lost through the nearshore poleward counter current that is carrying the drifters southwards. In summer, this poleward current is stronger than in winter resulting in the drifter distribution seen in figure 5.1 where in some years, the drifters travel all the way to Cape Point.

The total surface water retains more drifters than the total deep water. At depth influence of the Benguela Jet and the nearshore poleward counter current are reduced in comparison to the surface. This results in less retention at depth as the Jet and the poleward counter current create the recirculation observed in the bay are less intense. The Cape Columbine upwelling plume also contributes to more retention on the surface however its effects decrease with depth, decreasing the retention potential at depth.

In summer, the deep waters retain more drifters than the surface waters. The currents are slower at depth contributing to more drifters remaining in the retention zone. The winds have more of an effect on the drifters on the surface waters blowing them out of the retention zone. The winter season surface and deep water comparisons differ from the summer surface and deep retention. In winter, more drifters are retained in the surface than in the deep winter waters. This is due to the stronger poleward nearshore counter current on the surface than at depth. The strength of this current on the surface together with the Jet increase the clockwise circulation in the bay, inhibiting particles from drifting offshore.

At depth, more drifters remain in the retention zone in winter than in summer. The reason for this occurrence is the shifting of the cyclonic circulation at depth. In winter, it is more onshore, keeping the drifters onshore. The shifting of the circulation is due to the weakening of the winds. The pattern of how the drifters are lost between the summer and winter deep waters is very similar (figure 5.3 and 5.4).

Chapter 6

Conclusion

The aim of this numerical study was to use a high-resolution model to study the physical properties of the retention observed in previous studies in St Helena Bay. The retention in this region is important as St Helena Bay is a nursery area for pelagic fish that are vital to the fishing industry. In this chapter, the results are summarised according to the research objectives of the study underlined in chapter one.

The seasonality of the retention is investigated. The circulation patterns of all four seasons were examined using atmospheric forcing, sea temperature and ocean currents. The model was able to simulate the upwelling, the surface currents (including the Benguela Jet) and the nearshore poleward counter current and a retention pattern. Over the study region, especially in summer, a high SST bias exists however these biases are believed, to a large extent, to not have any influence on the results obtained.

The Ichtyop Lagrangian tracking tool was used to quantify the retention. 8000 particles were released each year from 1991 to 2011 on the first of January and July which are a proxy for the summer and winter seasons correspondingly. The particles were released in St Helena Bay throughout the water column and the simulation was ran for 30 days. The results show a clear seasonal cycle in the retention of particles. More particles in were retained in winter than in summer due to the circulation patterns. This is because in winter, the change in the wind regime decreased the upwelling and the offshore Ekman transport. The direction of the wind was more onshore aiding retention. The cyclonic circulation observed in previous studies believed to be one of the main mechanisms of retention was also observed more strongly in summer than winter. The reduction in the Benguela Jet speed in winter resulted in less drifter particles being transported north westward and remaining in the retention zone.

Looking at retention through the water column, more drifters were retained in the surface than in the deep water. In summer, more drifter particles were retained in the deep water than in the shallower water. The surface waters were defined as waters from the surface to 30 m and deep waters were defined as waters from 31 m to the water column bottom. At depth, the currents are moving slower than the surface with less influence from atmospheric forcing. The Benguela Jet is weaker at depth with the nearshore poleward current is stronger. The cyclonic circulation is more defined at depth in contrast to the surface. All of these factors aid in more retention being observed in the deeper waters than the surface waters. When the particles have left the retention zone, the ocean circulation pattern prohibit them re-entering.

The study can be further improved. Although the model used is a high resolution, further improvements can be made. The wind forcing used in the model can be improved to decrease the warm bias observed in the inner shelf. The finer scale dynamics of the inner shelf may be better captured through an enhancement of the horizontal resolution. The understanding of the seasonality of the retention may better understood by studying the autumn and spring seasons using the particle tracking method. This study only quantified the retention for the January and July months. It might be interesting to study the other months to further improve the comprehension of retention.

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