BUILDING A MEAN-STATE OF OCEANOGRAPHIC PROPERTIES (TEMPERATURE AND SALINITY) FOR THE KWAZULU-NATAL BIGHT USING THE ROMS MODEL: A CONTRIBUTION TOWARDS MARINE PROTECTED AREAS ANALYSIS

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NRF National Research Foundation | SAEON South African Environmental Observation Network

AMSOL AFRICAN MARINE SOLUTIONS

PLAGIARISM DECLARATION

I, Mathabo Noxolo Malange, declare that the contents of this dissertation/thesis represent my own unaided work, and that the dissertation has not previously been submitted for academic examination towards any qualification. Furthermore, it represents my own opinions and not necessarily those of the University of Cape Town. Harvard reference style was used in this dissertation.

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ABSTRACT

The KwaZulu-Natal Bight, located along the east coast of South Africa, is an important recruitment and nursery area for various marine species. In an effort to conserve a number of threatened species, two Marine Protected Areas (MPA) have been established in the Bight. The African Coelacanth Ecosystem Programme is conducting MPA analyses along the Bight through a series of biological and oceanographic studies and this study forms part of the oceanographic research component that will assist in the decision-making process of MPAs in the region.

This study uses a 30-year, high-resolution, regional ROMS simulation to build a climatology representative of the mean-state of the Bight. The model is also used to investigate the seasonal and annual variability as well as the influence of the Agulhas Current on the shelf. The Bight was cooler and less saline than the surrounding waters and seasonal variation was limited to the upper 50 m of the water column. The depth of the Bight ranges from 50 m in the inner shelf to 100 m at the shelf edge in the central region of the Bight. In the northern and southern region of the Bight, the depth of the water column extends down to about 150 m at the shelf edge. In summer, surface temperatures were on average 4.8°C and 4.3°C warmer than in winter over the uThukela Banks and Aliwal Shoal respectively. Bottom temperatures at both MPAs had a mean seasonal variation of about 3°C. Salinity, a more conservative variable, showed little variability over the year throughout the water column except for at 50 m where lower salinities were observed in the winter months. Wavelet analysis showed that a strong annual (12 month) signal was dominant at the surface (10 m). Bottom temperatures displayed a weaker annual signal than the surface in addition to a slight semi-annual cycle. Further investigations indicated that the Agulhas Current influenced the Aliwal Shoal MPA more than the uThukela Banks MPA as they shared similar temperature values (at the surface and bottom) throughout the 30-year period. In contrast, the uThukela was cooler than the Agulhas Current by 0.5 to 1.5°C at the surface and 1 to 2.5°C at the bottom. These time series also enabled us to identify anomalous features such as the Natal Pulse that could have important implications for temperature-sensitive species in the area.

Table of Contents

PLAGIARISM DECLARATION i

ABSTRACT ii

ACKNOWLEDGEMENTS xi

1 INTRODUCTION 1

1.1 Study Area 3

1.2 Objectives of this study 3

2 LITERATURE REVIEW 5

2.1 The KwaZulu-Natal Bight 5

2.2 Oceanographic Features 7

2.2.1 The Agulhas Current 7

2.2.2 Upwelling at Richards Bay 9

2.2.3 Durban Cyclonic Eddy 9

2.3 Water Characteristics 10

2.3.1 Water Masses 11

2.3.2 Temperature 12

2.3.3 Salinity 14

2.4 Importance of Oceanography for MPA Analysis 15

3 DATA AND METHODS 16

3.1 Regional Ocean Modelling Systems (ROMS) 16

3.1.1 Model Domains 16

3.1.2 Bathymetry 18

3.1.3 Lateral Boundary Conditions 19

3.1.4 Surface Boundary Conditions (Forcing) 19

3.2 Conductivity Temperature and Depth (CTD) Measurements 20

3.2.1 Temperature Profiles 22

3.2.2 Salinity Profiles 24

4 RESULTS 26

4.1 Mean-State Oceanographic Conditions of the Bight 26

4.1.1 Water Masses 27

4.1.2 Horizontal Distribution of Temperature and Salinity 28

4.1.3 Vertical Distribution of Temperature and Salinity 36

4.2 Interannual variability 40

4.3 The Influence of the Agulhas Current on the Bight 49

4.3.1 Anomalous Events 50

5 DISCUSSION 53

5.1 Mean-State of the Bight 54

5.1.1 Water Masses 54

5.1.2 Mean-state of temperature and salinity 54

5.2 Interannual Variability 56

5.3 Influence of the Agulhas Current on the Shelf 57

5.3.1 Anomalous Events 57

5.4 Importance of the Study and Limitations 57

6 CONCLUSION 58

7 REFERENCES 61

Table of Figures

Figure 1-1: The two newly established Marine Protected Area sites in the KwaZulu-Natal Bight (adapted from Meyer et al. 2002) 3

Figure 2-1: Map of the KwaZulu-Natal Bight (highlighted in grey) on the east coast of South Africa from Cape St. Lucia (1) to Durban (2) with the Thukela River (A) situated in the central region of the Bight. The contours show the general bathymetry of the Bight (adapted from Meyer et al. 2002). 5

Figure 2-2: Monthly freshwater inflow from rivers that flow into the KZN coast as a percentage of annual inflow. Summer months (October to April) have a higher inflow due to increased rain fall in summer and the winter months (May to September) have lower inflow (%) due less rain fall in the winter (Hutchings et al. 2010 modified by de Lecea and Cooper, 2016). 6

Figure 2-3: The path of the Agulhas Current along the east coast of South Africa (bold arrows), which flows close and parallel to the east coast of South Africa but diverges at St. Lucia around the Bight and converges south of Durban, near Port St. Johns (Lutjeharms, 2006b). Note: The Natal Bight term used in Lutjeharms (2006b) refers to the Bight... 8

Figure 2-4: The temperature and salinity structure of the water column when: (a and b) the eddy is not present, the isotherms are fairly horizontal and less saline waters are found on the shelf (c and d) the eddy is present, there is an upward doming of the isotherms bringing cooler and more saline waters to the surface (outlined in dashed black rectangle) (Guastella and Roberts, 2016). 10

Figure 2-5: Temperature salinity (TS) diagram of the south east coast of South Africa. Bight waters consist of TSW, which dominate the surface waters and below them are SSTW. Central waters have been reported to occasionally enter the Bight through upwelling mechanisms. Antarctic Intermediate Water, North Atlantic Deep Waters and Antarctic Bottom Water are found further offshore of the Bight in much deeper waters. The outdated figure emphasises the need to revisit the Bight oceanographically (Schumann and Orren, 1980) 12

Figure 2-6: Vertical profiles of temperature at five focus sites during February 2010 (top row) and August 2010 (bottom row). DE: Durban Eddy; MS: Mid Shelf; TM: Thukela Mouth; RS: Richards Bay South; RN: Richards Bay North (Barlow et al. 2013). 13

Figure 2-7: Mean SST (°C) from 14 airborne Radiation thermometry (ART) surveys (dashed line is flight track) also showing the colder water in the northern region of the Bight (Roberts and Nieuwenhuys, 2016). 14

Figure 2-8: Salinity (PSU) vertical cross sections north of the Bight at Richards Bay (left) and in the Central Bight (right) during The Natal Bight Cruise (16-22 July 1989) (Lutjeharms et al. 2000a). 15

Figure 3-1: The ROMS configuration consists of a 1/12° (~ 9km) domain of the southeast and southwest coast of Southern Africa (3 - 34°E, 16 - 45°S) nested in a 1/4° (~ 25km) domain of the southeast Atlantic and south-west Indian Ocean (27°W - 70°E, 7°N - 48°S) outlined in black. The location of the Bight is outlined in red. The domains are shown over a map of bathymetry (m). 17

Figure 3-2: The grid spacing of the a) outer domain at 1/4° resolution and b) the inner domain at 1/12° resolution. 18

Figure 3-3: a) Smoothed bathymetry over the Bight b) Raw 1' GEBCO bathymetry 19

Figure 3-4: Surface momentum (top panel), heat (middle panel) and freshwater (bottom panel) fluxes for summer (left panel) and winter (right panel). Summer and winter are represented by a monthly average for January 2010 and July 2010, respectively. 20

Figure 3-5: Location of where the CTD casts were deployed across the Bight for all years (2014 to 2017) plotted over GEBCO bathymetry.. 22

Figure 3-6: CTD temperature (°C) profiles taken in the May to July period for the ACEP KZN Bight project in a) 2014 b) 2015 c) 2016 where there is a distinct variation between casts taken on the bank (shallower) and off the bank (deeper) and d) 2017. The number of casts taken by ACEP varied each year with 2016 having the most casts and 2017 having the least. 24

Figure 3-7: CTD salinity (PSU) profiles taken in the May to July period for the ACEP project in a) 2014 b) 2015 c) 2016 where there is a distinct variation between casts taken on the bank (shallower) and off the bank (deeper) which is also seen in the temperature profiles and d) 2017. The number of casts taken by ACEP varied each year with 2016 having the most casts and 2017 having the least. 25

Figure 4-1: The uThukela Banks MPA and Aliwal Shoal MPA, demarcated by black dashed boxes (--), plotted over a ROMS bathymetry map. Black stars (*) indicate the points where the time series were potted. White dashed lines indicate where the vertical sections were plotted from. Blue crosses (x) indicate the points where TS diagrams were plotted from. 27

Figure 4-2: Temperature salinity (TS) diagram, obtained from ROMS, at all three focus sites: Richards Bay, the Central Bight and south of Durban with an additional site offshore of the Bight in the Agulhas Current used as a reference point. ITSW: Indian Tropical Surface Waters; SSTW: South Indian Subtropical Surface Waters; SICW: South Indian Central Water. 28

Figure 4-3: The path of the Agulhas Current along the east coast of South Africa. The arrows indicate the direction and magnitude of the current and the colour palette indicates the speed. The black lines demarcate the Thukela Banks MPA (north) and the Aliwal Shoal MPA (south). 29

Figure 4-4: ROMS monthly climatology maps of temperature (°C) across the Bight with isotherms (grey lines) at a depth of 10 m for every month of the year. The location of Richards Bay (north) and Durban (south) along the coast are indicated by the black dots. 31

Figure 4-5: ROMS monthly climatology maps of salinity (PSU) a depth of 10 m across the Bight. The grey lines represent isohalines. The location of Richards Bay (north) and Durban (south) along the coast are indicated by the black dots. 32

Figure 4-6: ROMS monthly climatology maps of temperature (°C) across the Bight with isotherms (grey lines) at a depth of 50 m for every month of the year. The location of Richards Bay (north) and Durban (south) along the coast are indicated by the black dots. The bathymetry is indicated in white. This is where the bight is shallower than 50 m in the model. 33

Figure 4-7: ROMS monthly climatology maps of salinity (PSU) a depth of 50 m across the Bight. The grey lines represent isohalines. The location of Richards Bay (north) and Durban (south) along the coast are indicated by the black dots. The bathymetry is indicated in white. This is where the bight is shallower than 50 m in the model. 34

Figure 4-8: ROMS monthly climatology maps of temperature (°C) across the Bight with isotherms (grey lines) at a depth of 100 m for every month of the year. The location of

Richards Bay (north) and Durban (south) along the coast are indicated by the black dots. The bathymetry is indicated in white. 35

Figure 4-9: ROMS monthly climatology maps of salinity (PSU) across the Bight with isotherms (grey lines) at a depth of 100 m for every month of the year. The location of Richards Bay (north) and Durban (south) along the coast are indicated by the black dots. The bathymetry is indicated in white. 36

Figure 4-10: Temperature (°C) vertical sections, obtained from ROMS, across the uThukela Banks MPA for each month of the year. The coast and bathymetry are indicated in white. 38

Figure 4-11: Salinity (PSU) vertical sections, obtained from ROMS, across the uThukela Banks MPA for each month of the year. The coast and bathymetry are indicated in white.38

Figure 4-12: Temperature (°C) vertical sections, obtained from ROMS, across the Aliwal Shoal MPA for each month of the year. The coast and bathymetry are indicated in white.39

Figure 4-13: Salinity (PSU) vertical sections, obtained from ROMS, across the Bight offshore Aliwal Shoal MPA for each month of the year. The coast and bathymetry are indicated in white. 39

Figure 4-14: Time series of monthly-averaged temperature (°C) at the uThukela Banks MPA from 1980-2010 (top figure). Monthly temperature anomalies (°C) at the uThukela Banks from 1980-2010 (bottom figure). The red time series represents the temperature at the surface (10 m) and the blue time series represents the temperature at the bottom (50 m). 42

Figure 4-15: (a and c) Wavelet power spectrum and (b and d) power of the wavelet analysis of temperature over the uThukela Banks MPA at the surface (10 m) and at the bottom (50 m) for ROMS. The cone of influence (COI) is indicated by the dashed black line, and the thick black contours indicate the 95% significance levels. Significance in the global wavelet spectrum is indicated by the red dashed line. 43

Figure 4-16: Time series of monthly-averaged salinity (PSU) at the uThukela Banks MPA from 1980-2010. Monthly salinity anomalies (PSU) at the uThukela Banks from 1980-2010 (bottom figure). The orange time series represents the salinity at the surface (-10 m) and the light blue time series represents the salinity at -50 m). 44

Figure 4-17: (a and c) Wavelet power spectrum and (b and d) power of the wavelet analysis of salinity over the uThukela Banks MPA at the surface (10 m) and bottom (50 m) for

ROMS. The cone of influence (COI) is indicated by the dashed black line, and the thick black contours indicate the 95% significance levels. Significance in the global wavelet spectrum is indicated by the red dashed line. 44

Figure 4-18: Time series of monthly-averaged temperature (°C) at Aliwal Shoal from 1980-2010 (top figure). Monthly temperature anomalies (°C) at the Aliwal Shoal MPA from 1980-2010 (bottom figure). The red time series represents the temperature at the surface (10 m) and the blue time series represents the temperature at (50 m). 46

Figure 4-19: (a and c) Wavelet power spectrum and (b and d) power of the wavelet analysis of temperature over the Aliwal Shoal MPA at the surface (10m) and bottom (50 m) for ROMS. The cone of influence (COI) is indicated by the dashed black line, and the thick black contours indicate the 95% significance levels. Significance in the global wavelet spectrum is indicated by the red dashed line. 47

Figure 4-20: Time series of monthly-averaged salinity (PSU) at the Aliwal Shoal MPA from 1980-2010. Monthly salinity anomalies (PSU) at the Aliwal Shoal MPA from 1980-2010 (bottom figure). The orange time series represents the salinity at the surface (10 m) and the light blue time series represents the salinity at (50 m). 48

Figure 4-21: (a and c) Wavelet power spectrum and (b and d) power of the wavelet analysis of salinity over the Aliwal Shoal MPA at the surface (10 m) and bottom (50 m) for ROMS. The cone of influence (COI) is indicated by the dashed black line, and the thick black contours indicate the 95% significance levels. Significance in the global wavelet spectrum is indicated by the red dashed line. 48

Figure 4-22: Temperature differences between inshore and offshore the uThukela Banks MPA at the surface (10 m) (top figure) and at the bottom (50 m) (bottom figure). Red time series indicate the offshore temperatures and the blue time series indicate the inshore temperatures. 49

Figure 4-23: Temperature differences between inshore and offshore the Aliwal Shoal MPA at the surface (10 m) (top figure) and at the bottom (50 m) (bottom figure). Red time series indicate the offshore temperatures and the blue time series indicate the inshore temperatures. The black circles indicate anomalous periods. 50

Figure 4-24: (a and b) Temperature (°C) map for January 1996, the coolest month over a 30-year period at the Aliwal Shoal MPA and the corresponding anomaly map. (c and d)

Temperature map for April 2006, the warmest month over a 30-year period at both MPAs and the corresponding anomaly map. 51
Figure 4-25: The downstream travel of the Natal Pulse in January 1996 plotted in 3-day averages. 52

List of Tables

Table 2-1: Statistics of the Durban Eddy based on ADCP current data and MODIS and MERIS satellite imagery for a period of 17 months (Guastella and Roberts, 2016). 10

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1 INTRODUCTION

Marine environments globally are under threat due to climate change and other anthropogenic stresses such as pollution, ocean acidification and habitat degradation. Nonetheless, less than 4% of the oceans are formally protected, compared to about 15% of terrestrial environments (Spalding et al. 2013). Despite being under protected, the ocean plays a crucial role in providing food and other services as well as regulating the earth's climate.

Marine protected areas (MPAs) are regions of the ocean, estuaries or even large lakes where human activity is restricted to protect an endangered or threatened natural resource for conservation purposes (Spalding et al. 2013). MPAs have been widely proposed to protect estuarine and coastal systems, fisheries resources and critical habitats of endangered species (Edgar et al. 2007).

Many resource species have shown significant declines in biomass and abundance over the past few decades and need spatial management solutions that protect their habitats, and particularly their nursery/spawning areas. Bays and bights are nursery/spawning areas that are often influenced by anthropogenic activities, mainly fishing, due to their proximity to the coast (Ayers and Scharler, 2011). One of the key areas identified for protection along the South African east coast is the KwaZulu-Natal (KZN) Bight (hereafter referred to as 'the Bight') (Figure 2-1) because it is a region of larval retention, recruitment and a general nursery area (Fennessy et al. 2016b). Although the Bight is an oligotrophic environment, it receives a variable amount of nutrients throughout the year from oceanographic processes such as upwelling and riverine input, mainly during the rainy season (Omarjee, de Lecea and Smit, 2015). There are currently two newly established MPAs in the Bight: the uThukela Banks MPA situated offshore of the Thukela River, in the central region of the Bight and the expansion of the Aliwal Shoal MPA situated south of Durban (Figure 2-1). These MPAs fall under the Minister of Environmental Affairs' 22 newly established MPAs as part of Operation Phakisa, which is a government initiative to drive the development of the ocean economy (Sink, 2016). The uThukela Banks (5666 km^2) contains soft sediment habitats and is a nursery area for various pelagic fish species. The largest "Seventy-four seabreams" (*Polysteganus undulosus)* of the century have also been seen on the deep reefs of this area. The Aliwal Shoal MPA (1200 km^2) consists of deep reefs and is a spawning and nursery area for the threatened linefish. It is also the historic spawning grounds of overexploited “Seventy-four seabream” (RSA, 2016; MPAs South Africa, 2018). The purpose of these MPAs is to protect vulnerable habitats and secure spawning grounds for various marine species, therefore helping to sustain fisheries and ensure long-term benefits important to food and job security (RSA, 2016).

Despite the importance of this region, no dedicated Bight-wide oceanographic surveys or extensive measurements have taken place since 1989 and even afterwards, most surveys were once-off and taken only in specific regions of the Bight (Fennessy et al., 2016a; Green, 2015). In response to the paucity of environmental data, the South African Department of Science and Technology’s African Coelacanth Ecosystem Programme (ACEP), which has been prominent in supporting research on the east coast of South Africa and collected data for this project, is conducting MPA analyses along the Bight through a series of biological and oceanographic studies. This thesis forms part of the oceanographic research component that will assist in the decision-making process of MPAs in the region. Although some aspects of the oceanography of the Bight are known, there is a lack of long-term data at a suitable spatial and temporal resolution required for MPA analysis. This study aims to further our understanding of the oceanography of the Bight using oceanographic data collected in 2014-2017 between Richards Bay and Port Edward (Figure 1-1) as well as data obtained from a high-resolution regional ocean model.

In-situ measurements of key oceanographic variables such as temperature and salinity are vital when refining conservation plans that identify critical areas of biodiversity that require protection (Green, 2015). Since the Bight is a relatively under-sampled region, it is difficult to build a climatology and note long-term trends based on the in-situ data alone. Despite this, in-situ, subsurface, measurements are essential as they are able to obtain accurate data, detect small-scale variability and provide reliable information on short-term changes (Smit et al. 2013). Another possible source of data is satellite data; however, satellites are capable of only measuring the surface and with MPA analysis, it is important to understand the structure of the entire water column. With marine ecosystems existing in the bottom waters of the ocean, it is important to understand the dynamics below the surface. Fortunately, we are able to obtain long-term data from models, such as the Regional Ocean Modelling System (ROMS), that are able to simulate the ocean dynamics of a region. With ROMS, we are able to extract data for the entire water column to create a climatology.

1.1 STUDY AREA

This study focusses on the KwaZulu-Natal Bight ('the Bight') situated on the east coast of South Africa. As previously discussed, there are two newly established MPAs in the Bight: The Thukela Banks MPA situated offshore of the Thukela River and the Aliwal Shoal MPA situated south of Durban (Figure 1-1).

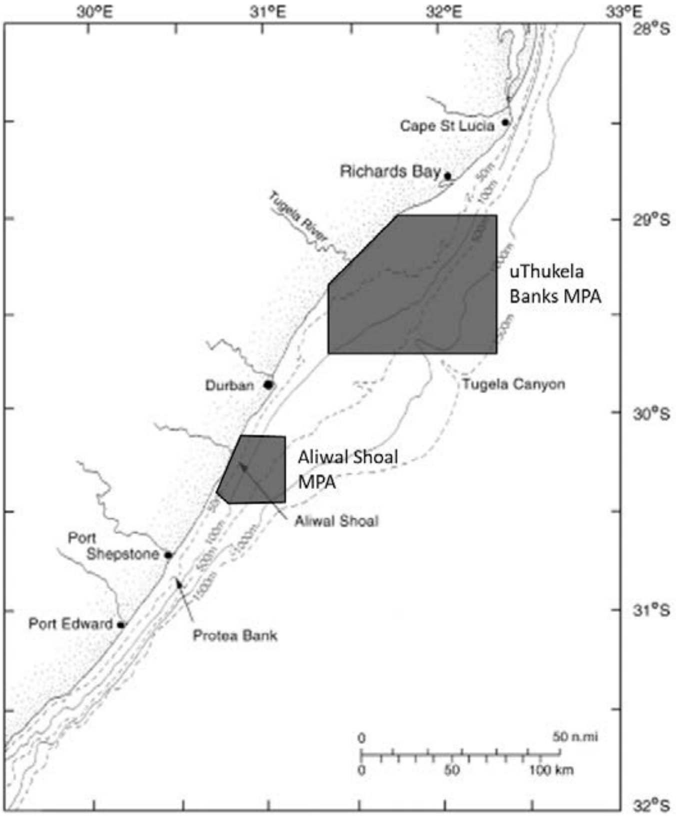


Figure 1-1: The two newly established Marine Protected Area sites in the KwaZulu-Natal Bight (adapted from Meyer et al. 2002)

1.2 OBJECTIVES OF THIS STUDY

Understanding the oceanographic environment of a region is important for MPA analysis. The knowledge of variables such as ocean temperature allows for an improved understanding of the response of the marine communities and enables more informed management decisions for MPAs. The aim of the project is to build a climatology of the oceanographic temperature and salinity in the Bight using an eddy-resolving ROMS simulation. This data will be used in conjunction with CTD data collected for the ACEP Marine Spatial Solutions project to enhance the work in the MPA regions of interest.

To achieve this aim, this project is separated into two components and will address the following objectives:

- Create a climatology from an eddy-resolving ROMS simulation over the Bight's newly established MPA regions and provide a description of the mean oceanographic environment with respect to seasonal variability.
- Discuss the effects of the Agulhas Current on the shelf at the newly established MPAs.

These objectives will be achieved by answering the following research questions:

- What are the baseline conditions in the Bight's established MPAs?
- What is the seasonal variability in the Bight?
- What influence does the Agulhas Current have on the Bight's shelf at the established MPAs?

To summarise what is already known about the Bight, a comprehensive literature review on the KZN Bight is presented in the next chapter. The general characteristics and major oceanographic features of the Bight are discussed here. Chapter 3 includes details of the model output and CTD data used in this study as well as the full methodology undertaken within this study. In Chapter 4, the results from the model are presented to give the baseline conditions of the Bight and the influence of the Agulhas Current on the shelf. Chapter 5 presents a synthesis and discussion of results. Finally, a conclusion about the mean oceanographic state of the Bight and the implications of this on MPA analysis are given in Chapter 6. The shortcomings of the model are also discussed in this chapter.

2 LITERATURE REVIEW

2.1 THE KWAZULU-NATAL BIGHT

The Bight is a distinct coastal offset between St. Lucia (Figure 2-1, 1) in the north and Durban (Figure 2-1, 2) in the south along the east coast of South Africa (Lutjeharms et al. 2000a). It is approximately 160 km long and the continental shelf extends 45-50 km offshore at the Thukela River mouth (Figure 2-1, A). This is the shelf's widest extent in contrast to the rest of the east coast which has an average shelf width of about 3-12 km (Schumann, 1987; Lutjeharms et al. 2000a). The Bight, and the wider continental shelf, was formed by a change in the tectonic origin of the continental shelf margin, from a sheared to a short-rifted section (Martin and Flemming, 1988).

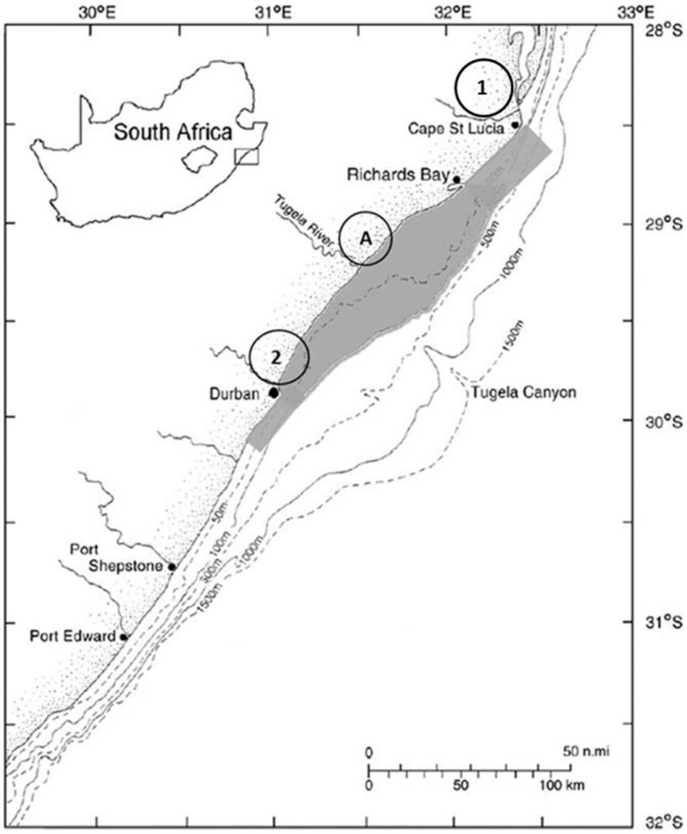


Figure 2-1: Map of the KwaZulu-Natal Bight (highlighted in grey) on the east coast of South Africa from Cape St. Lucia (1) to Durban (2) with the Thukela River (A) situated in the central region of the Bight. The contours show the general bathymetry of the Bight (adapted from Meyer et al. 2002).

Thukela River

The Bight has a large number of estuaries and rivers that discharge fresh water and nutrients into the sea (Schumann, 1988). The most notable is the Thukela River, which terminates in a permanently open estuary (Figure 2-1, A) (Meyer et al., 2002). Hutchings *et al*. (2010) report that the input of freshwater and nutrients varies seasonally with high flow in the summer (October to April) and low flow in the winter (May to September) (Figure 2-2). This is due to the seasonal variation in rainfall on the KZN coast, which receives high rainfall in the summer (average of ~120 mm in Durban during 2000-2010) and low rainfall (average of ~33 mm in Durban during 2000-2010) in the winter resulting in low river flow and therefore smaller estuaries being closed off from the sea (Meyer et al., 2002; Scharler et al., 2016). However, the influence of river (and estuary) input is local and overall, it has a small effect on the vertical density and currents (Schumann, 1988). Heavy rains also influence the Bight through the outflow of highly turbid waters into the sea, but these effects are generally short lived (Schumann, 1988).

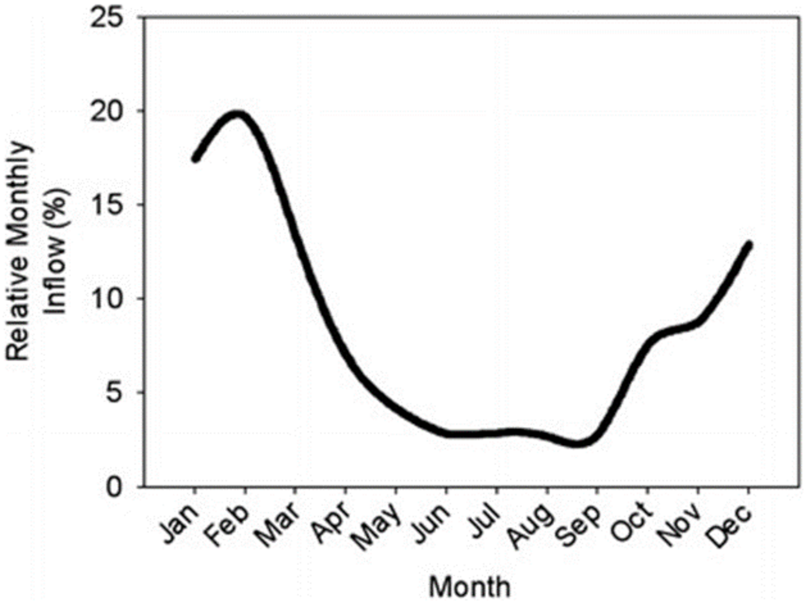


Figure 2-2: Monthly freshwater inflow from rivers that flow into the KZN coast as a percentage of annual inflow. Summer months (October to April) have a higher inflow due to increased rain fall in summer and the winter months (May to September) have lower inflow (%) due less rain fall in the winter (Hutchings et al. 2010 modified by de Lecea and Cooper, 2016).

In addition, the inner shelf of the Bight responds relatively quickly to atmospheric conditions such as wind that result in short-term fluctuations (Schumann, 1988) as well as other influences such as waves (Schumann, 1987).

The most important large-scale oceanographic feature, the Agulhas Current, is located at the shelf break (200m). It follows the shelf-break closely and therefore both influences and encloses the shelf waters of the Bight (Pearce, 1977; Schumann, 1988). The displacement of the Agulhas Current also gives rise to other oceanographic features such as topographically induced upwelling off Richards Bay, north of the Bight; shelf-edge upwelling and the cyclonic, Durban lee-eddy that also induces upwelling to the south of Durban (Guastella and Roberts, 2016; Lutjeharms et al. 2000a). The following section will further discuss the Agulhas Current and other oceanographic features of the Bight.

2.2 OCEANOGRAPHIC FEATURES

2.2.1 The Agulhas Current

The coastal ocean dynamics of the east coast of South Africa are highly influenced by the strong and intense western boundary current, the Agulhas Current. The Agulhas Current is one of the strongest and fastest flowing boundary currents in the world with an average velocity of 1.6 m/s and peak velocities reaching 2.5 m/s (Lutjeharms, 2006a). It flows southwards, transporting warm water from the tropics poleward (Lutjeharms, 2006a; Lutjeharms and de Ruijter, 1996).

The current flows parallel and close to the coast. The location of the current is generally stable in comparison to other western boundary currents. This is due to the narrow continental shelf and the steep continental slope of the east coast of South Africa which stabilises the current (Lutjeharms and de Ruijter, 1996). However, the current diverges seawards at Cape St. Lucia due to the broadening of the shelf and converges again south of Durban, near Port St. Johns, enclosing the KwaZulu-Natal Bight (Figure 2-3) (Harris, 1978; Lutjeharms et al. 2000a). The displacement of the current gives rise to other oceanographic features such as the Durban cyclonic eddy and upwelling at Richards Bay (see section 2.2.2 and 2.2.3).

The Bight’s shelf circulation is strongly influenced by the proximity of the Agulhas Current to the coast, with Agulhas waters occasionally penetrating the bank. These waters give the Bight its tropical and subtropical characteristics which are detailed in section 2.3 (Pearce, 1977; Lutjeharms et al. 2000a). In the northern region of the Bight, the shelf is narrower than 10 km in some places which results in the Agulhas Current having a dominant influence on shelf waters particularly where it flows close to the shelf break (Lutjeharms and de Ruijter, 1996; Schumann, 1988). In the central region of the shelf where the current flows further offshore, the Agulhas Current still has an influence particularly near the shelf break, however in this region, winds also influence the shelf circulation (Schumann, 1988). Further south, where the current converges towards the coast again, the current has dominant influence again.

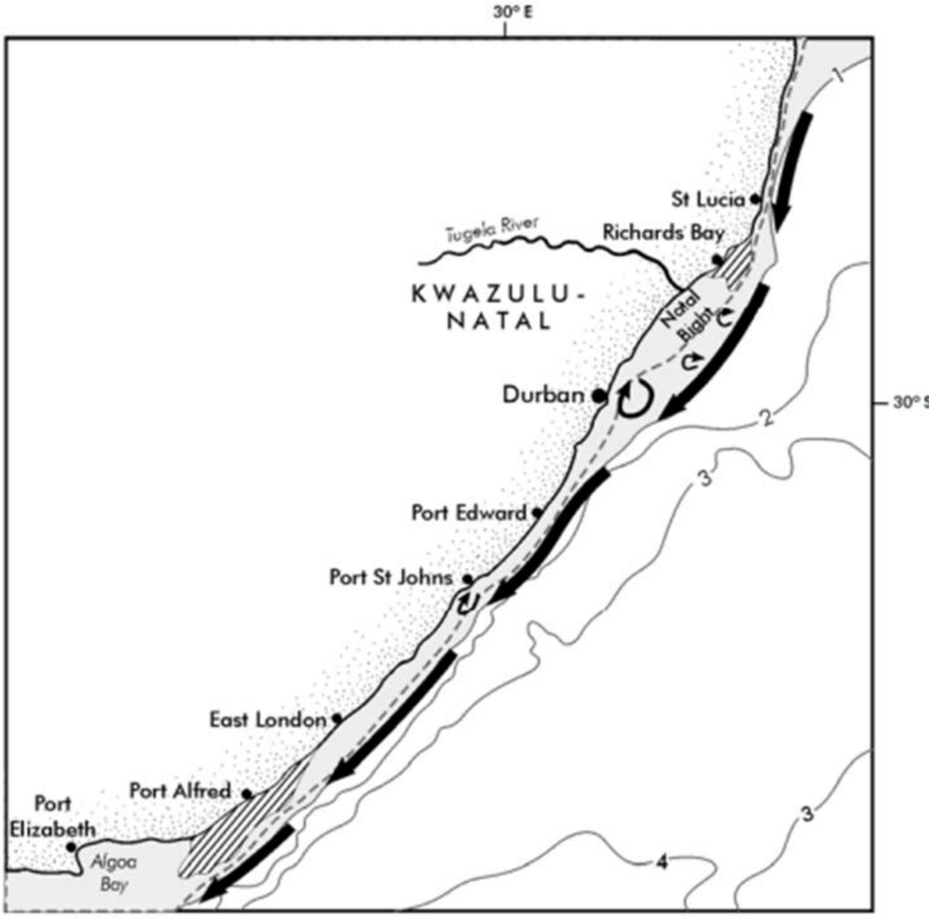


Figure 2-3: The path of the Agulhas Current along the east coast of South Africa (bold arrows), which flows close and parallel to the east coast of South Africa but diverges at St. Lucia around the Bight and converges south of Durban, near Port St. Johns (Lutjeharms, 2006b). Note: The Natal Bight term used in Lutjeharms (2006b) refers to the Bight.

The Bight is also the inception region for the Natal Pulse. The Natal Pulse is the collective name for large, solitary meanders that travel downstream in the Agulhas Current. They are reported to start in the Bight as cyclonic, lee-trapped eddies which grow laterally as they progress southward towards Algoa Bay (Figure 2-3) at a rate of 0.21 m/s. When the shelf begins to broaden at Algoa Bay, they slow down to 0.05 m/s (Lutjeharms and Roberts, 1988). The Natal Pulse has also been shown to influence the Agulhas retroflection which is where the current turns back on itself and where Agulhas rings are shed. Agulhas rings are anticyclonic warm core eddies that are pinched off from the current at the retroflection. They play an important role in transporting warm water from the Indian Ocean into the South Atlantic Ocean (Duncombe Rae, 1991; Lutjeharms and Roberts, 1988).

2.2.2 Upwelling at Richards Bay

As discussed in the previous section, the Agulhas Current diverges seaward at St. Lucia, at the northern end of the Bight, due to the broadening of the continental shelf. This results in topographically induced upwelling along Richards Bay bringing cooler, nutrient-rich water onto the shelf creating a region of enriched biological production (Lutjeharms et al. 2000a; Lutjeharms et al. 2000b; Lutjeharms, 2006b). This area has been shown to be important for understanding the ecosystem of this region (Lutjeharms, 2006b) and has been observed to influence phytoplankton productivity substantially around Richards Bay (Roberts and Nieuwenhuys, 2016).

Although it was originally thought by Lutjeharms et al., (1989) that upwelling at Richards Bay was solely a result of the divergence of the Agulhas Current from the coast, Roberts and Nieuwenhuys (2016) argued that it is not the only mechanism responsible for it. Their results reported strong evidence of wind-driven upwelling and current-slope Ekman veering off Richards Bay. Evidence of wind-driven upwelling was also found in the inner Bight, away from the shelf edge (Roberts and Nieuwenhuys, 2016).

2.2.3 Durban Cyclonic Eddy

As the Agulhas Current converges south of Durban, the current overshoots the shelf edge and only joins the 200 m isobath further downstream. In this area, on the lee of the shelf edge, a semi-permanent mesoscale eddy referred to as the Durban Eddy can be found (Roberts et al. 2010). The presence of the eddy results in the upward doming of the thermal structure at the eddy core and brings cooler, more saline water rich in nutrients closer to the surface which stimulates primary production (Figure 2-4). Guastella and Roberts (2016) report that the eddy is present 55% of the time in a period of 17 months, lasting for about 8.6 days (Table 2-1). When present, it brings strong north-eastward counter-currents reaching 1 m/s to the region (Guastella and Roberts, 2016). The eddy is highly variable in occurrence and strength with no detectable seasonal pattern (Guastella and Roberts, 2016). There are inferences that when these eddies are absorbed into the inshore edge of the Agulhas Current, they may trigger the formation of the Natal Pulse (Lutjeharms and Roberts, 1988).

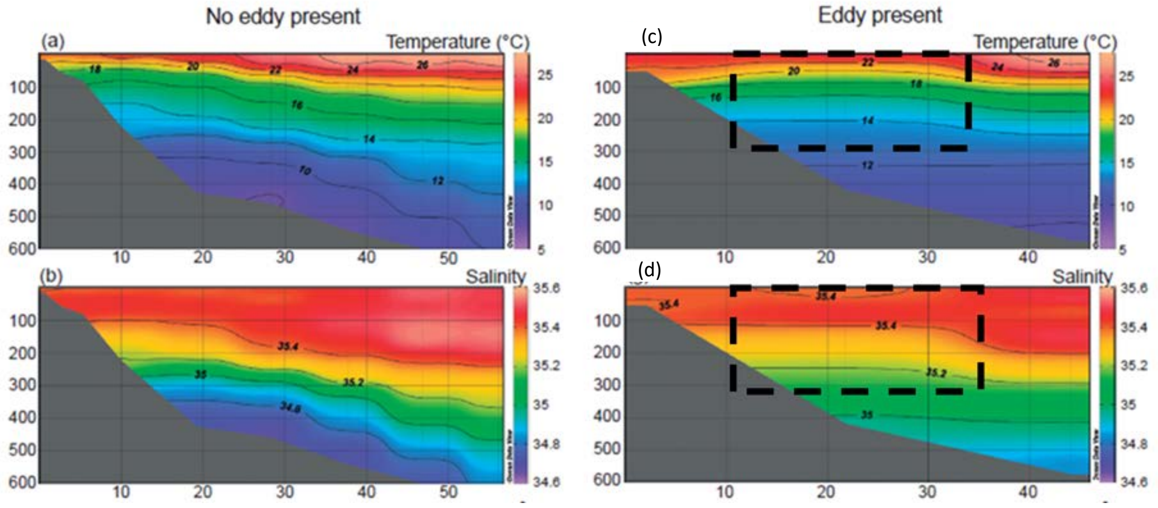


Figure 2-4: The temperature and salinity structure of the water column when: (a and b) the eddy is not present, the isotherms are fairly horizontal and less saline waters are found on the shelf (c and d) the eddy is present, there is an upward doming of the isotherms bringing cooler and more saline waters to the surface (outlined in dashed black rectangle) (Guastella and Roberts, 2016).

Table 2-1: Statistics of the Durban Eddy based on ADCP current data and MODIS and MERIS satellite imagery for a period of 17 months (Guastella and Roberts, 2016).

Parameter	Values
Percentage of the time eddy present	55%
Number of eddy days per year	200 days
Number of eddies per year	22.5 (almost 2 per month)
Average eddy lifespan	8.6 days (Standard deviation of 4.5)
Minimum eddy lifespan	3 days
Maximum eddy lifespan	19 days

2.3 WATER CHARACTERISTICS

The water column of the Bight is considered to be generally well mixed with movement in the upper layers being reported to be well-correlated with synoptic winds (Lutjeharms et al. 2000a). Seasonal patterns in the water column, over the shelf, are mainly restricted to the upper 70 m of the water column (Pearce, 1978). Pearce (1978) conducted a study on the northern KZN shelf and reported that in summer (December to February), the mixed layer was only 20 to 30 m deep with the seasonal thermocline lying between 30 and 60 m that had an average gradient of 0.13°C/m. Whereas in the winter months (June to October in this study), the mixed layer deepened to 50 m and the seasonal thermocline disappeared. Additionally, the seasonal effects in the shallower waters were apparent at all depths down to the seabed and may therefore have a vital impact on the distribution and migration of both pelagic and benthic organisms that live along the inner shelf (Pearce, 1978).

The main water characteristics used to describe water type in physical oceanography are temperature and salinity (Schumann, 1988). The following section will present the literature on the water masses, temperature and salinity in the Bight.

2.3.1 Water Masses

The Bight waters generally have tropical or subtropical origin with the Agulhas Current playing a vital role in transferring water on to the shelf. Cooler, deeper water, likely to be central water, is occasionally brought onto the shelf by various upwelling mechanisms such as the Durban Eddy in the southern region of the Bight (Schumann, 1988). In the Bight, Indian Tropical Surface Water (ITSW) (Figure 2-5) can be found. It is transported from the tropics down through the Mozambican Channel where it joins the Agulhas Current. The ITSW has slightly lower salinities (between 35 and 35.4 PSU; Figure 2-5) compared to the waters beneath it as it gains its freshness at the tropics due to excess precipitation over evaporation. Below ITSW is the South Indian Subtropical Surface Waters (SSTW) (Figure 2-5), which is more saline (35.3-35.6 PSU) and form a salinity maximum at depth of 200 m seaward of the Agulhas Current (Lutjeharms et al. 2000a). Antarctic Intermediate Water, North Atlantic Deep Waters and Antarctic Bottom Water are found further offshore of the Bight in much deeper waters (Figure 2-5).

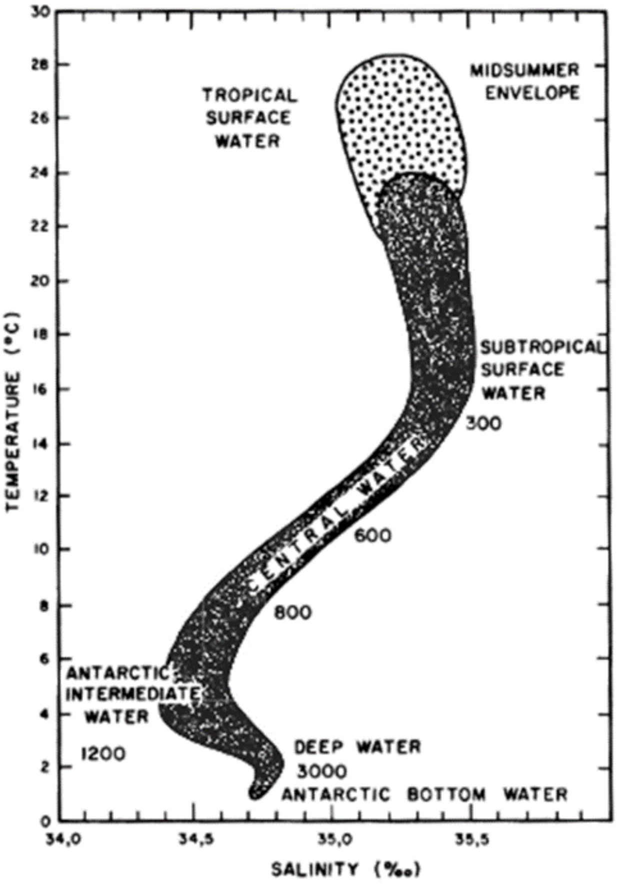


Figure 2-5: Temperature salinity (TS) diagram of the south east coast of South Africa. Bight waters consist of TSW, which dominate the surface waters and below them are SSTW. Central waters have been reported to occasionally enter the Bight through upwelling mechanisms. Antarctic Intermediate Water, North Atlantic Deep Waters and Antarctic Bottom Water are found further offshore of the Bight in much deeper waters. The outdated figure emphasises the need to revisit the Bight oceanographically (Schumann and Orren, 1980).

2.3.2 Temperature

Barlow et al. (2013) conducted a study over the Bight where they collected CTD measurements in February (summer month) and August 2010 (winter month). The study deployed CTD casts over five regions in the Bight: the Durban Eddy (DE), Mid Shelf (MS), Thukela Mouth (TM), Richards Bay south (RS) and Richards Bay north (RN). The temperature profiles suggest fairly uniform temperature structures that indicate a well-mixed regime. In February 2010, the surface waters over the Bight were generally warm ranging between 22°C at the Thukela mouth and 28°C at Richards Bay north (Figure 2-6 top row) (Barlow et al. 2013). In the Durban Eddy region, surface temperatures were between 24 and 26°C. The mixed layer depths of the five regions were relatively shallow and ranged from 13 to 40 m which are similar to depths found by Pearce (1978) for the summer months. In the winter month (August 2010), the water columns were more uniform in the upper layers and the temperatures were lower than in the summer for all five focus areas. The central Bight (TM and MS sites) was cooler (19 to 20°C) than the rest of the Bight (21 to 22°C) (south at DE site and north RS and RN site). The biggest change in temperature was in Richards Bay North and South which had a 7°C surface temperature difference between February and August. Schumann's (1988) study on the Bight also recorded on average a 4°C temperature change from summer to winter. All five focus areas had cooler surface temperature values between 19 and 22°C, during winter (Figure 2-6 bottom row).

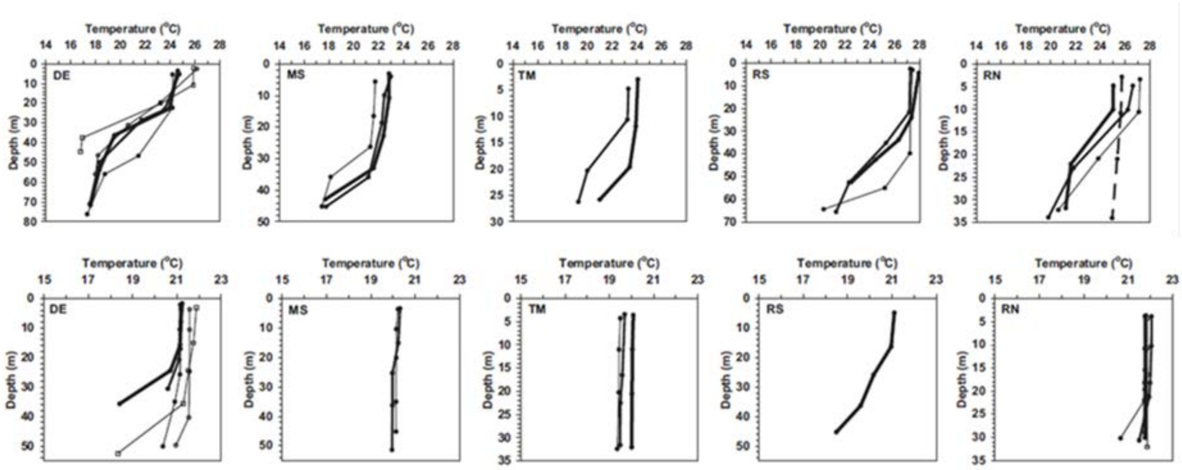


Figure 2-6: Vertical profiles of temperature at five focus sites during February 2010 (top row) and August 2010 (bottom row). DE: Durban Eddy; MS: Mid Shelf; TM: Thukela Mouth; RS: Richards Bay South; RN: Richards Bay North (Barlow et al. 2013).

Snyman (1969) recorded sea surface temperatures across the Bight to range from about 20°C to 23°C (Figure 2-7) using airborne radiation thermometry (ART) surveys during an extensive ocean-measurement programme. In addition, studies have reported that there are regions of upwelling along the KZN coast, in particular the northern region of the Bight at Richards Bay (Roberts and Nieuwenhuys, 2016). There have been reports of plumes of colder, less saline water in the northern region near the Bight (off Richards Bay) (Figure 2-7) where temperatures were shown to fluctuate by as much as 5°C (Schumann, 1981). This highlights the short-term fluctuations that occur in the Bight.

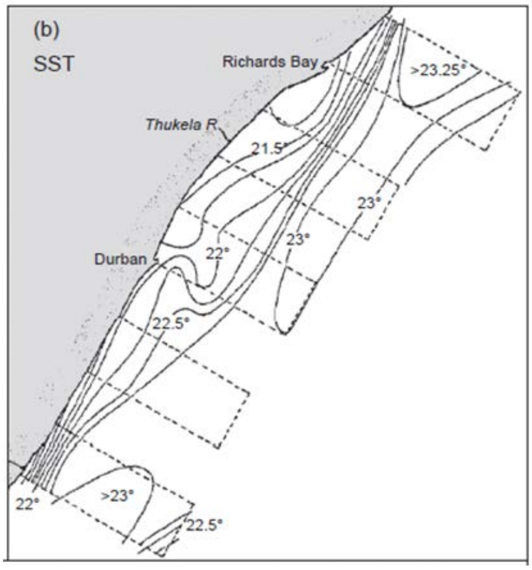


Figure 2-7: Mean SST (°C) from 14 airborne Radiation thermometry (ART) surveys (dashed line is flight track) also showing the colder water in the northern region of the Bight (Roberts and Nieuwenhuys, 2016).

2.3.3 Salinity

Salinity in the Bight has been recorded to generally be between 35.25 and 35.35 PSU (Figure 2-8) with summer waters having slightly lower salinity values due to heavy rainfalls and an increase in freshwater input from rivers, especially in the Central Bight (Pearce, 1978; Schumann, 1988; Lutjeharms et al. 2000a). Other changes in salinity can be attributed to short term variability caused by the following:

- Local run-off which decreases salinity
- Evaporation from solar radiation which increases salinity
- Direct precipitation on the sea surface, which decreases salinity (Pearce, 1978)

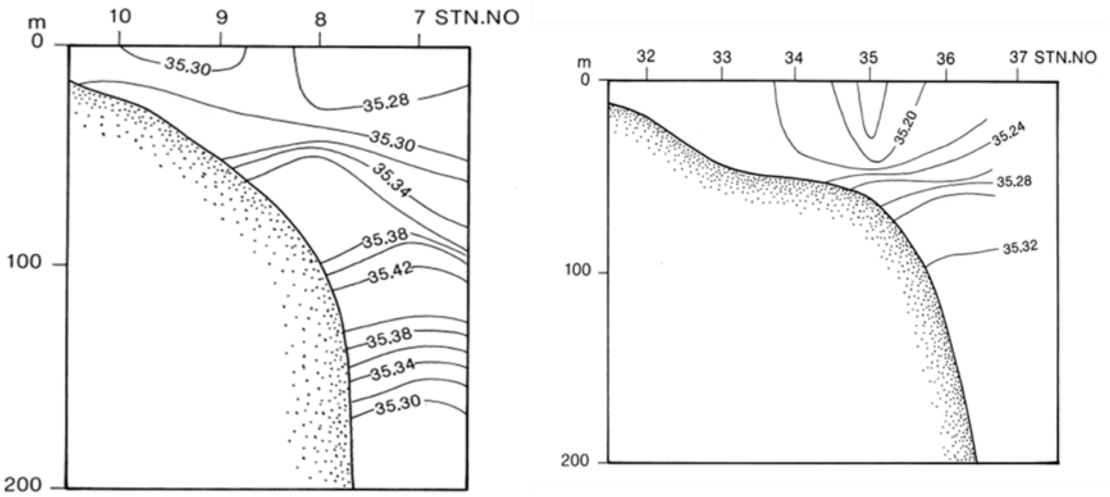


Figure 2-8: Salinity (PSU) vertical cross sections north of the Bight at Richards Bay (left) and in the Central Bight (right) during The Natal Bight Cruise (16-22 July 1989) (Lutjeharms et al. 2000a).

2.4 Importance of Oceanography for MPA Analysis

A main determinant of marine biogeographical patterns and ecosystem processes is seawater temperature throughout the water column (Smit et al. 2013). Seawater temperature controls the survival and reproduction of organisms in the ocean and therefore how they migrate. However, despite the crucial role that temperature plays in species distribution, biogeographic and ecological studies provide few or no supporting temperature data (Smit et al. 2013). This also may be due to the lack of the availability of temperature profiles for the coastal zone locally and even globally.

Currently, there are limited number of published seawater temperature climatologies for South Africa’s coastal zone and only a few exist globally. Satellite imagery has provided an important understanding of offshore oceanographic processes in South Africa. The advantage of using satellite data is that it is usually spatially complete and temporally coherent. However, the main disadvantage is that when it comes to the coast, it becomes difficult to resolve coastal features (e.g. bays, river mouths, upwelling cells) (Smit et al. 2013). This stresses the importance of using model output, which can give a long-term analysis throughout the water column as well as in-situ data that can be used to confirm that the model provides a realistic solution.

3 DATA AND METHODS

3.1 REGIONAL OCEAN MODELLING SYSTEMS (ROMS)

ROMS is a free-surface, split explicit, sigma (terrain-following) coordinate model that solves the incompressible primitive equations under the Boussinesq and hydrostatic approximations (Shchepetkin and McWilliams, 2005). It possesses a variety of parameterisations for horizontal and vertical mixing and open boundary conditions, as well as an extensive suite of numerical algorithms for momentum and tracer advection/diffusion.

3.1.1 Model Domains

The ROMS configuration used in this study consists of a 1/12° (~ 9km) model of the southeast and southwest coast of Southern Africa (3.6 - 34°E, 16 - 44.8°S) nested in a 1/4° (~ 25km) domain of the southeast Atlantic and southwest Indian Ocean (27°W - 69.25°E, 6.95°N - 48.25°S) by means of the Adaptive Grid Refinement in Fortran (AGRIF) two-way nesting ability (Figure 3-1; Debreu et al., 2008). The AGRIF approach facilitates two-way information exchange between the outer and inner grid, allowing the high-resolution signal in the nest to be communicated to the wider lower resolution domain.

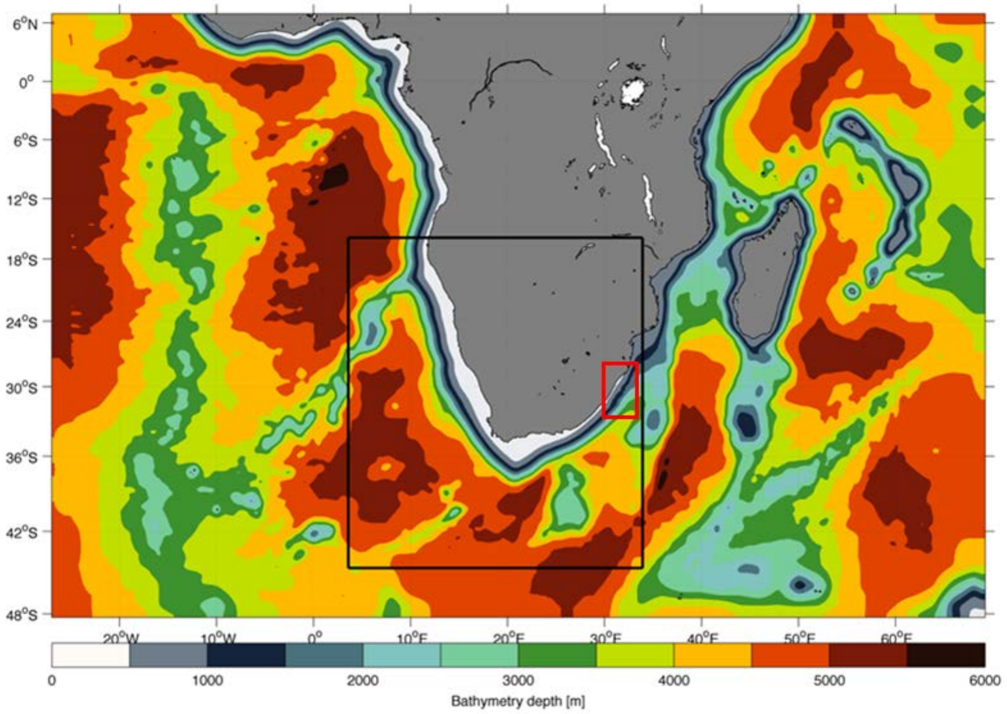


Figure 3-1: The ROMS configuration consists of a 1/12° (~ 9km) domain of the southeast and southwest coast of Southern Africa (3 - 34°E, 16 - 45°S) nested in a 1/4° (~ 25km) domain of the southeast Atlantic and south-west Indian Ocean (27°W - 70°E, 7°N - 48°S) outlined in black. The location of the Bight is outlined in red. The domains are shown over a map of bathymetry (m).

The grid spacing of the outer domain ranges from 18.5 km in the southern part of the domain to 27.8 km in the north (Figure 3-2). The outer domain is considered eddy-permitting as the spatial scale of the domain is less than the wavelength associated with the first Rossby radius of deformation which ranges from ~250 km near the equator to ~20 km in the south (Chelton et al. 1998). The high-resolution inner domain has a mean grid spacing of 7.8 km (Figure 3-2) and is considered eddy-resolving. It is designed to resolve the highly dynamic Agulhas Current system as well as the coastal upwelling processes of the Benguela Upwelling System.

Both the outer and inner domains have 50 vertical levels (σ) that are stretched towards the surface to establish the vertical resolution. The vertical resolution ranges from a maximum of 560 m at the bottom to 1 - 4 m in the surface layers. The model outputs are available as 3-day averages from 1980 to 2010.

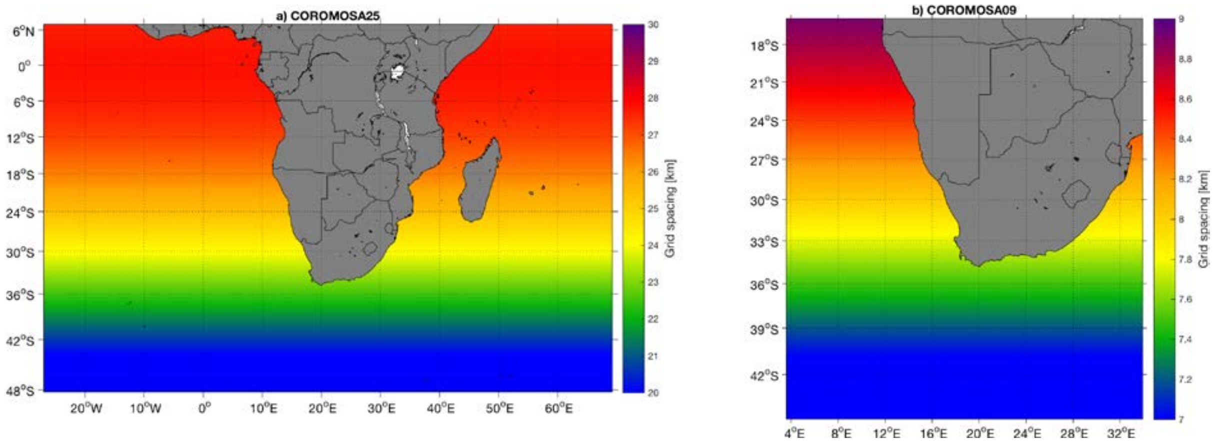


Figure 3-2: The grid spacing of the a) outer domain at 1/4° resolution and b) the inner domain at 1/12° resolution.

3.1.2 Bathymetry

The bathymetry for this simulation is derived from the 1’ General Bathymetric Chart of the Oceans (GEBCO) global topography data set, and bilinearly interpolated onto the model grid. Pressure gradient errors are reduced by smoothing the bathymetry such that the smoothing parameter, r, is less than a critical value of 0.2 (Haidvogel and Beckmann, 1999). In comparison to the GEBCO bathymetry, ROMS smooths the bathymetry inshore of the Bight and is slightly deeper, with the continental shelf smoothed of features such as submarine canyons. It also reduces the topographic gradient especially that of the continental slope (Figure 3-3).

As shelf dynamics are not accurately resolved at the resolution of the low-resolution grid, the minimum depth at the coast is set to 50 m. In addition to prevent the formation of large coastal walls, the maximum depth at the coast is set to 500 m.

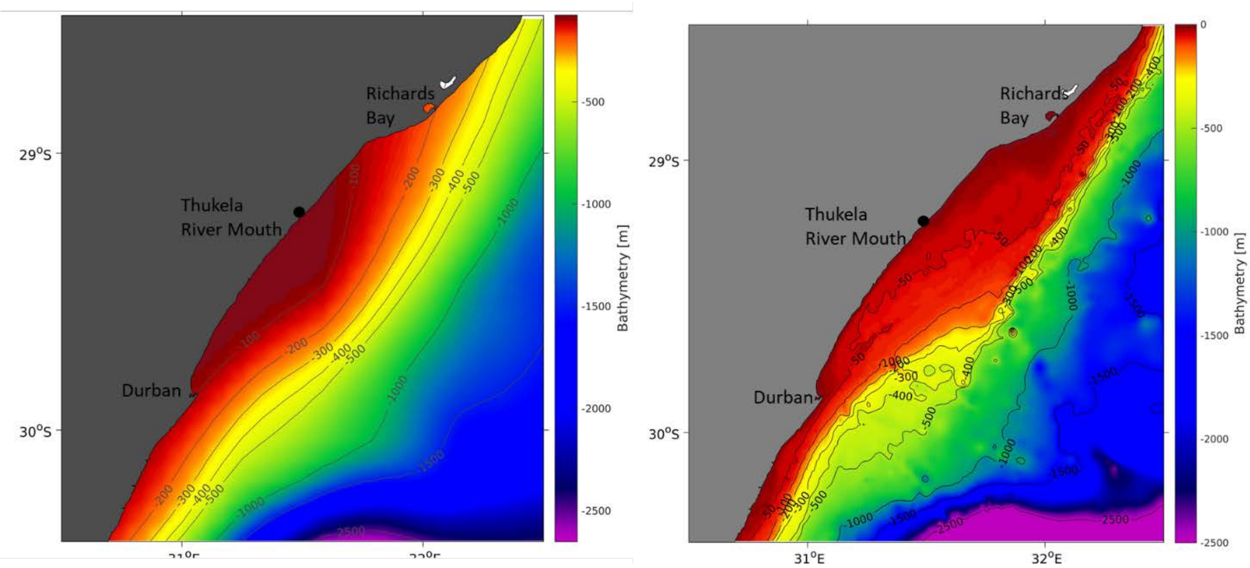


Figure 3-3: a) Smoothed bathymetry over the Bight b) Raw 1' GEBCO bathymetry

3.1.3 Lateral Boundary Conditions

The initial and boundary conditions of the outer domain are derived from ORCA025, a NEMO (Nucleus for European Modelling of the Ocean) based global ocean model. ORCA025 is a 1/4° global ocean-only model that appropriately simulates the large-scale circulation of the Atlantic, Indian and Southern Oceans. The adaptive radiation/nudging scheme allows for outgoing information to be weakly nudged to external conditions and the incoming signal is constrained to the external solution by adaptive nudging (Marchesiello et al. 2001). Blayo and Debreu's (2005) characteristic-based open boundary scheme is used for the barotropic velocities. Information on incoming characteristic variables is specified while outgoing quantities are calculated from interior values. The 1/12° resolution inner domain's boundary conditions are relaxed towards the outer domain through a 50 km sponge layer.

3.1.4 Surface Boundary Conditions (Forcing)

Surface heat, freshwater and momentum fluxes (Figure 3-4) used to drive the ocean are derived from DFS5.2. The DFS5.2 has a spatial resolution of ~ 0.7° and includes the following surface variables required by the bulk formula to calculate heat, freshwater and momentum fluxes across the air-sea surface:

- 3-hourly zonal and meridional components of the 10 m winds (m/s)
- 3-hourly 2 m air humidity

- 3-hourly 2 m air temperature
- Daily downward shortwave and longwave radiation at the sea surface (W/m^2)
- Daily precipitation rate (cm/day)

The fields listed above for the period 1980-2010 are bilinearly interpolated onto the inner domain grid at a common daily resolution, using daily averages in the case of the 3-hourly fields.

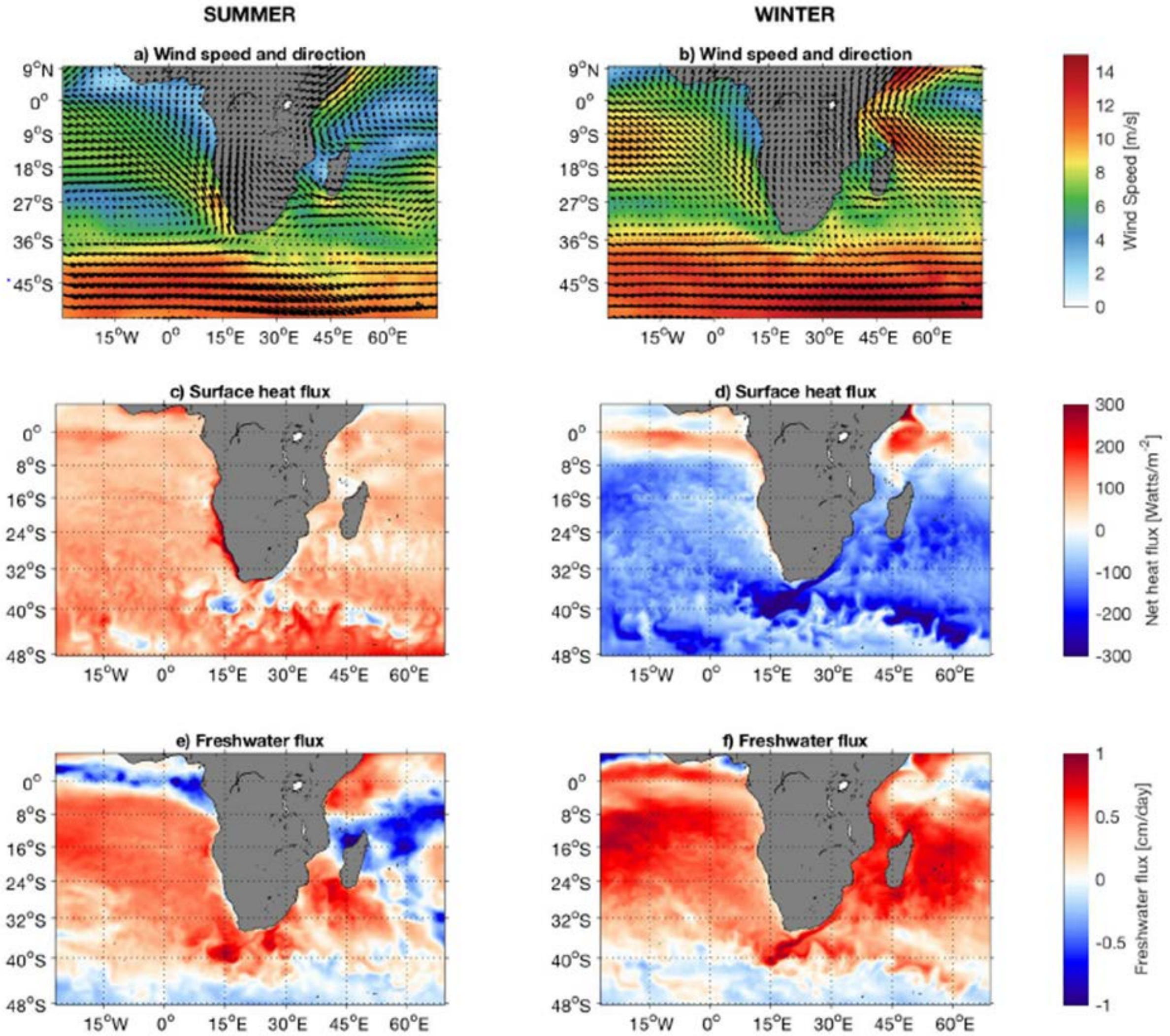


Figure 3-4: Surface momentum (top panel), heat (middle panel) and freshwater (bottom panel) fluxes for summer (left panel) and winter (right panel). Summer and winter are represented by a monthly average for January 2010 and July 2010, respectively.

3.2 CONDUCTIVITY TEMPERATURE AND DEPTH (CTD) MEASUREMENTS

The in-situ data used in this study was obtained from CTD casts that were deployed during research cruises aboard the M.Y. Angra Pequena from 2014 to 2017 (May to July only). The

CTDs were deployed along the Bight from Richards Bay to Port Edward (south of Durban). The locations of the CTD measurements are shown in Figure 3-5.

The measurements were taken with SBE19plus V2 SeaCAT CTD that was lowered by hand. The raw data was processed using Seabird Data Processing software (SBE Data Processing) in accordance with the SBE Data Processing Manual (Available at: http://www.seabird.com/software/sbe-data-processing under documents). The CTD measures conductivity, temperature, and pressure at 4 scans/sec (4 Hz). It has a pump-controlled, T-C duct flow that assists in minimising salinity spikes and enables the CTD to be descended slowly without reducing sensor responses which improves dynamic accuracy and resolves small-scale structures in the water column (Sea-Bird Scientific, 2017).

The CTD casts were deployed by the ACEP Spatial Solutions Project team at different locations in the Bight (Figure 3-5). They were taken in addition to biological samples (Baited remote underwater video (BRUV) and plankton nets), so the sites were chosen in relation to biological areas of interest and the casts were not undertaken as part of ordered transects. The data was collected over a period of four years, at random locations as per vessel logistics and weather permitting. In those four years, the cruises were focussed over a two-month window in winter (May – July). Initially, the project wanted to use the available CTD data to build a mean-state of the Bight. However, this data was sparse, was only collected during one season and has not been continuously collected over a long time period. Historical CTD data are limited to once-off surveys conducted in 1989 and 2010. The data collected in the 2014-2017 is the most recent conducted in the area. The results of the survey are presented below.

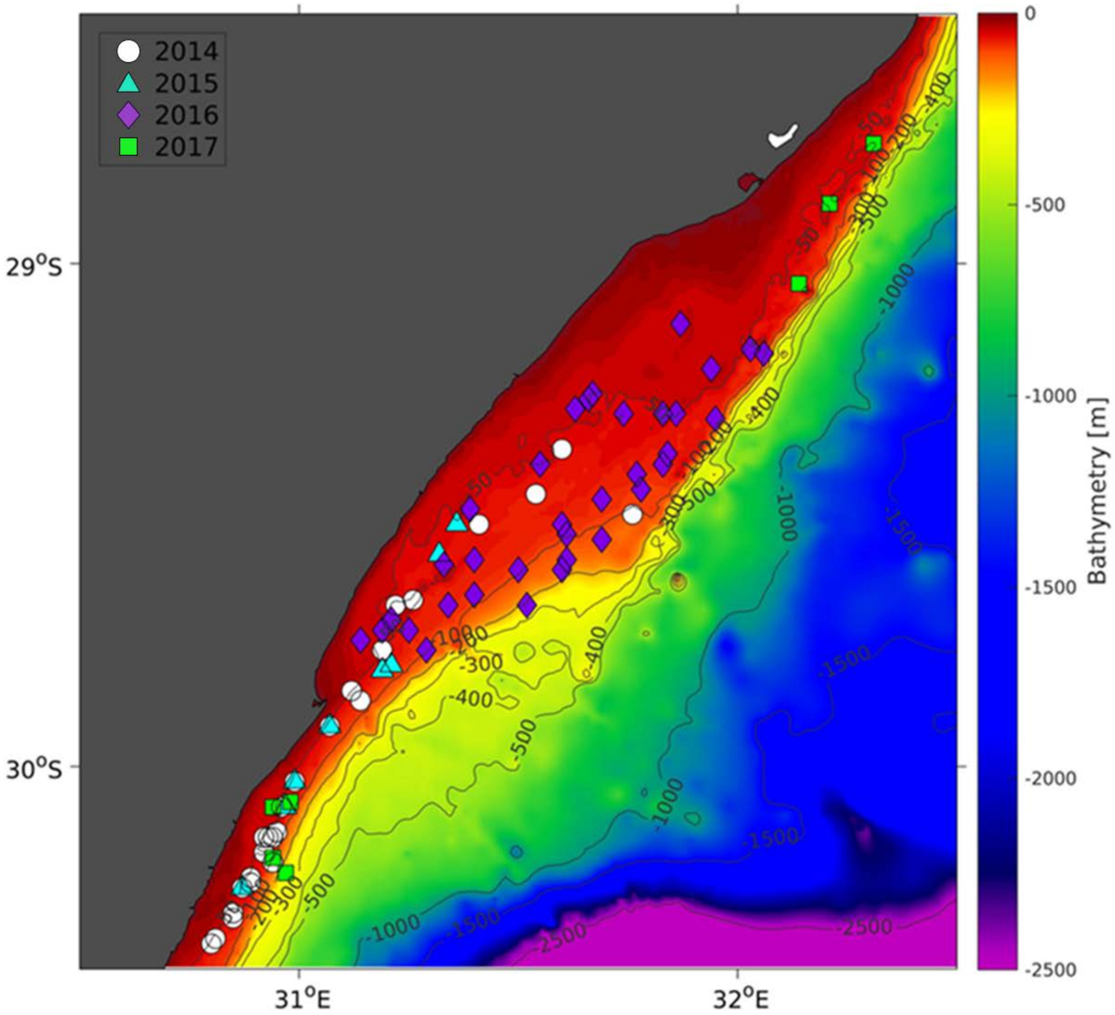


Figure 3-5: Location of where the CTD casts were deployed across the Bight for all years (2014 to 2017) plotted over GEBCO bathymetry.

3.2.1 Temperature Profiles

During the measurement period (2014 - 2017), sea surface temperatures in the Bight ranged between 20 °C and 25 °C, with exception of surface temperatures in 2016 where temperatures dropped as low as 14 °C (Figure 3-6c). This could have been due to freshwater input from Thukela Banks or the presence of a Natal Pulse. In 2014, the casts were deployed mainly in the Central Bight and south of Durban. The surface temperatures in these regions ranged between 20 °C and 24.5 °C (Figure 3-6a). The mixed layer varied in depth for all profiles and ranged from 20 to 60 m. The minimum temperature recorded, during this period, was 15.05 °C at 57 m; this was relatively cooler than the rest of the bottom temperatures which were mainly between 17 and 23 °C. The deepest cast to 103 m recorded a temperature of

17.12 °C. During this period (2014), the maximum range in temperature between the surface and bottom waters was 9.5 °C.

In 2015, casts were also deployed in the Central Bight and south of Durban. Surface temperatures increased from the previous year and ranged between 23.5 and 25 °C (Figure 3-6b). The mixed layer depth was mainly between 30 and 60 m with one of the profiles showing a deep mixed layer depth of 80 m. The minimum temperature recorded was 16.91 °C at 150 m which was the deepest cast taken in this period. The maximum range in temperature throughout the water column was 8 °C.

The number of CTD casts deployed in 2016 was the highest out of all years (Figure 3-6c). The casts were taken across the Central Bight. There was a distinct difference between casts deployed along the Thukela bank (‘the bank’), which were characterised by shallow waters (20 to 60 m deep), and the casts taken offshore of the bank in deeper water. Cooler surface temperatures (14.5 to 20.1 °C) were observed on the bank in comparison to the warmer surface temperatures (21 to 24.2 °C) found off the bank. The cooler temperatures were not just at the surface but persisted throughout the water column with bottom temperatures reaching up to 11.87 °C at 40 m, making the largest range in temperature between the surface and bottom waters 8 °C. Despite having a deeper water column, bottom temperatures were on average warmer off the bank and the lowest bottom temperature recorded was 13.9 °C at 104 m. The mixed layers on the bank varied between 10 and 20 m followed by strong thermoclines developed through the upliftment of cooler waters from below. Off the bank, the mixed layers extended deeper and varied between 10 and 60 m.

In 2017 (Figure 3-6d), the CTD casts were deployed offshore of Richards Bay and south of Durban. The upper layers of the water column were more uniform than previous years and the mixed layer depths were between 40 and 60 m. The surface temperatures were relatively cooler ranging between 20.5 °C and 22.2 °C. The water column here was relatively shallow, only extending up to 84 m. The coldest bottom temperature recorded was 18 °C at 58 m.

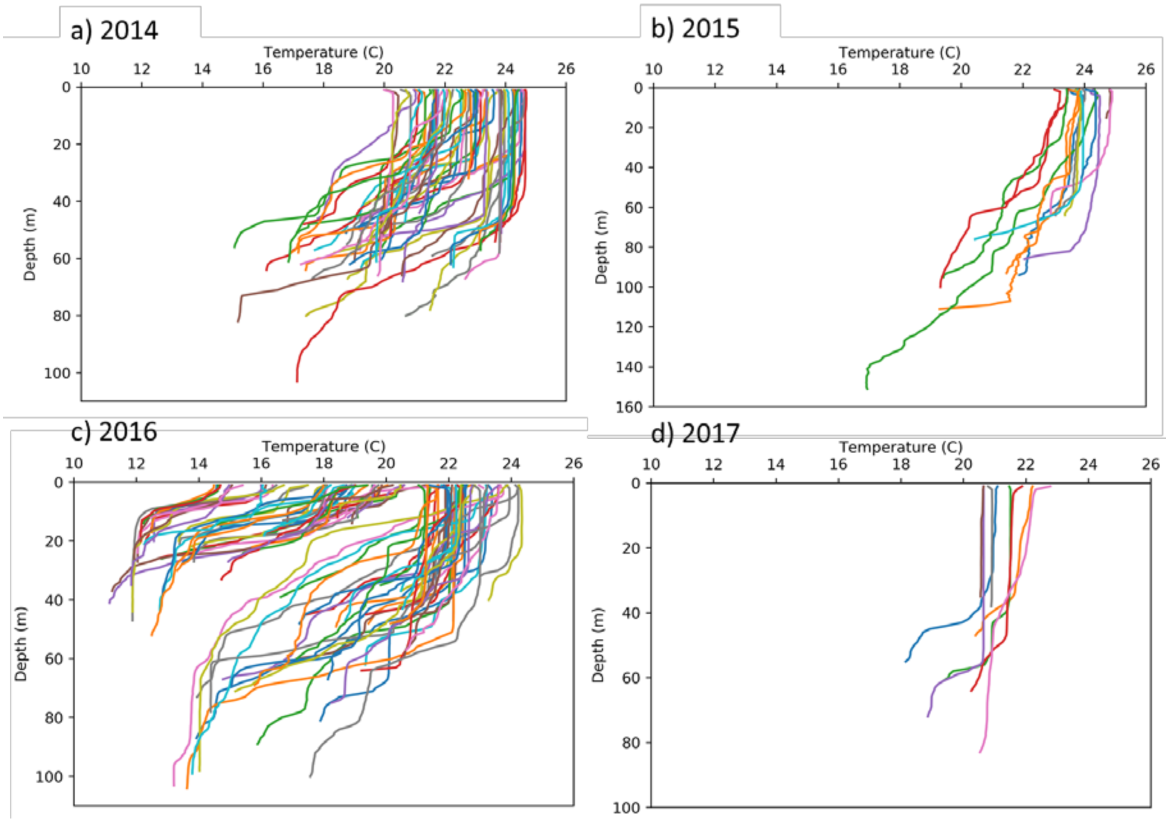


Figure 3-6: CTD temperature (°C) profiles taken in the May to July period for the ACEP KZN Bight project in a) 2014 b) 2015 c) 2016 where there is a distinct variation between casts taken on the bank (shallower) and off the bank (deeper) and d) 2017. The number of casts taken by ACEP varied each year with 2016 having the most casts and 2017 having the least.

3.2.2 Salinity Profiles

Throughout all four years, salinity ranged from 35.1 to 35.55 PSU (excluding the 35.6 outlier in 2016; Figure 3-7c). In 2014, salinity generally ranged from 35.3 to 35.46 PSU throughout the water column (Figure 3-7a). In 2015, the salinity values decreased and ranged from 35.1 to 35.22 PSU at the surface (Figure 3-7b). These relatively fresh waters coincided with the warmer temperatures seen in Figure 3-7b and may be an indication of the intrusion of the Agulhas Current on to the shelf of the Bight. The majority of the 2015 profiles showed an increase of salinity with depth going up to 35.4 PSU. In 2016 (Figure 3-7c), salinities showed a distinct variation between salinity values on and around the bank (Figure 3-7c) as seen with the corresponding temperature profiles in Figure 3-7c. Relatively fresh waters (35.1 to 35.3 PSU) were observed on the bank in comparison to the more saline waters offshore of the bank (35.3 to 35.55). The year 2017 showed more uniform salinity profiles (Figure 3-7d) similar to what was seen in the temperature profiles (Figure 3-6d). Salinity values varied between 35.35 and 35.5 PSU persisting throughout the water column. One of the profiles showed an input of more saline waters of 35.5 PSU at 60 m.

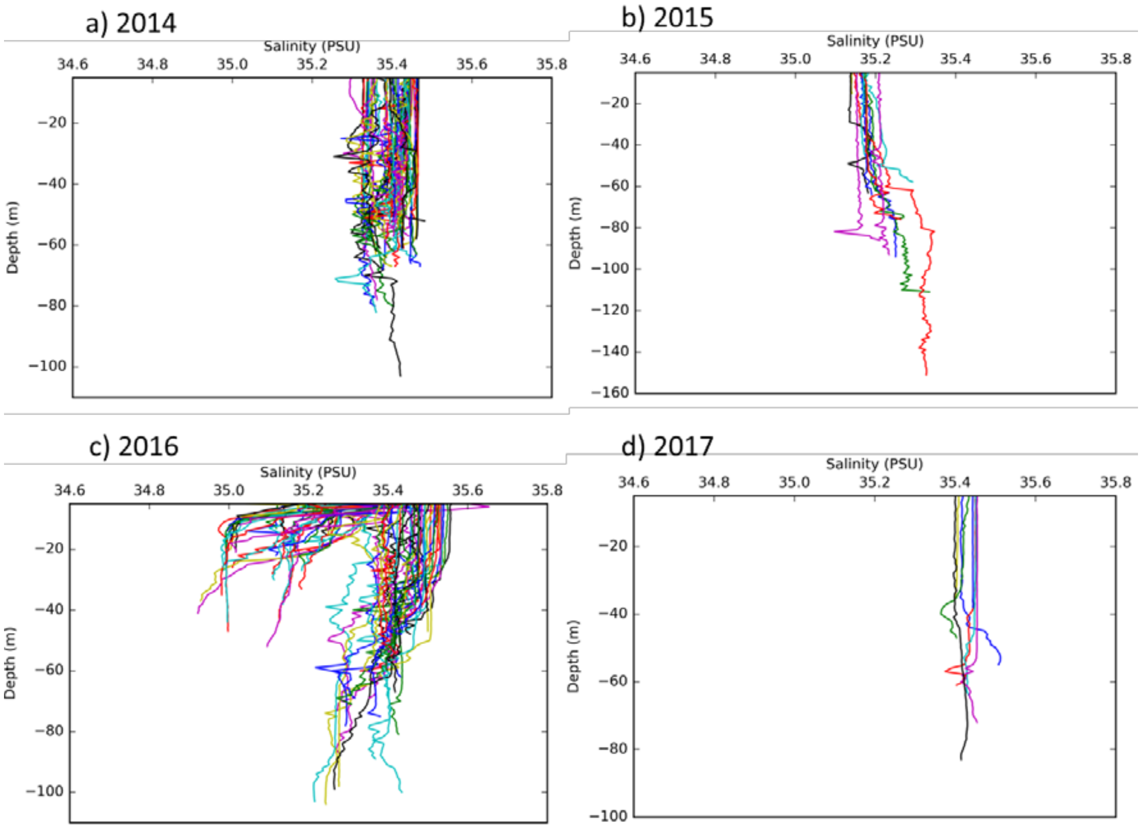


Figure 3-7: CTD salinity (PSU) profiles taken in the May to July period for the ACEP project in a) 2014 b) 2015 c) 2016 where there is a distinct variation between casts taken on the bank (shallower) and off the bank (deeper) which is also seen in the temperature profiles and d) 2017. The number of casts taken by ACEP varied each year with 2016 having the most casts and 2017 having the least.

With these results, it would not be ideal to make conclusions about the mean-structure of the Bight given:

1. The sparseness of the data,
2. The data was only collected during one season,
3. Areas such as Richards Bay were not sampled enough and
4. There was no repetition of sampling at any point of the Bight.

Therefore, this study uses model output which provides us with information of the Bight over a longer period. This information is provided in the following section.

4 RESULTS

4.1 MEAN-STATE OCEANOGRAPHIC CONDITIONS OF THE BIGHT

As previously mentioned, there are currently only a few published sea water temperature climatologies for South Africa's coastal zone and globally (Smit et al., 2013). For MPA studies, an understanding of how oceanographic variables vary, from the surface to the sea floor is important. Models are one way of retrieving such information. The model output generated from ROMS was used to provide a baseline oceanographic description of the Bight. The purpose was to use the provided model output and provide a climatology of the Bight, specifically its two newly established MPAs. The model outputs, such as the one used in this study, can be used to produce maps, vertical sections and time series of important oceanographic variables that can be used in conjunction with species occurrence to identify or assess important areas where management is required (Grantham et al., 2011). The monthly averages used in this study were calculated from the 3-day averages. Subsequently, the monthly climatology was created by averaging the 30 monthly fields for each month of the year. This study focussed on temperature and salinity as they are the main water characteristics used to describe physical oceanography and are variables that have known effects on marine species (Schumann, 1987; Green, 2015).

The uThukela Banks and Aliwal Shoal MPAs, and the points from which data was taken from to plot temperature-salinity (TS) diagrams, vertical sections and time series are shown in Figure 4-1.

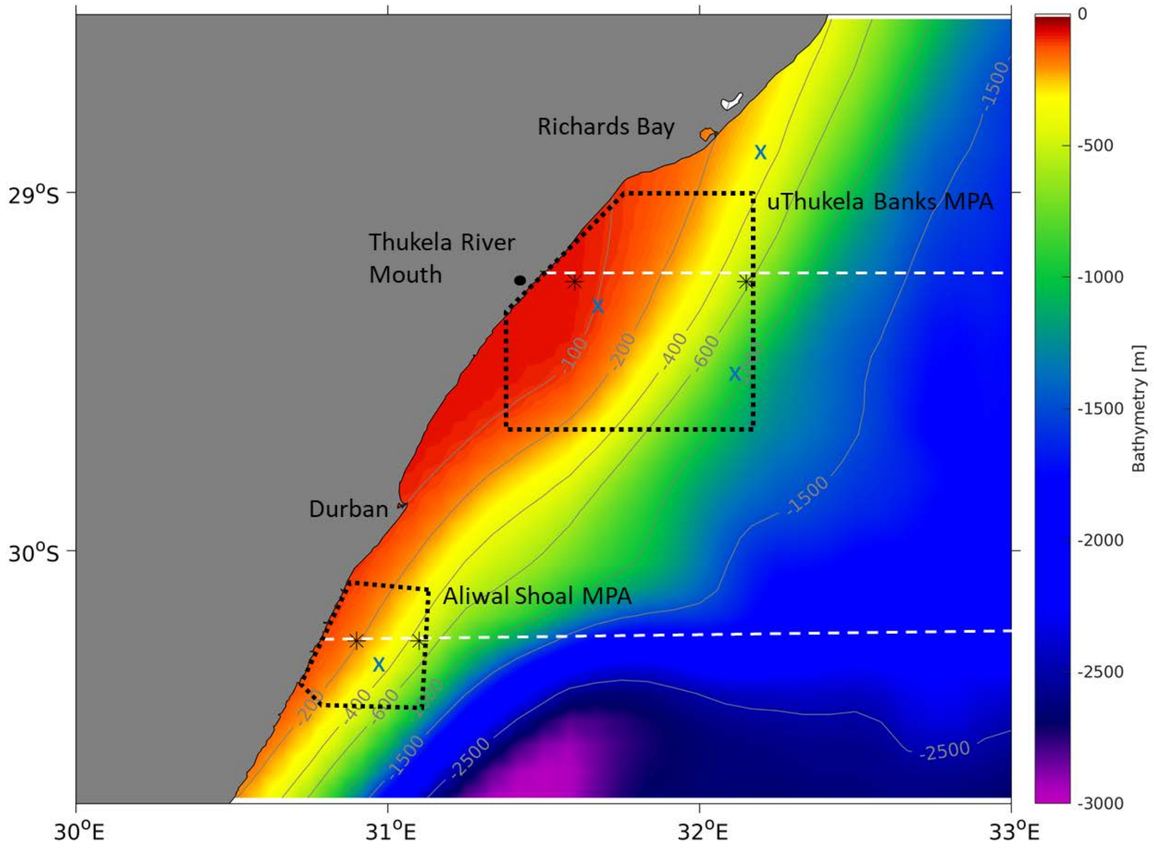


Figure 4-1: The uThukela Banks MPA and Aliwal Shoal MPA, demarcated by black dashed boxes (--), plotted over a ROMS bathymetry map. Black stars (*) indicate the points where the time series were potted. White dashed lines indicate where the vertical sections were plotted from. Blue crosses (x) indicate the points where TS diagrams were plotted from.

4.1.1 Water Masses

Representation of the different water masses present within the Bight are shown in Figure 4-2. TS diagrams for the following points were plotted: offshore Richards Bay, the Central Bight, south of Durban and off the shelf of the Bight in the path of the Agulhas Current (for reference purposes, Figure 4-1), using the climatological output. The TS characteristics of the three points across the Bight were similar to those seen in the upper part of the Agulhas Current (Figure 4-2).

The diagram shows that surface waters across the Bight were dominated by Indian Tropical Surface Waters (ITSW) characterised by warm temperatures between 20 and 25°C and salinity values of 35.45 to 35.65 PSU. Cooler (15 to 20°C) South Indian Subtropical Waters (SSTW) was located below ITSW. SSTW, located at the inshore sites in the Bight, was slightly fresher (35.3 to 35.45 PSU) compared to that further offshore (35.55 PSU). Since the Bight waters were relatively shallow, there was no presence of cooler (5 to 15°C), less saline (34.55 to 35.3 PSU)

South Indian Central Waters (SICW) at the Central Bight and south of Durban (Figure 4-2). However, SICW was present offshore of the Bight where the water column was deeper. The TS diagram also showed the presence of SICW at Richards Bay brought onto the shelf by the Agulhas Current. With knowledge of the water masses, the following section will look at the horizontal distribution of temperature and salinity across the Bight at the surface (10 m) and at 50 m where we expect to see characteristics of the ITSW as well as at 100 m where the SSTW was found.

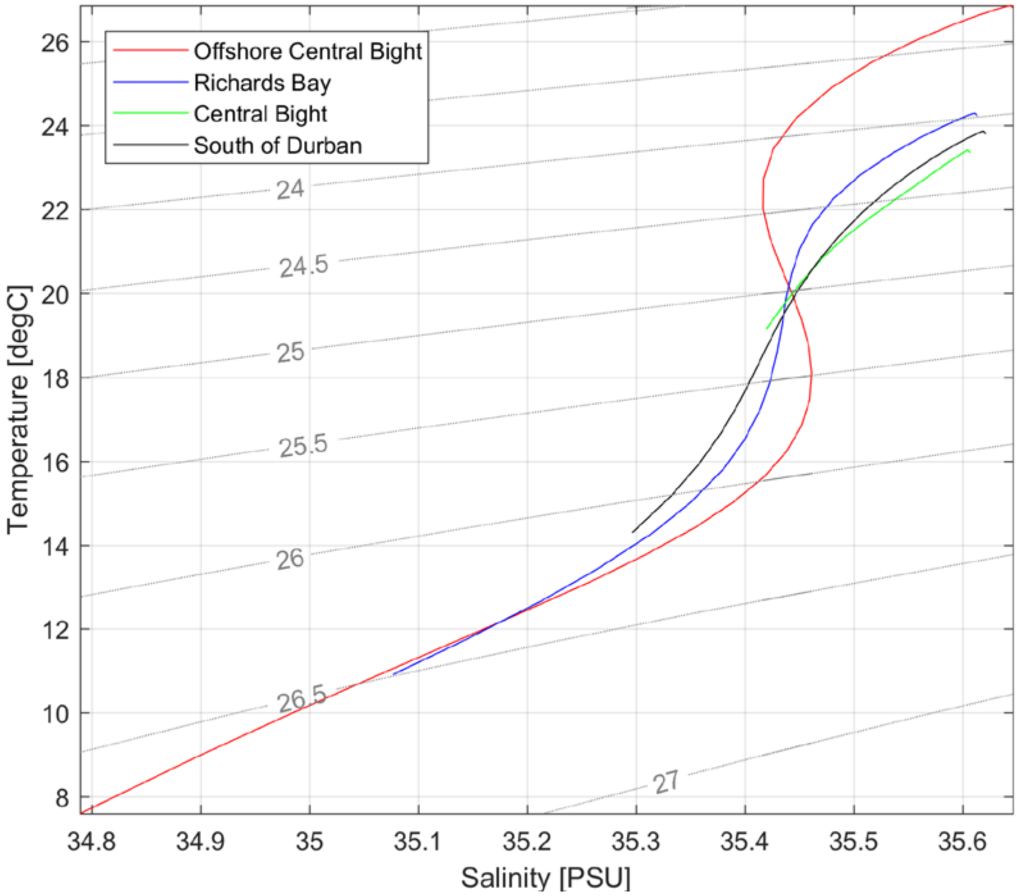


Figure 4-2: Temperature salinity (TS) diagram, obtained from ROMS, at all three focus sites: Richards Bay, the Central Bight and south of Durban with an additional site offshore of the Bight in the Agulhas Current used as a reference point. ITSW: Indian Tropical Surface Waters; SSTW: South Indian Subtropical Surface Waters; SICW: South Indian Central Water.

4.1.2 Horizontal Distribution of Temperature and Salinity

The follwing maps were produced using a 30-year climatology output. Throughout the water column, temperatures in the Bight including the propsed MPAs were cooler and fresher than the surrounding waters. Within the Bight the uThukela Banks region was generally cooler than the northern region at Richards Bay and the Aliwal Shoal MPA region south of Durban. The path of the Agulhas Current was also visible to the west of the Bight and was notably warmer and more saline than the Bight at all depths and throughout the year (Figure 4-4 to Figure 4-9). As also seen in previous literature (Lutjeharms and de Ruijter, 1996; Schumann, 1988), the current diverges seawards north of the Bight due to the broadening of the shelf and converges again south of Durban where the shelf becomes narrower again. This results in the current having a dominant influence on shelf waters north and south of the Bight where it flows close to the shelf break (Lutjeharms and de Ruijter, 1996; Schumann, 1988). To delineate the current, quiver plots were plotted using the ROMS climatology output for the months of January (summer month) and June (winter month) (Figure 4-3). As noted in literature, the current flows southward and slightly decreases in speed as it flows past the central region of the bight (Figure 4-3). The current flows over most of the Aliwal Shoal MPA and only at the offshore edge of the Thukela Banks MPA.

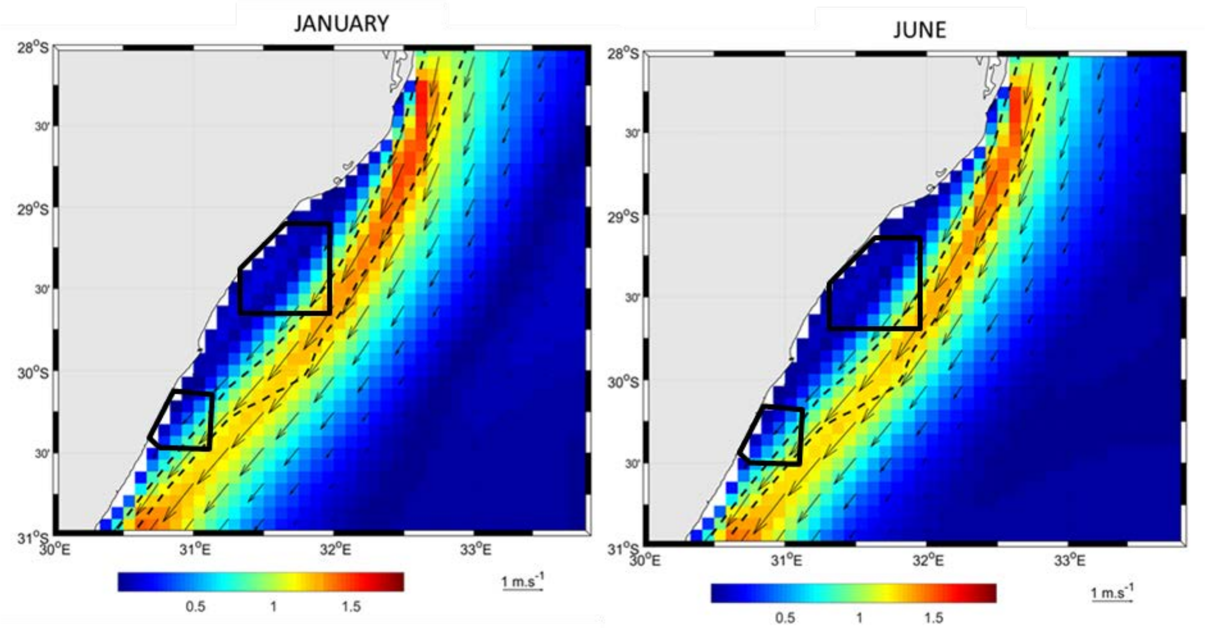


Figure 4-3: The path of the Agulhas Current along the east coast of South Africa. The arrows indicate the direction and magnitude of the current and the colour palette indicates the speed. The black lines demarcate the Thukela Banks MPA (north) and the Aliwal Shoal MPA (south).

The distribution of temperature and salinity over the Bight at 10 m depth, considered representative of the surface layer, is shown in Figure 4-4 and 4-5 respectively. At this depth, there was a presence of the warm (20 to 26°C) ITSW over the Bight throughout the year. Surface salinities varied between 35.5 and 35.6 PSU which was characteristic of ITSW.

Overall, the warmest surface temperatures in the Bight occured from January to March with a value of 26°C, a degree cooler than the Agulhas Current further offshore. In contrast, July to September were the coolest months with temeratures sitting at 22-22.5°C in the Bight and 23°C in the path of the Agulhas Current. Throughout the year, the uThukela Banks MPA was 0.5-1°C cooler than the rest of the Bight including the Aliwal Shoal MPA (Figure 4-4).

The temperature distribution every month showed similar charcaterisitics, with lower temperatures at the central region of the Bight and higher temperaures observed seaward, offshore of the Bight. However, temperature gradients in the summer months were greater than those in the colder months. From these climatological maps, the average surface temperature at the uThukela Banks ranges from 21-26°C in a year and from 22-27°C at the Aliwal Shoal MPA which was highly influenced by its close proximity to the Agulhas Current (Figure 4-4).

Similar to the temperature distribution, surface salinities increased seaward. The Bight's surface salinities on average range between 35.5 and 35.6 PSU during the year. Unlike with temperature, there was no significant difference in the salinities of the uThukela Banks MPA and the Aliwal Shoal MPA. However, in March and April there was a pool of less saline (35.5 PSU) water at Richards Bay and in the region of the uThukela Banks respectively (Figure 4-5). It was still seen in May, however smaller and located north of Durban. This pool of less saline water was limited to the surface as it is not seen at 50 m (Figure 4-5). May and June were months of relatively high salinities that go up to 35.6 PSU whilst the rest of the year ranges between 35.5 and 35.55 PSU (Figure 4-5).

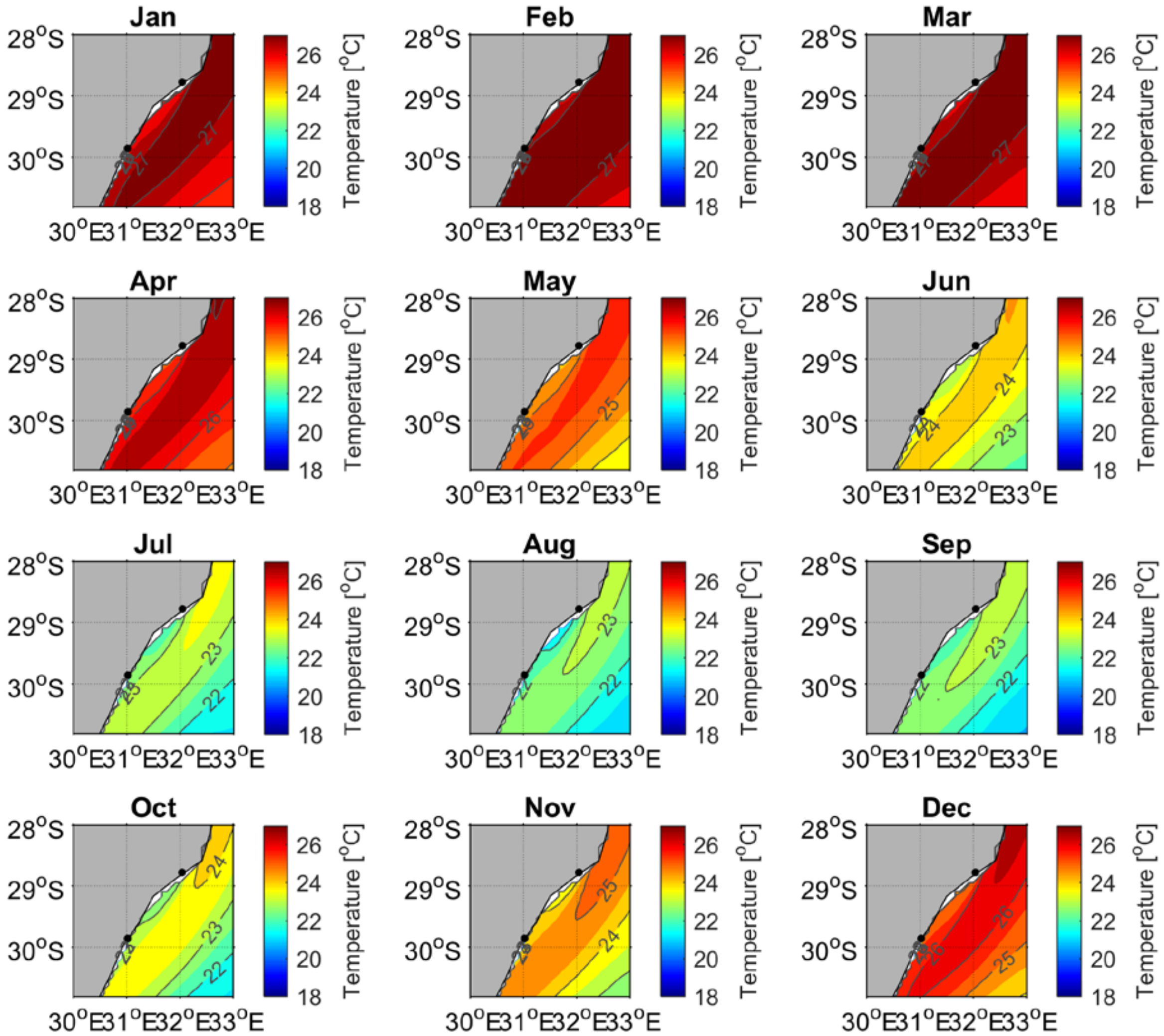


Figure 4-4: ROMS monthly climatology maps of temperature (°C) across the Bight with isotherms (grey lines) at a depth of 10 m for every month of the year. The location of Richards Bay (north) and Durban (south) along the coast are indicated by the black dots.

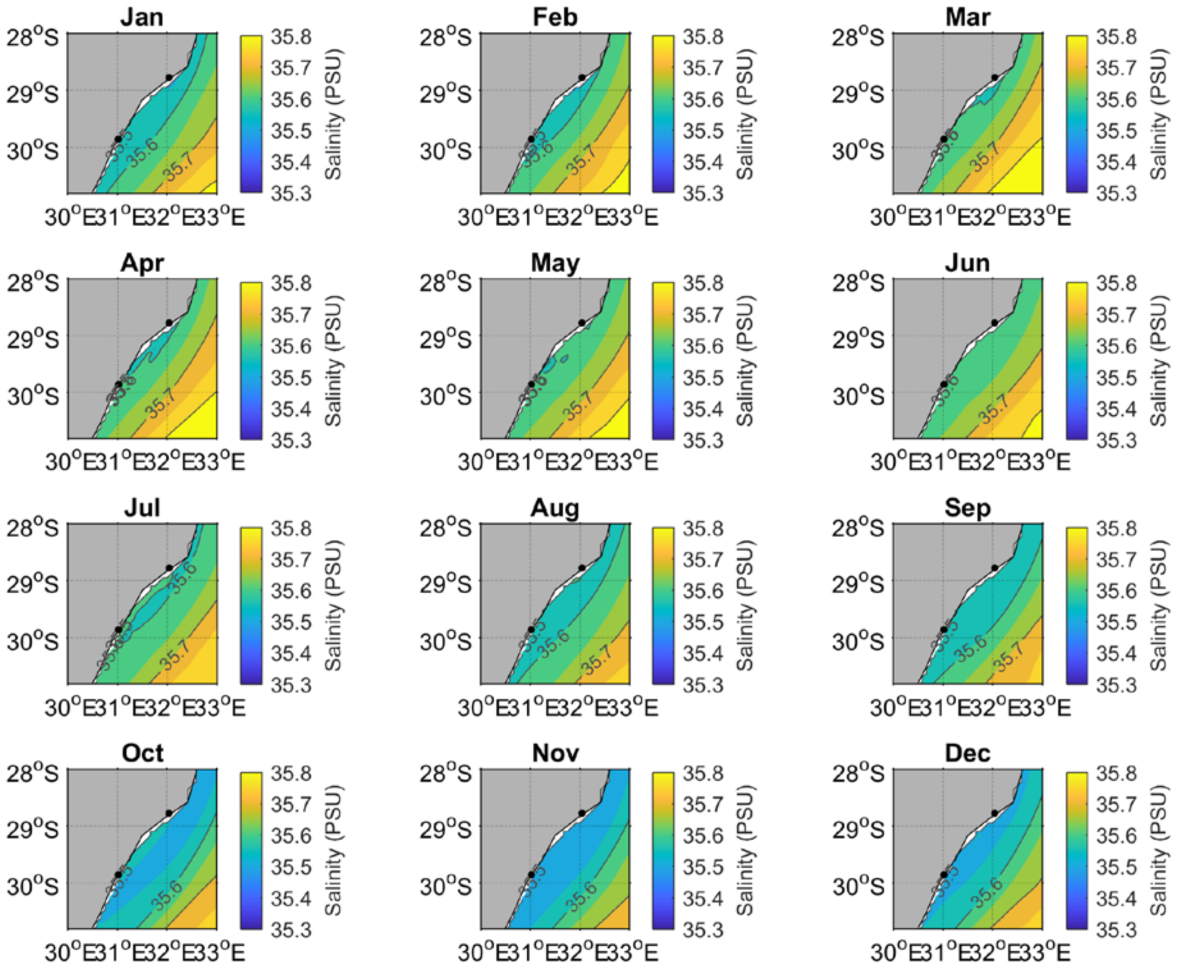


Figure 4-5: ROMS monthly climatology maps of salinity (PSU) a depth of 10 m across the Bight. The grey lines represent isohalines. The location of Richards Bay (north) and Durban (south) along the coast are indicated by the black dots.

At 50 m, ITSW was still observed across the Bight, although temperatures were slightly cooler and more saline than at the surface. Similar temperature and salinity distributions were observed at this depth with both variables showing an increase seaward (Figure 4-6 and Figure 4-7). The Agulhas Current was still visible to the west of the Bight in the temperature maps although it is cooler at 23-25°C throughout the year and the influence on the shelf was less (Figure 4-6).

There was less seasonal variation seen at this depth in the Bight as temperatures remain relatively the same between 21 and 23°C every month, although seasonal variation offshore of the Bight was still present. At the surface, summer months are much warmer than the rest of the months whereas at 50m this difference is less distinctive (Figure 4-4 and Figure 4-6). However, uThukela Banks MPA was still up to 1°C cooler than its surroundings. This was more noticeable at this depth with a distinct area of cool water (21 to 23°C) persisting throughout most of the year (Figure 4-6).

The salinities at 50 m were slightly less saline than at the surface with values going down to 35.4-35.45 PSU between December and April. In contrast to the surface, a seasonal pattern in salinity was seen across the Bight at 50 m with December to April having the least saline waters as stated previously and June to September having salinities of 35.5-35.55 PSU (Figure 4-9). As previously mentioned, the pool of less saline water observed in March and April at the surface was not seen at 50 m but rather areas of higher salinity surrounded by lower salinity were seen at the uThukela Banks MPA in January and May (Figure 4-7).

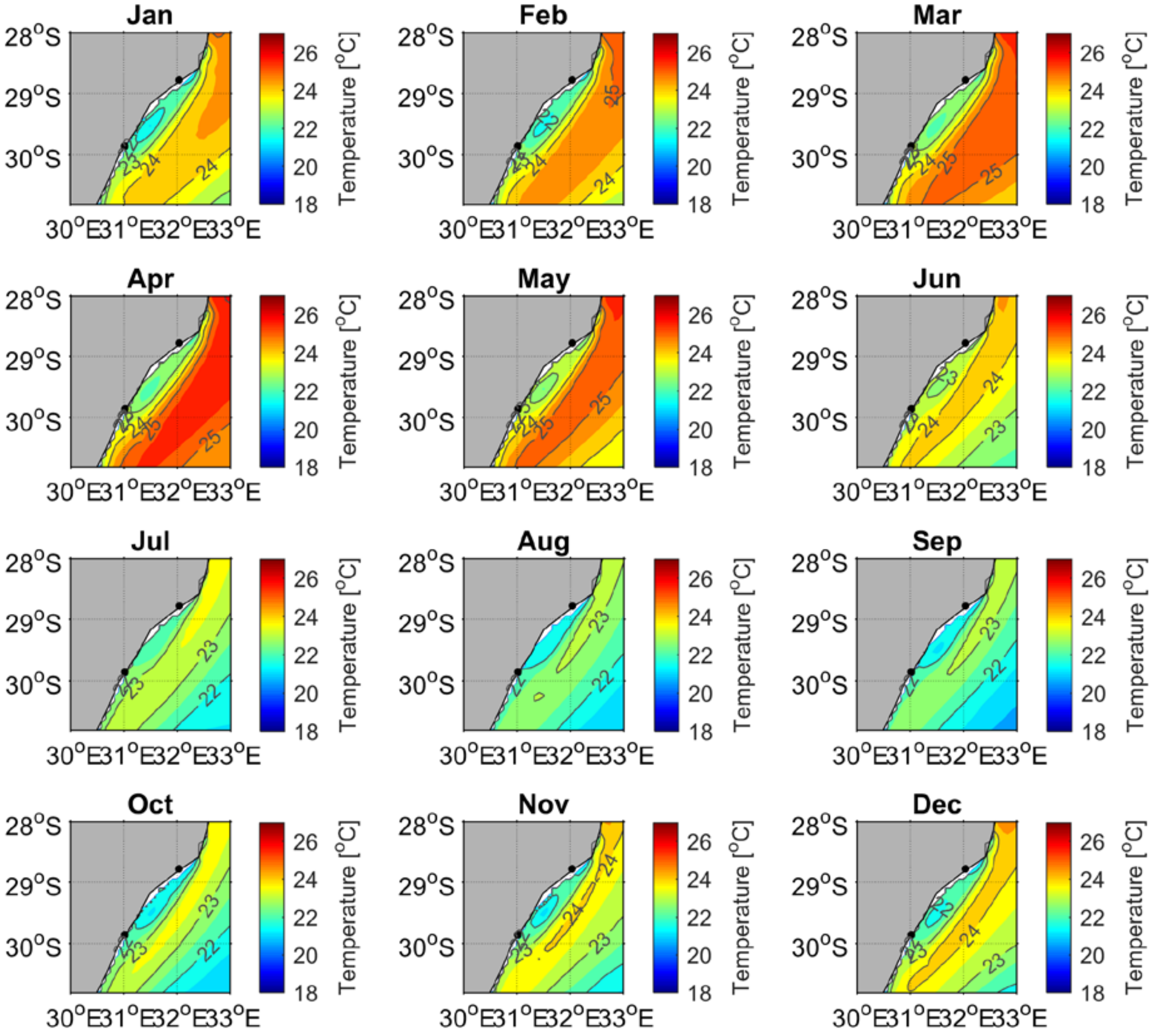


Figure 4-6: ROMS monthly climatology maps of temperature (°C) across the Bight with isotherms (grey lines) at a depth of 50 m for every month of the year. The location of Richards Bay (north) and Durban (south) along the coast are indicated by the black dots. The bathymetry is indicated in white. This is where the bight is shallower than 50 m in the model.

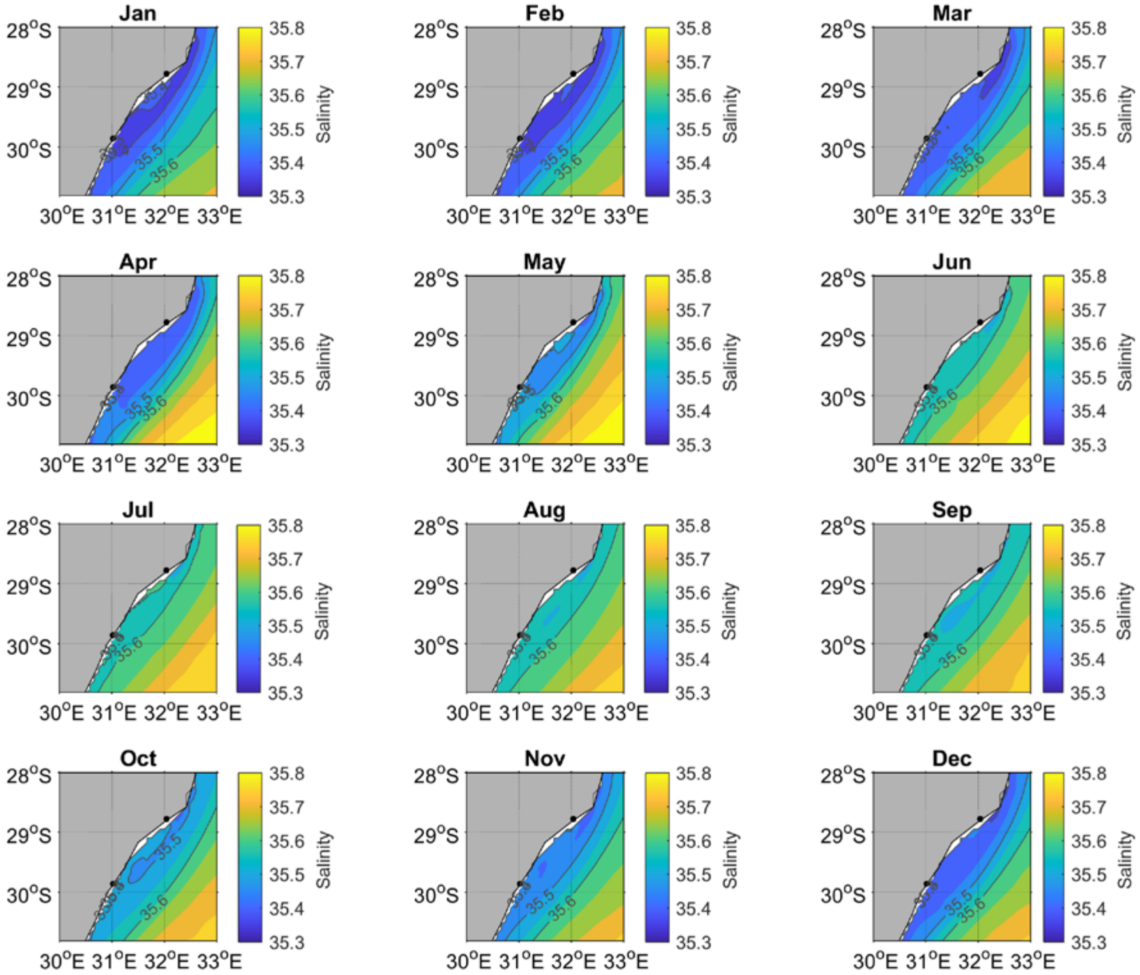


Figure 4-7: ROMS monthly climatology maps of salinity (PSU) a depth of 50 m across the Bight. The grey lines represent isohalines. The location of Richards Bay (north) and Durban (south) along the coast are indicated by the black dots. The bathymetry is indicated in white. This is where the bight is shallower than 50 m in the model.

At 100m, similar temperature and salinity distribution patterns were once again seen at this depth with both temperature and salinity increasing seaward, although no significant seasonal variation could be noted in and around the Bight (Figure 4-8 and Figure 4-9). It was at this depth where SSTW is present at temperatures of 18-19°C and salinities of 35.35-35.45 PSU (Figure 4-8 and Figure 4-9).

Temperatures in the region of the Bight decreased to 18°C offshore of the uThukela Banks MPA and to 19°C at the Aliwal Shoal MPA and the rest of the Bight. The Agulhas Current was still warmer than shelf waters with temperatures ranging between 21 and 22°C (Figure 4-8).

Salinity maps at 100 m show that salinity was lower than the surface and at 50 m with values remaining between at 35.4 and 34.45 PSU for the majority of the year offshore of the uThukela Banks MPA and the rest of the the Bight, with an exception of January and February where salinities dropped to 35.35 PSU . In March and April, only a few regions in the Bight remained at 35.35 PSU as salinities increased to 35.4 PSU (Figure 4-9).

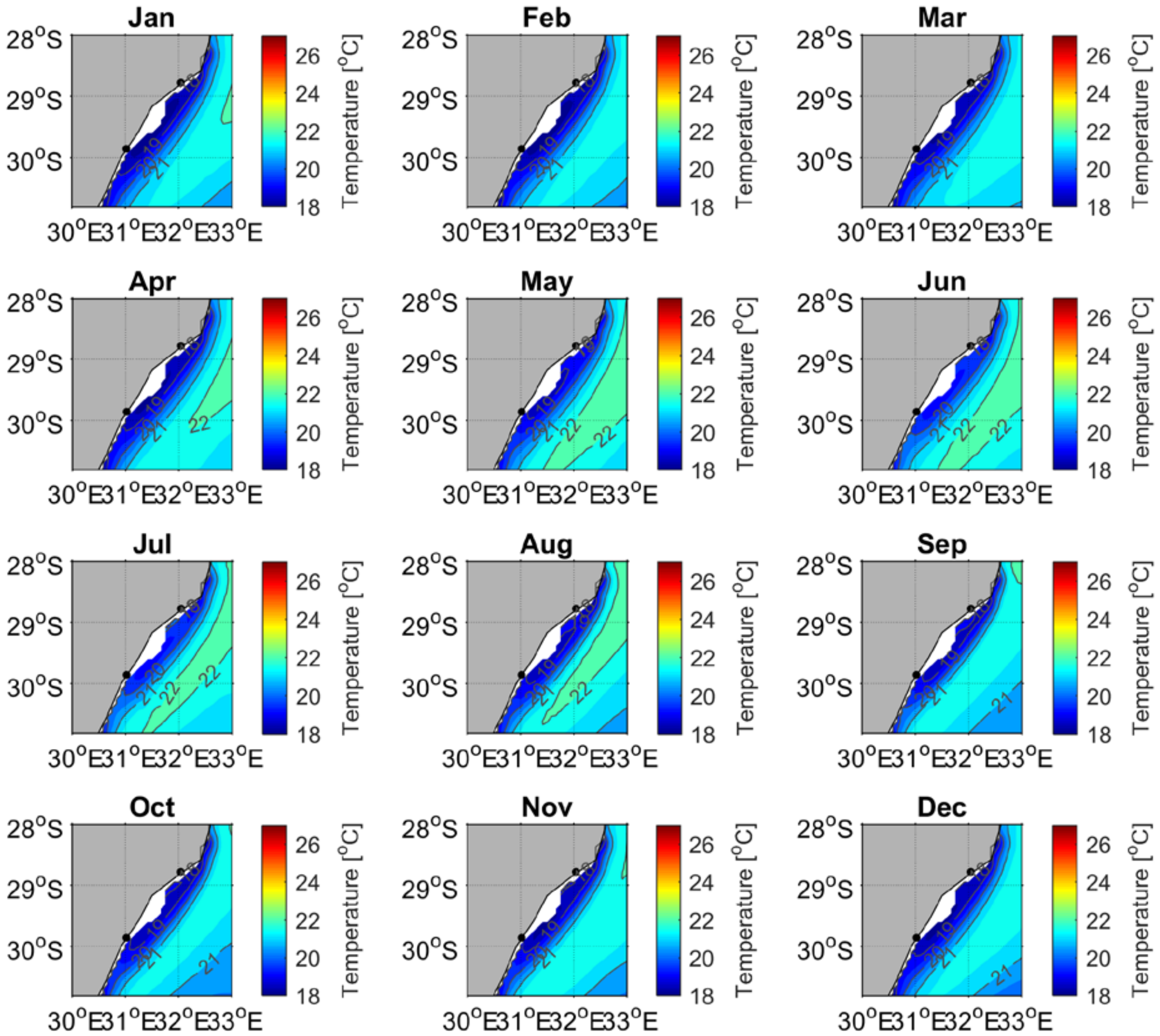


Figure 4-8: ROMS monthly climatology maps of temperature (°C) across the Bight with isotherms (grey lines) at a depth of 100 m for every month of the year. The location of Richards Bay (north) and Durban (south) along the coast are indicated by the black dots. The bathymetry is indicated in white.

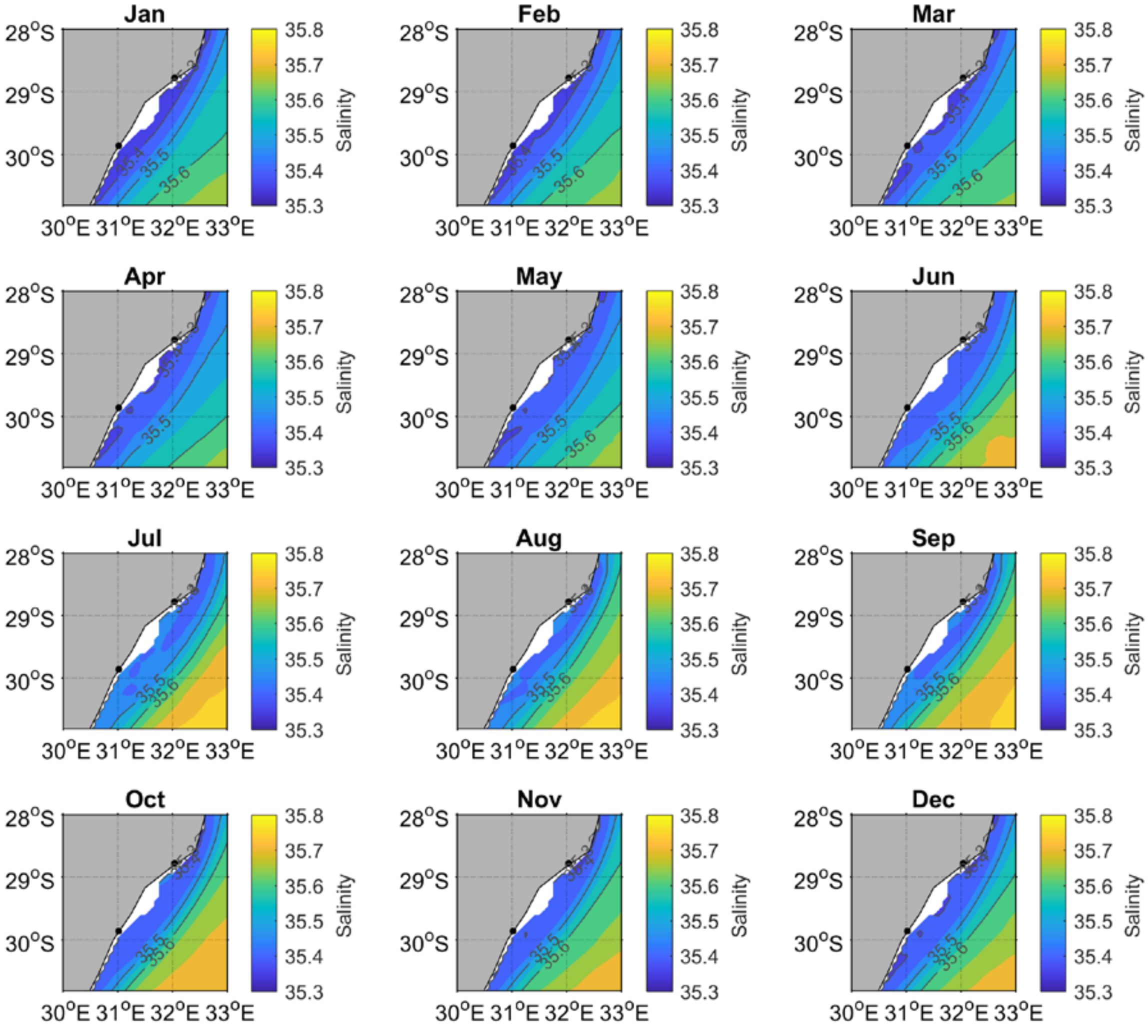


Figure 4-9: ROMS monthly climatology maps of salinity (PSU) across the Bight with isotherms (grey lines) at a depth of 100 m for every month of the year. The location of Richards Bay (north) and Durban (south) along the coast are indicated by the black dots. The bathymetry is indicated in white.

4.1.3 Vertical Distribution of Temperature and Salinity

Vertical sections of temperature and salinity were plotted across the continental shelf and Agulhas Current at the latitudes of the uThukela Banks and Aliwal Shoal MPAs (Figure 4-9 to 4-12) to get a better understanding of how temperature and salinity change with depth in the upper 500 m of the ocean. At both MPAs, seasonal variation in both temperature and salinity, is restricted to the upper 100 m of the water column. Characteristics of all three water masses mentioned in section 4.1.1 are seen in the sections with ITSW (characterised by temperatures <20°C and salinities of 35.45-35.65 PSU) found from the surface down to 100 m and SSTW (15-20°C and 35.3 and 35.45 PSU) just below it extending down to about 200 m at the bottom of the shelf. On the continental slope, bottom waters are dominated by SICW (<15°C and <35.3 PSU). This is applicable to both MPAs throughout the year (Figure 4-10 to Figure 4-13).

uThukela Banks

As stated previously, the uThukela Banks region is relatively shallow and has a wider continental shelf in comparison to the rest of the Bight and this is evident in the vertical sections presented below. The sections show that the water column, over the shelf, was more stratified in the summer months, particularly from January to March. As noted in the horizontal maps, surface temperatures of >25°C dominated across the section from January to April and began to decrease in May to 23°C. The coolest surface temperatures (21°C) were observed from June to October. Bottom temperatures across the shelf ranged from 15 to 20°C and temperatures off the shelf were < 15°C (Figure 4-10).

Seasonal patterns were evident in the surface salinity with maximum salinities of surface 35.5 PSU and greater that dominated the shelf's upper 50 m of the water column from May until July (winter months). In August, fresher waters of 35.4 PSU started to intrude the shelf's surface water and dominated the upper 150-180 m of the water column until December. Less saline waters of 35.2 PSU were found further offshore on the continental shelf. Bottom waters on the contineta slope were dominated by salinities of lower than 35.2 PSU (Figure 4-11).

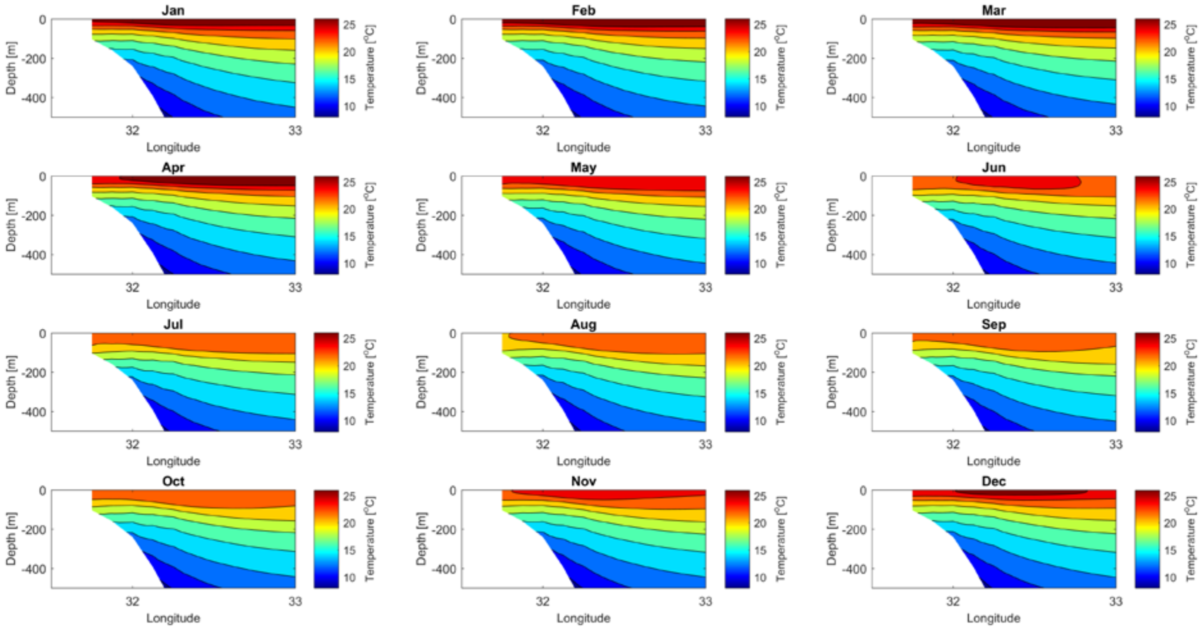


Figure 4-10: Temperature (°C) vertical sections, obtained from ROMS, across the uThukela Banks MPA for each month of the year. The coast and bathymetry are indicated in white.

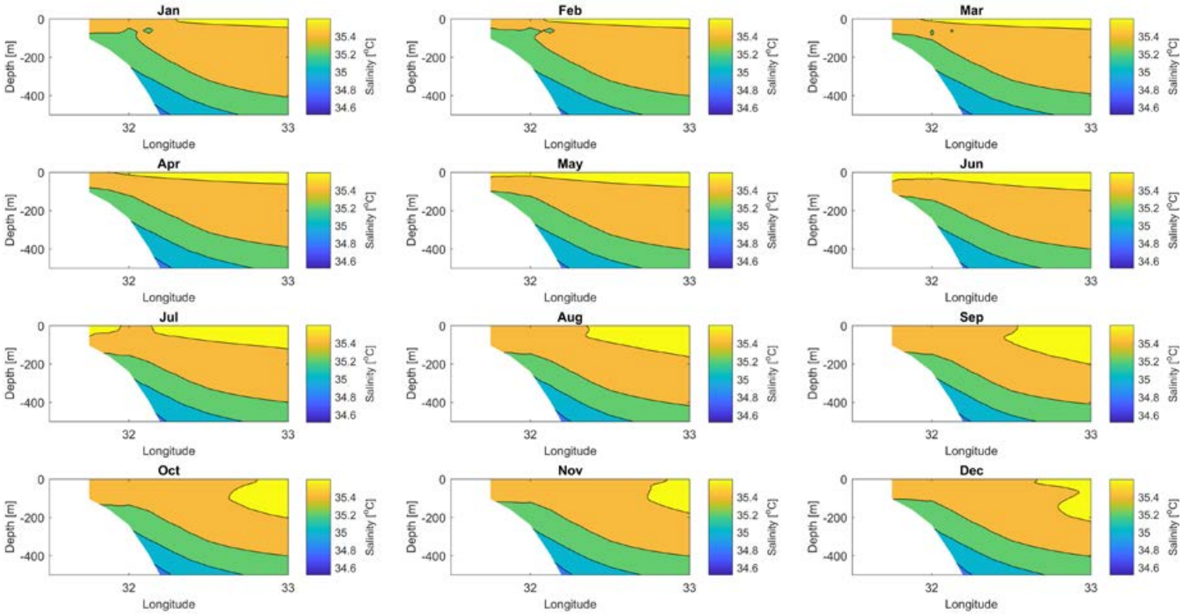


Figure 4-11: Salinity (PSU) vertical sections, obtained from ROMS, across the uThukela Banks MPA for each month of the year. The coast and bathymetry are indicated in white.

Aliwal Shoal

As we move south from the uThukela Banks MPA to the Aliwal Shoal MPA, the continental shelf begins to deepen again up to 200 m (Figure 4-11). Similar to the uThukela Banks MPA, the Aliwal Shoal MPA was dominated by warm surface temperatures of >25°C from January to April and began to decrease in May to 23°C. The coolest months were similarly observed from June to October; however, this was not spread across the entire surface as seen at the uThukela Banks MPA. Cooler surface waters of 20°C were also found at the surface between July and October. On the narrow shelf region, bottom waters ranged from 15 to 20°C and on the continental slope temperatures were <15°C (Figure 4-12).

There appeared to be more variability in salinity across the Aliwal Shoal MPA and offshore than across the uThukela Banks MPA. From August up until January, surface salinities over the shelf were 35.4 PSU as with the uThukela Banks MPA, however the more saline 35.5 PSU water was more prominent at the surface offshore of the Bight and extended deeper into the water column to about 200 m (Figure 4-13). The 35.5 PSU water intruded onto the shelf waters in June and July and retracted again in August. From February to May waters of 35.4

PSU were brought to within 50 m of the surface whereas at the uThukela Banks these waters remained mostly at the bottom of the shelf.

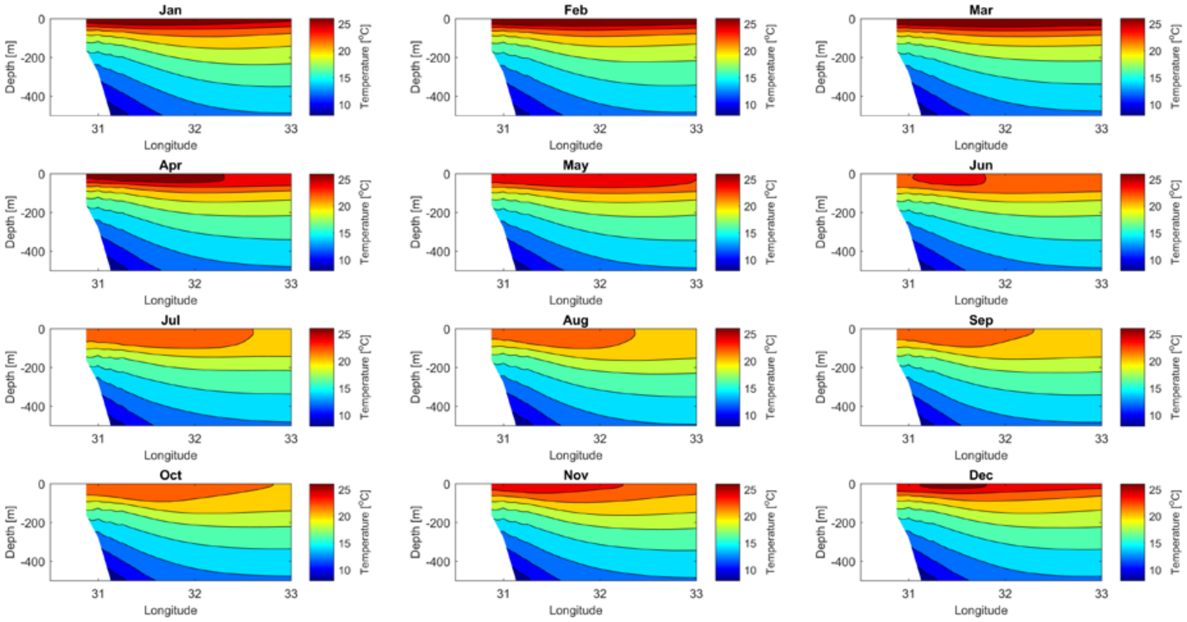


Figure 4-12: Temperature (°C) vertical sections, obtained from ROMS, across the Aliwal Shoal MPA for each month of the year. The coast and bathymetry are indicated in white.

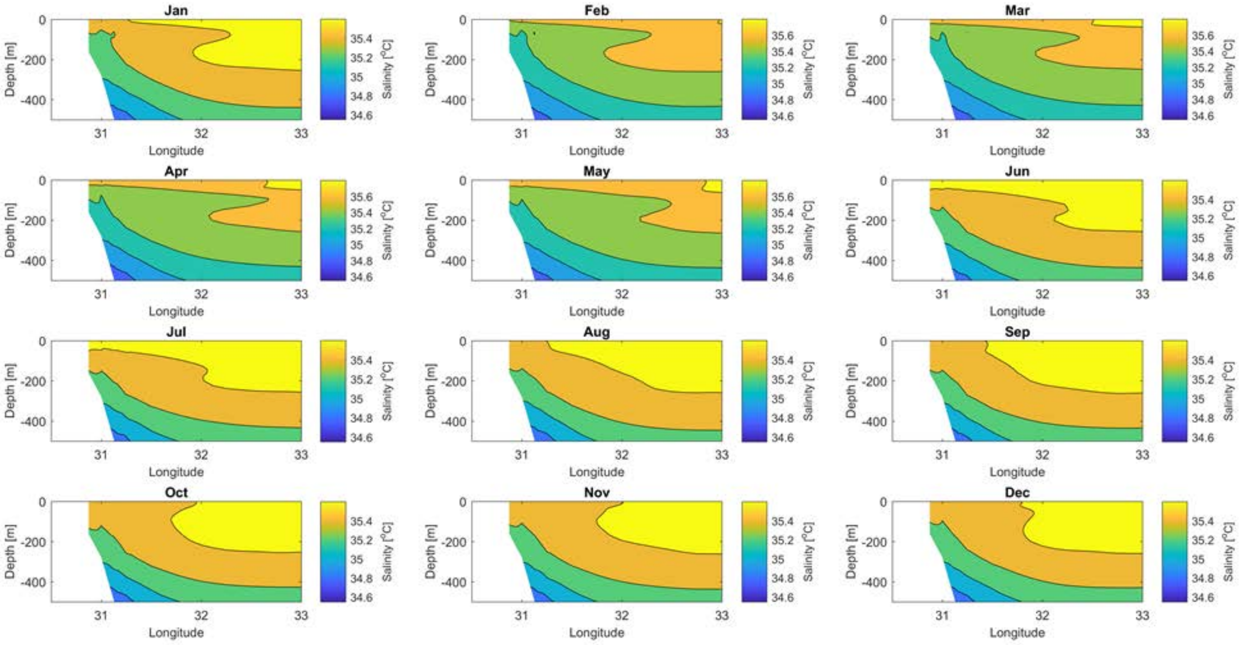


Figure 4-13: Salinity (PSU) vertical sections, obtained from ROMS, across the Bight offshore Aliwal Shoal MPA for each month of the year. The coast and bathymetry are indicated in white.

4.2 INTERANNUAL VARIABILITY

Time series for points inshore of the newly established MPAs (Figure 4-1) are plotted in this section. The time series were monthly averages calculated from 3-day outputs from the period 1980-2010. Additionally, the seasonal signal and long term trend were then removed from the time series by subtracting the climatology and the long term trend to produce anomaly time series. The purpose of these time series were to investigate the interannual variability in surface (10 m) and bottom (50 m) waters. Time series were not plotted at 100 m as inshore regions of the Bight were shallower than 100 m.

In additon, wavelet analyses were performed on the monthly temperature and salinity time series over the uThukela Banks and Aliwal Shoal MPA (Figure 4-15 and Figure 4-17 respectively) for the time period 1980 to 2010 to highlight the annual and semiannual cycles of these variables. The Morlet wavelet was used in this study as it has the ability to detect both time-dependent amplitude and phase for different frequencies (Daubechies, 1992). The local wavelet power spectrum was calculated as the square of the wavelet coefficients and the global wavelet power spectrum was the average of the wavelet power spectrum over time (Torrence and Compo, 1998; Collins et al., 2012). The wavelet power expresses the variance of the time series and therefore a high significance line in the global wavelet power spectrum was indicative of a noisy time series whereas a low significance line indicated a smooth time series. The significance lines are calculated using an appropriate background spectrum (white noise or red noise) that serves as a 'null hypothesis'. The 95% significance level determined from a chi-squared distribution, as well as the region of the wavelet analysis not subjected to edge effects, denoted by the cone of influence (COI) (Torrence and Compo, 1998), were indicated on the wavelet figures.

uThukela Banks

There were no notable increasing or decreasing trends in temperature and salinity over the 30-year period of the model output (Figure 4-14 and Figure 4-16). Both the monthly and anomaly time series show that there was more variability in temprature at the bottom. However, there are anomalous months e.g. January 1996 was 2.2°C cooler than the January climatology and April 2006 that was 2.2°C warmer than the April climatology. These two events will be further investiagted in section 4.3.1.

There was on average a 3°C difference in surface and bottom temperatures in summer in contrast to a 0.1-1°C difference during winter. Peak temperatures at the surface ranged between 26 and 27.5°C during summer and between 21 and 22.5°C during winter (Figure 4-14). Additionally, a strong annual (12 month) signal was seen in the wavelet power spectrum (Figure 4-15a and b) indicating a dominant annual cycle in temperature at the surface. Temperatures at the bottom were more variable than at the surface and a weaker annual signal was displayed (Figure 4-15c and d). Peak temperatures at 50 m during the summer were between 21.5 and 25°C, and 20 and 22°C during winter (Figure 4-14). A weaker annual cycle signal was displayed in the wavelet power speactrum, however it was still the dominant cycle. In contrast to temperature at 10 m, a weak but significant semi-annual signal was also displayed in the wavelet power spectrum (Figure 4-15c and d).

Salinities at the surface and at the bottom were similar in the summer months with peak salinities ranging between 35.5 and 35.88 PSU at both depths (Figure 4-16). Winter months showed larger differences between 10 and 50 m with salinities being up to 0.15 PSU lower at the bottom than at the surface. The lowest salinity value (35.25 PSU) occurred in February 1981. Both monthly averages and anomaly timeseries showed a period of increased salinities between 2001 and 2003 at the surface and bottom with surface salinities increasing to 35.88 PSU (0.28 PSU higher than the June climatology) in March 2002 and salinities at 50 m increasing to 35.84 PSU (0.24 PSU higher than the June climatology) in June 2002 (Figure 4-16).

Unlike temperature, the wavelet analysis showed that there was no significant cycle in salinity during this period (Figure 4-17a and b). However, at the bottom there was a strong annual signal displayed in the wavelet analysis cycle (Figure 4-17c and d). The absence of a cycle at the surface was as a result of the surface salinity being highly influenced by freshwater input from rainfall.

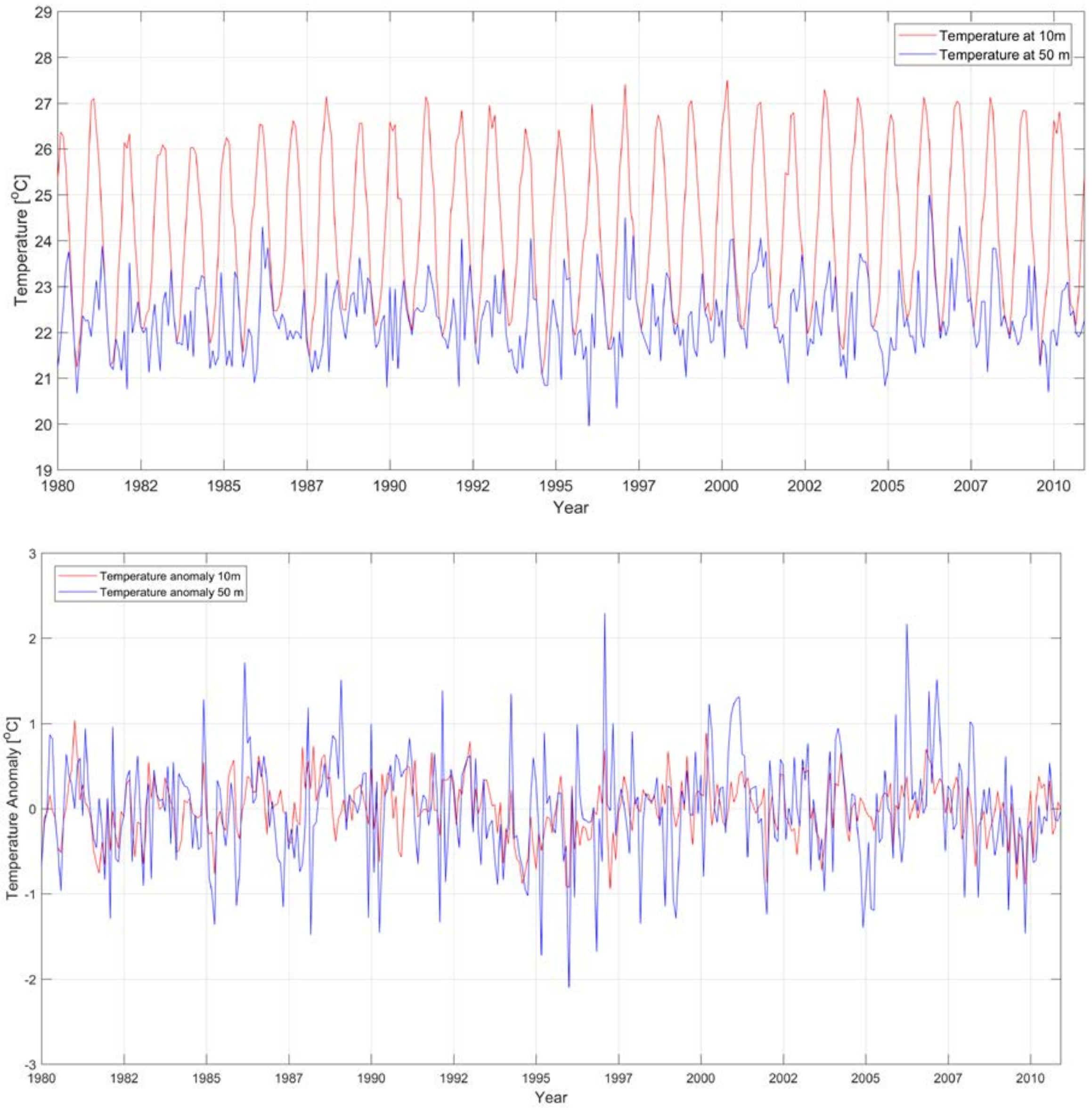


Figure 4-14: Time series of monthly-averaged temperature (°C) at the uThukela Banks MPA from 1980-2010 (top figure). Monthly temperature anomalies (°C) at the uThukela Banks from 1980-2010 (bottom figure). The red time series represents the temperature at the surface (10 m) and the blue time series represents the temperature at the bottom (50 m).

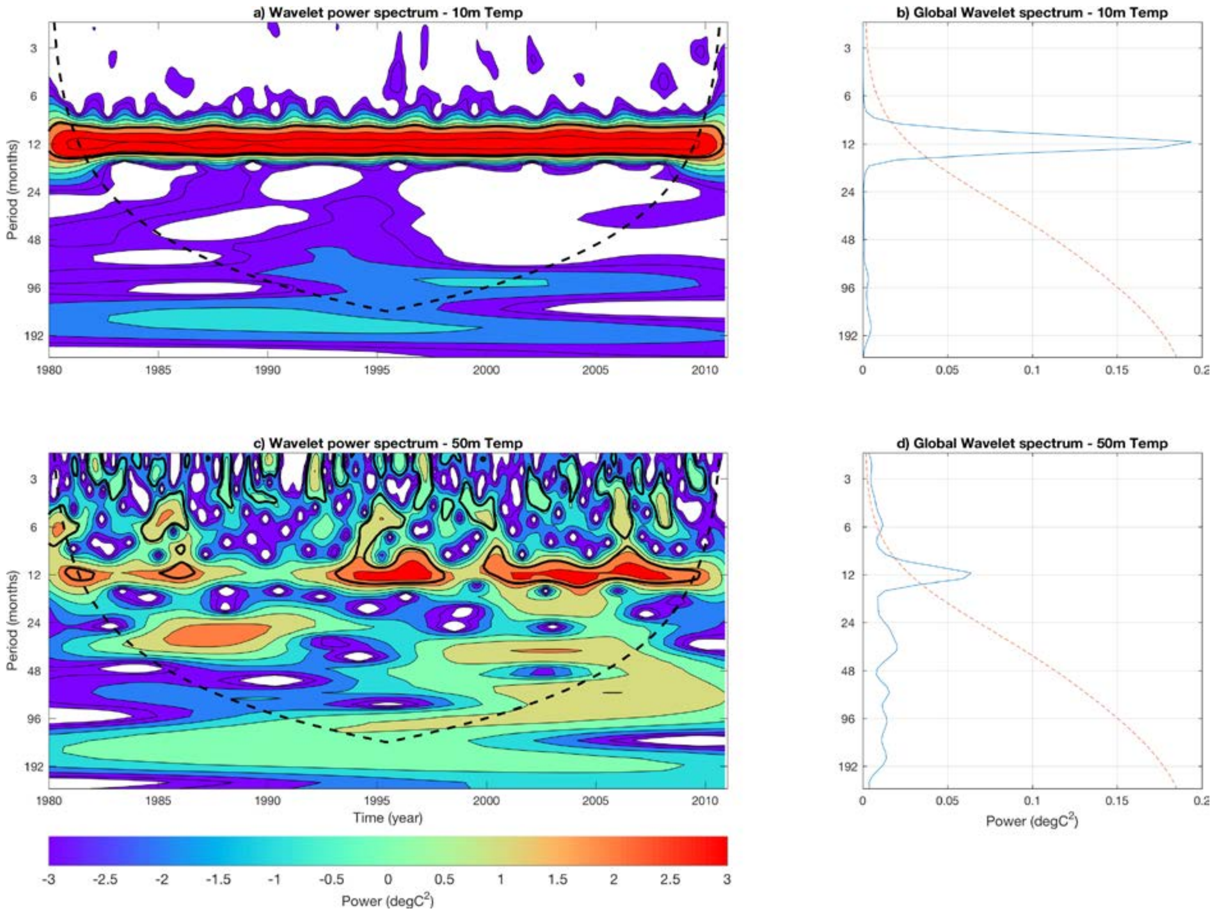
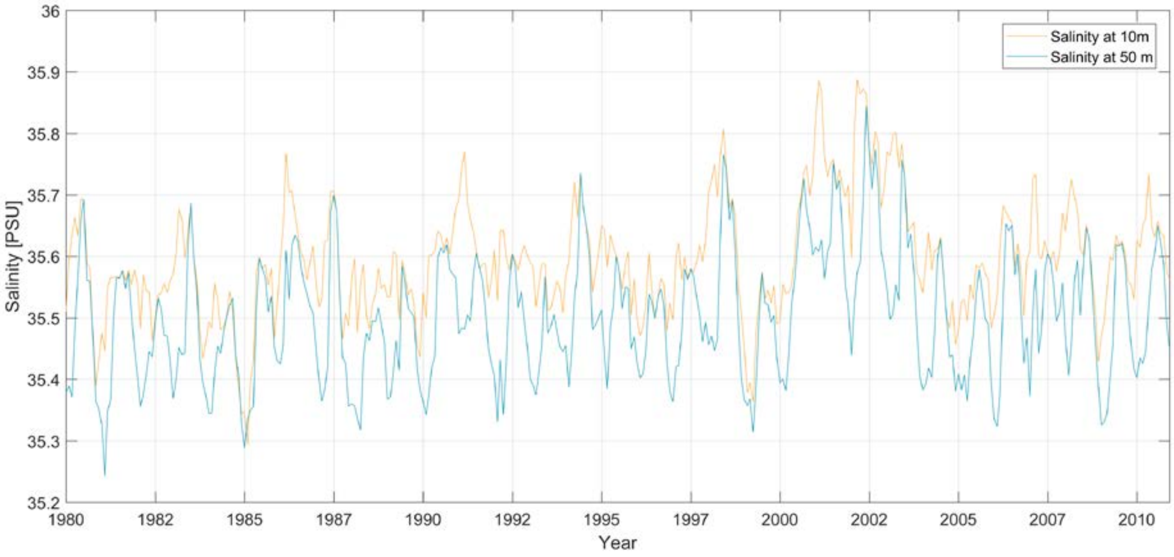


Figure 4-15: (a and c) Wavelet power spectrum and (b and d) power of the wavelet analysis of temperature over the uThukela Banks MPA at the surface (10 m) and at the bottom (50 m) for ROMS. The cone of influence (COI) is indicated by the dashed black line, and the thick black contours indicate the 95% significance levels. Significance in the global wavelet spectrum is indicated by the red dashed line.



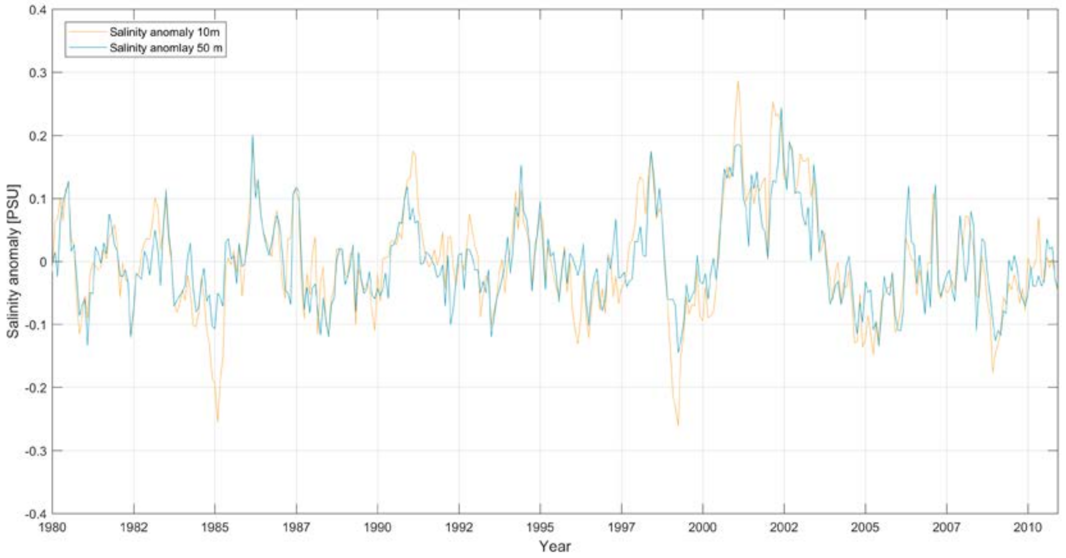


Figure 4-16: Time series of monthly-averaged salinity (PSU) at the uThukela Banks MPA from 1980-2010. Monthly salinity anomalies (PSU) at the uThukela Banks from 1980-2010 (bottom figure). The orange time series represents the salinity at the surface (-10 m) and the light blue time series represents the salinity at -50 m)

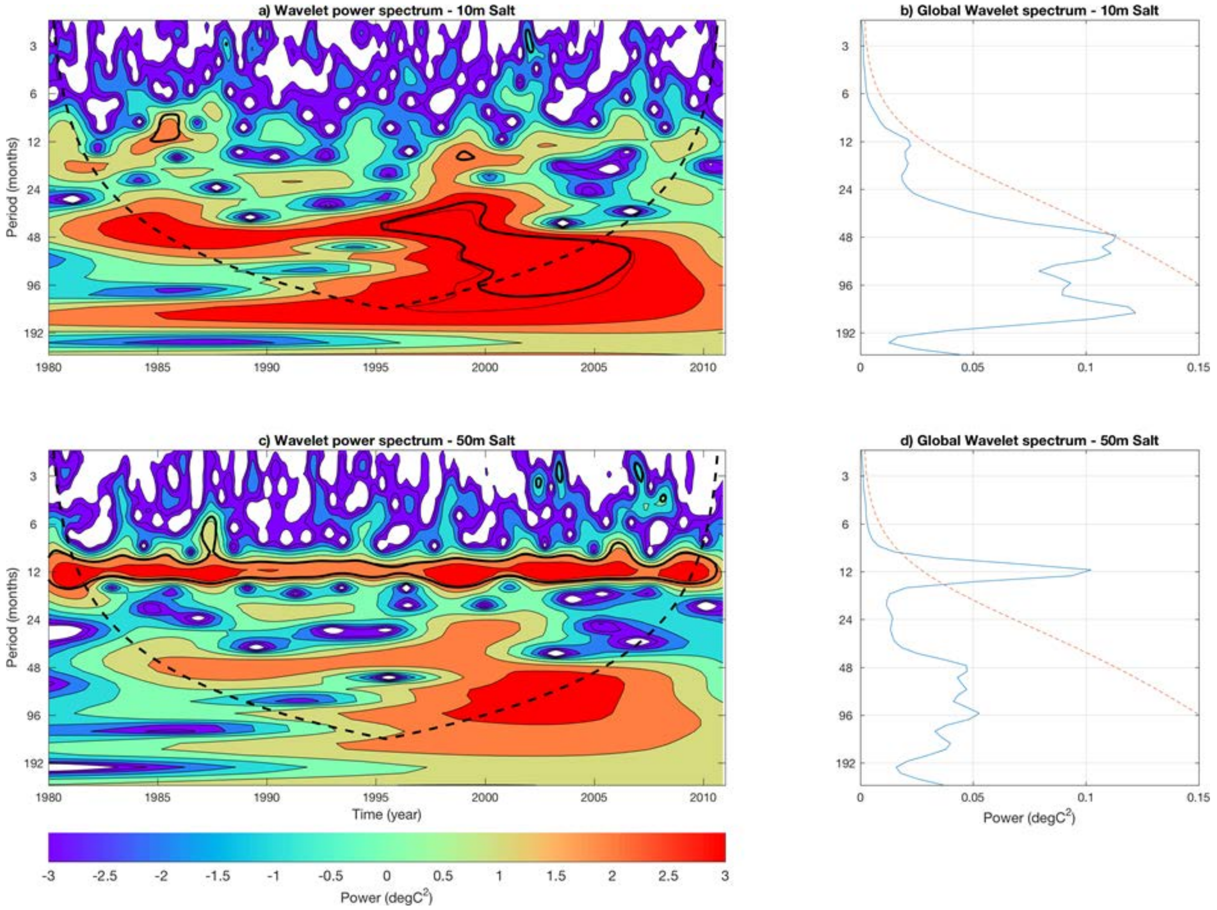


Figure 4-17: (a and c) Wavelet power spectrum and (b and d) power of the wavelet analysis of salinity over the uThukela Banks MPA at the surface (10 m) and bottom (50 m) for ROMS. The cone of influence (COI) is indicated by the dashed black line, and the thick black contours indicate the 95% significance levels. Significance in the global wavelet spectrum is indicated by the red dashed line.

Aliwal Shoal

Similar to the uThukela Banks MPA, the time series showed no notable increasing or decreasing trends in temperature and salinity through the water column over the 30-year period (Figure 4-18 and 4-18). Both the monthly and anomaly time series show that there was more variability in temprature at the bottom than at the surface. Surface temperatures are were less than 1°C cooler or warmer than the climatology. Bottom temperatures were more variable and often had periods that were notably cooler or warmer than the climatology. The greatest differences from the climatology are seen in January 1996 which was 2.3°C cooler than the climatology and April 2006 which was 1.9°C warmer than the climatology, similar to the uThukela Banks MPA. These two events will be further investiagted in the following section.

Monthly plots show that there was a 3°C average range in temperature at 10 and at 50 m and temperatures at 50 m also showed more variabililty. Although the time series at the two MPAs showed similar patterns, temperatures in the Aliwal Shoal MPA were warmer than in the uThukela Banks MPA at the surface and 50 m as also identified in the temperature maps in section 4.1.2. Peak temperatures at 10 m ranged between 26.6 and 27.8°C in summer and 21.8 and 23°C during winter. As seen in the uThukela Banks MPA, a strong dominant annual cycle was displayed in the wavelet power spectrum at 10 m (Figure 4-21a and b). At 50 m, peak temperatures during the summer were between 23 and 25.5°C and 20.7 and 22.5°C during winter, also higher than the uThukela Banks MPA. Although the temperature at this depth was more variable, a strong annual signal was evident in the wavelet power spectrum indicating a dominant annual cycle (Figure 4-19c and d). A weaker but significant semi-annual signal was also present in the wavelet power spectrum (Figure 4-19c and d).

Salinities at 10 and 50 m at the Aliwal Shoal MPA showed similar patterns to those obsereved at the uThukela Banks MPA with salinity values at 10 and 50 m showing little differences. The salinity time series also showed a period of increased salinities between 2001 and 2003, however, during this period salinities were slightly higher than at the uThukela Banks MPA with surface salinities increasing up to 35.93 PSU at 10 m in April 2002 PSU and 35.85 PSU at 50 m in June 2002 (Figure 4-20).

Furthermore, there was no dominant cycle present at 10 m for salinity unlike with temperature (Figure 4-21a and b). However, at 50 m there is a strong annual signal displayed in the wavelet analysis cycle (Figure 4 16c and d). The absence of a cycle at 10 m was as a result of the surface salinity being highly influenced by freshwater input from rainfall as mentioned previously for the uThukela Banks MPA.

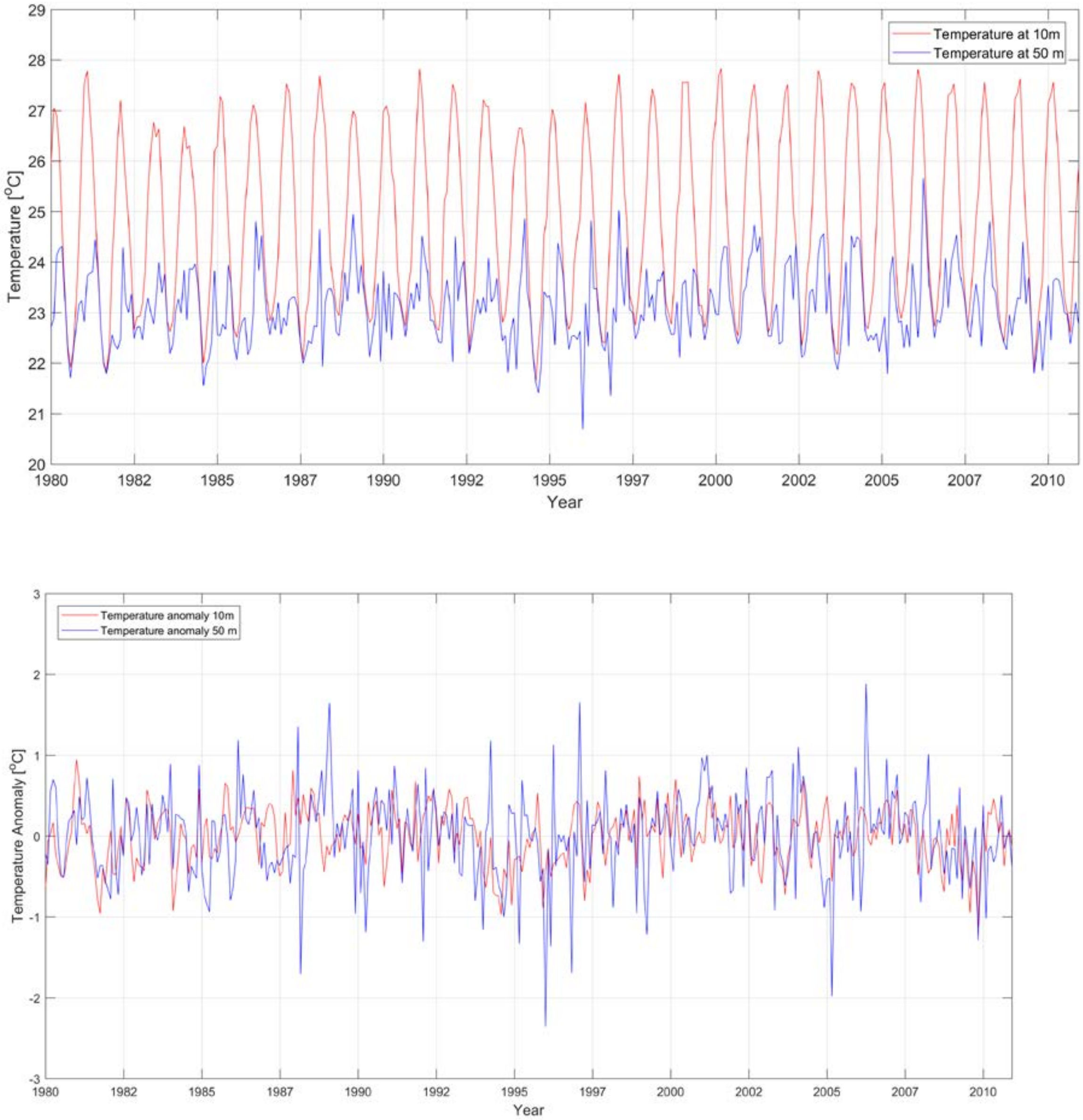


Figure 4-18: Time series of monthly-averaged temperature (°C) at Aliwal Shoal from 1980-2010 (top figure). Monthly temperature anomalies (°C) at the Aliwal Shoal MPA from 1980-2010 (bottom figure). The red time series represents the temperature at the surface (10 m) and the blue time series represents the temperature at (50 m).

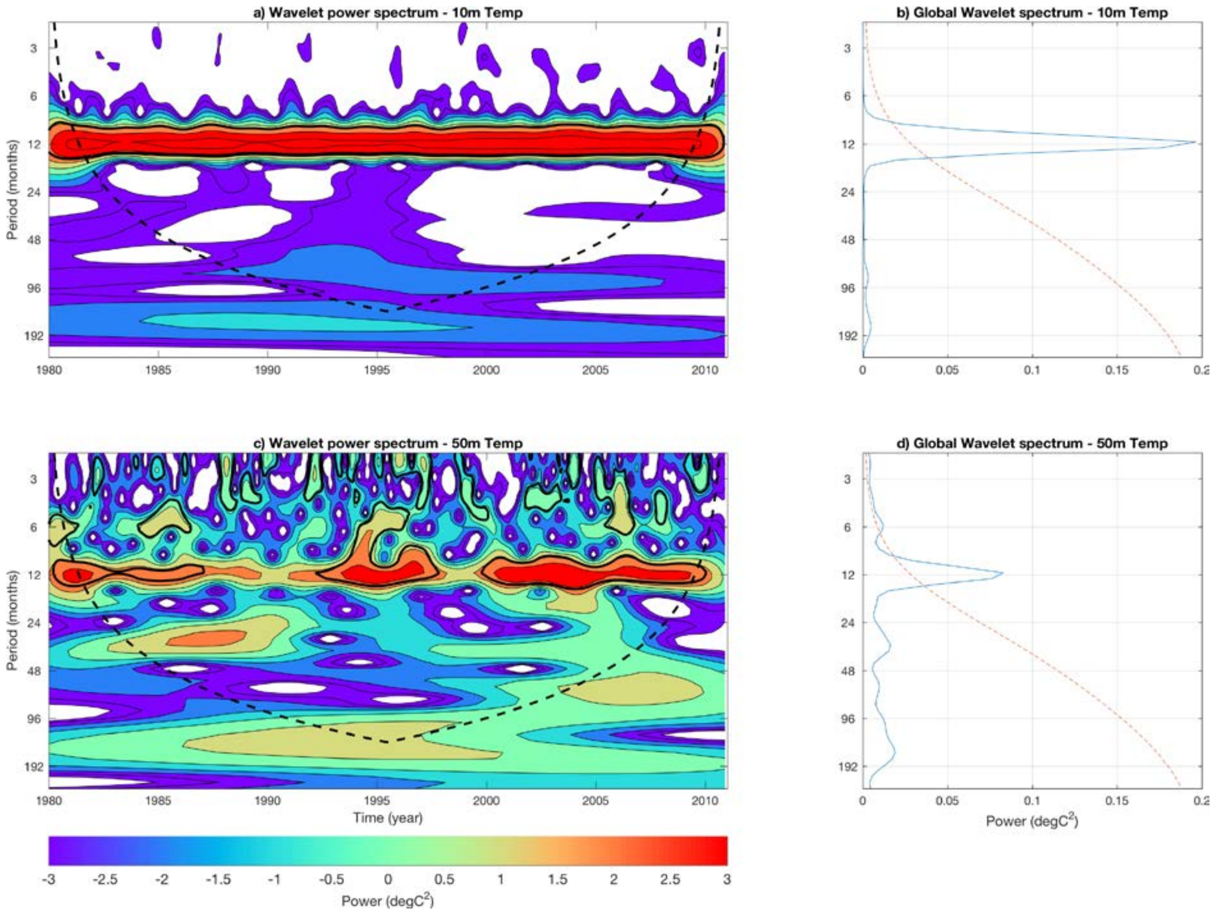
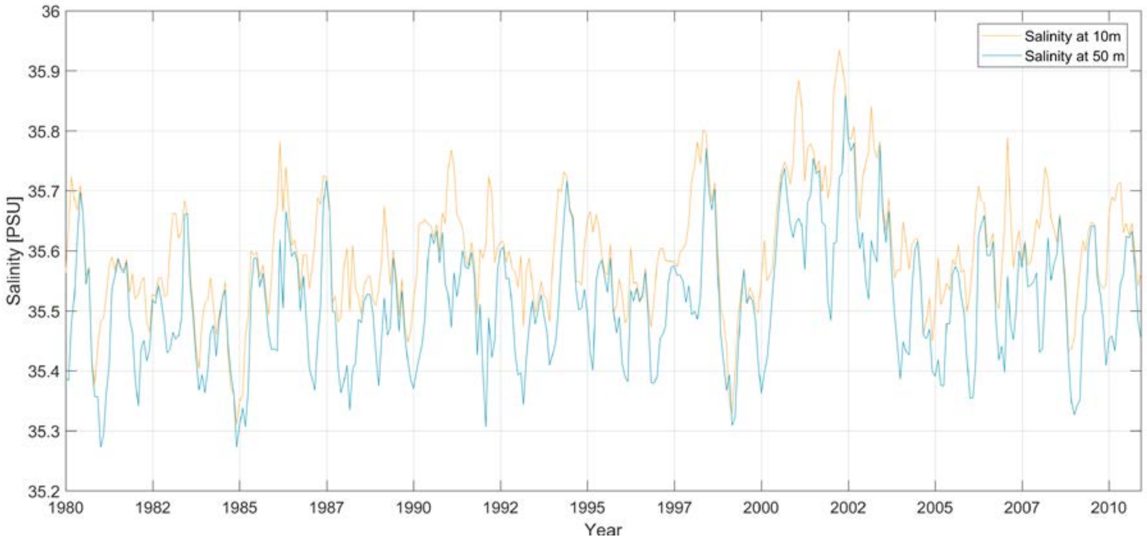


Figure 4-19: (a and c) Wavelet power spectrum and (b and d) power of the wavelet analysis of temperature over the Aliwal Shoal MPA at the surface (10m) and bottom (50 m) for ROMS. The cone of influence (COI) is indicated by the dashed black line, and the thick black contours indicate the 95% significance levels. Significance in the global wavelet spectrum is indicated by the red dashed line.



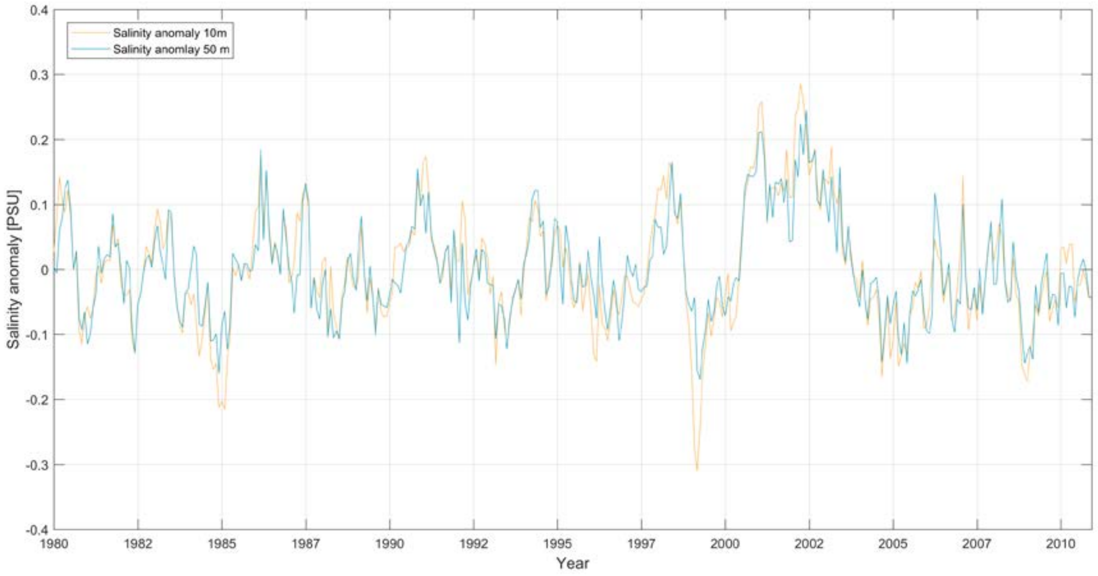


Figure 4-20: Time series of monthly-averaged salinity (PSU) at the Aliwal Shoal MPA from 1980-2010. Monthly salinity anomalies (PSU) at the Aliwal Shoal MPA from 1980-2010 (bottom figure). The orange time series represents the salinity at the surface (10 m) and the light blue time series represents the salinity at (50 m)

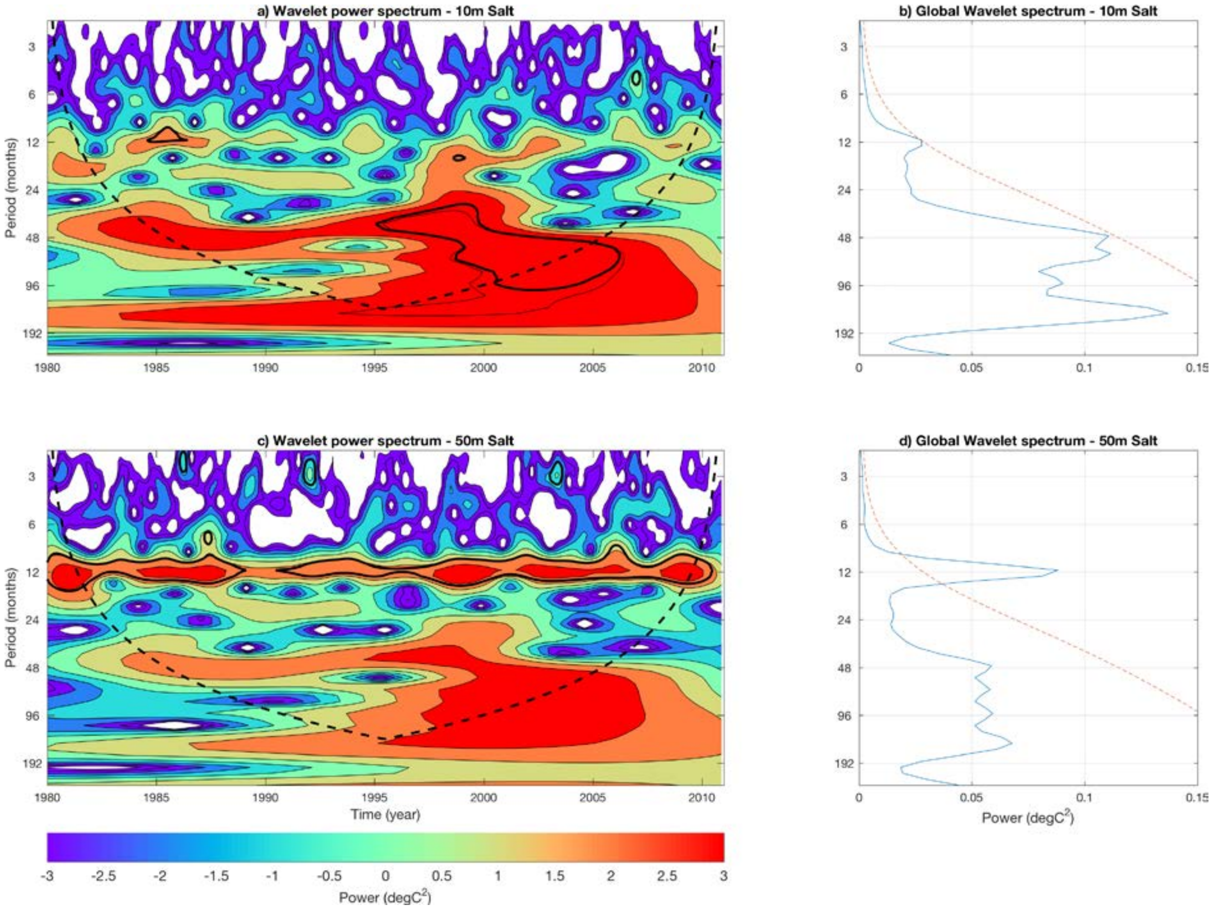


Figure 4-21: (a and c) Wavelet power spectrum and (b and d) power of the wavelet analysis of salinity over the Aliwal Shoal MPA at the surface (10 m) and bottom (50 m) for ROMS. The cone of influence (COI) is indicated by the dashed black line, and the thick black contours indicate the 95% significance levels. Significance in the global wavelet spectrum is indicated by the red dashed line.

4.3 THE INFLUENCE OF THE AGULHAS CURRENT ON THE BIGHT

As previously mentioned, the Agulhas Current has a more dominant influence, specifically with regards to temperature, on shelf waters north and south of the Bight where it flows close to the shelf break than in the central region of the Bight due to the divergence of the current in this region (Lutjeharms and de Ruijter, 1996; Schumann, 1988). The influence of the current can be seen through temperature differences between the inner region of the two MPAs and offshore where the Agulhas Current flows (points shown in Figure 4-1).

Although they share similar patterns, there were distinct differences in temperature between inshore and offshore temperatures at the uThukela Banks MPA at the surface and at the bottom (Figure 4-22). Surface temperatures differed by 0.5 to 2.4°C with a mean difference of 1.2°C over the 30 years. Bottom temperatures ranged from 0.2 to 3.8°C and with mean difference of 1.6°C (Figure 4-22). At the Aliwal Shoal MPA, the temperature time series showed a minor difference between the inshore region and offshore regions with the mean difference of 0.2°C at the surface and 0.3°C at 50 m (Figure 4-23).

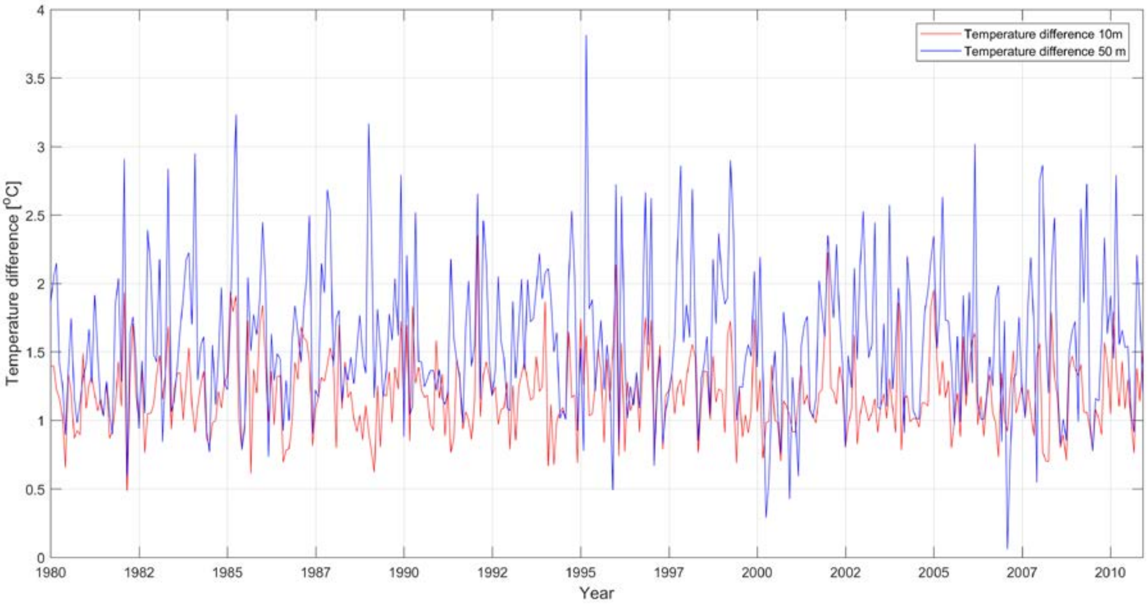


Figure 4-22: Temperature differences between inshore and offshore the uThukela Banks MPA at the surface (10 m) (top figure) and at the bottom (50 m) (bottom figure). Red time series indicate the offshore temperatures and the blue time series indicate the inshore temperatures.

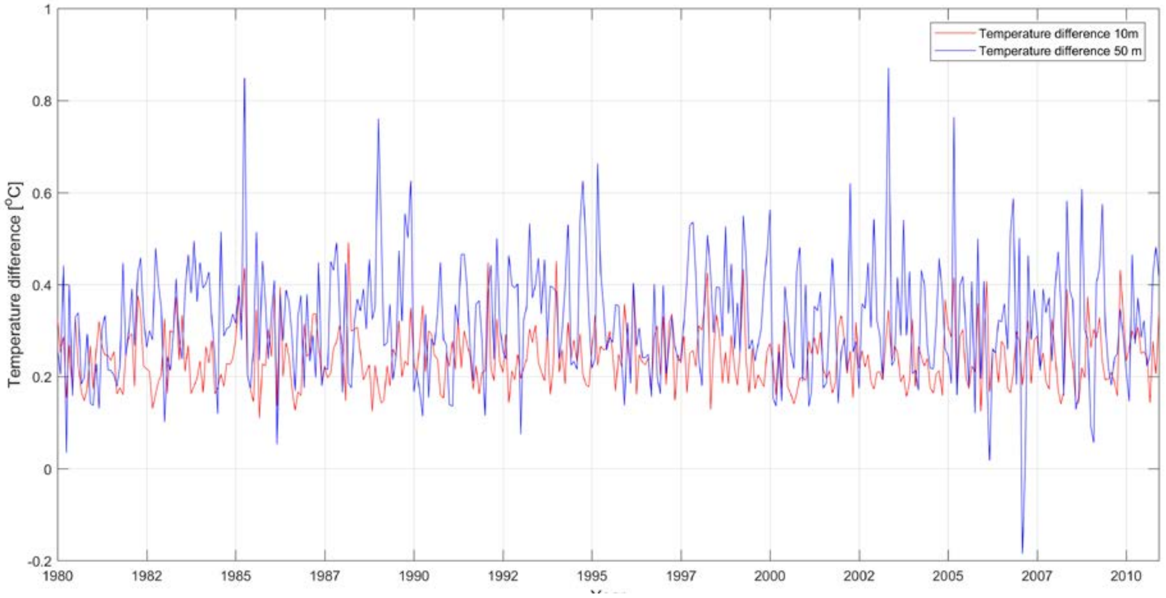


Figure 4-23: Temperature differences between inshore and offshore the Aliwal Shoal MPA at the surface (10 m) (top figure) and at the bottom (50 m) (bottom figure). Red time series indicate the offshore temperatures and the blue time series indicate the inshore temperatures. The black circles indicate anomalous periods.

4.3.1 Anomalous Events

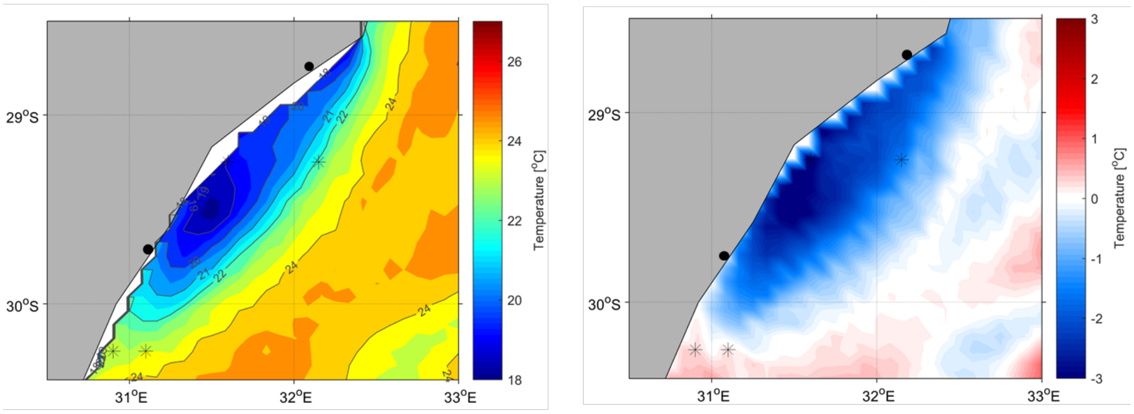
The two anomalous periods at 50 m: January 1996 and April 2006 at both MPAs were further investigated by plotting horizontal maps for the corresponding month (Figure 4-24). The horizontal maps also allowed us to see the path of the current and how it may play a role in the anomalous event.

January 1996 recorded the lowest temperature at 50 m over the 30-year period at both MPAs (Figure 4-14 and Figure 4-18) and was 2.2°C cooler than the January climatology. Temperature maps show that there is an anomalous structure in the Bight, a cooler body of water of 18-20°C from Richards Bay extending south to Durban. An anomaly map show that temperatures in the Bight were on average 2-3°C cooler than normal (climatological January) over this region (Figure 4-23b). This feature was characteristic of the Natal Pulse and the Agulhas Current was seen to flow further away from the coast during this time (Figure 4-24a). The feature has a dimension of about 170 km (distance between Durban and Richards Bay) and Figure 4-24 shows that the feature moved downstream at about 20 km/day.

The warmest month was April 2006 for both MPAs at 50m (Figure 4-24c) and the anomaly map shows that temperatures were 2-3°C higher than normal (Figure 4-24d). The Agulhas Current during this period was stronger and flowing closer to coast and therefore had more of an influence on the Bight.

a) Jan 1996 – 50 m

b) Jan 1996 – Anomaly



c) Apr 2006 – 50 m

d) Apr 2006 - Anomaly

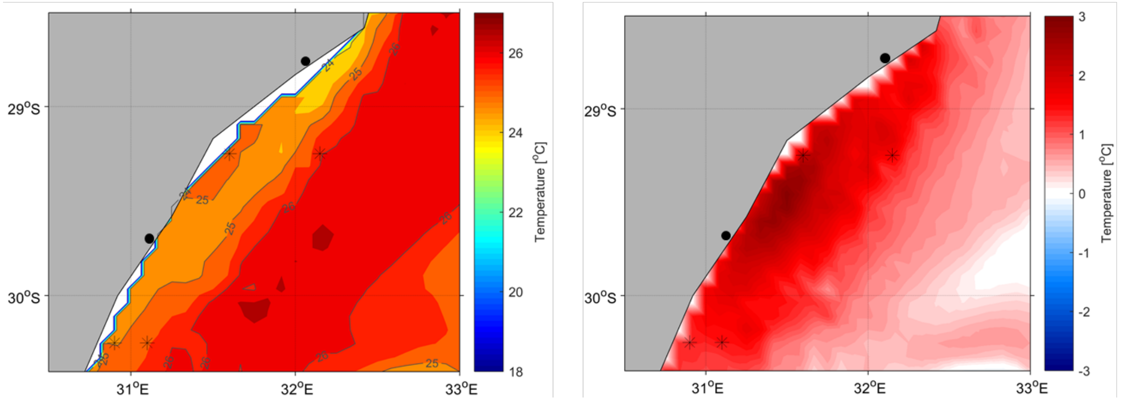


Figure 4-24: (a and b) Temperature (°C) map for January 1996, the coolest month over a 30-year period at the Aliwal Shoal MPA and the corresponding anomaly map. (c and d) Temperature map for April 2006, the warmest month over a 30-year period at both MPAs and the corresponding anomaly map.

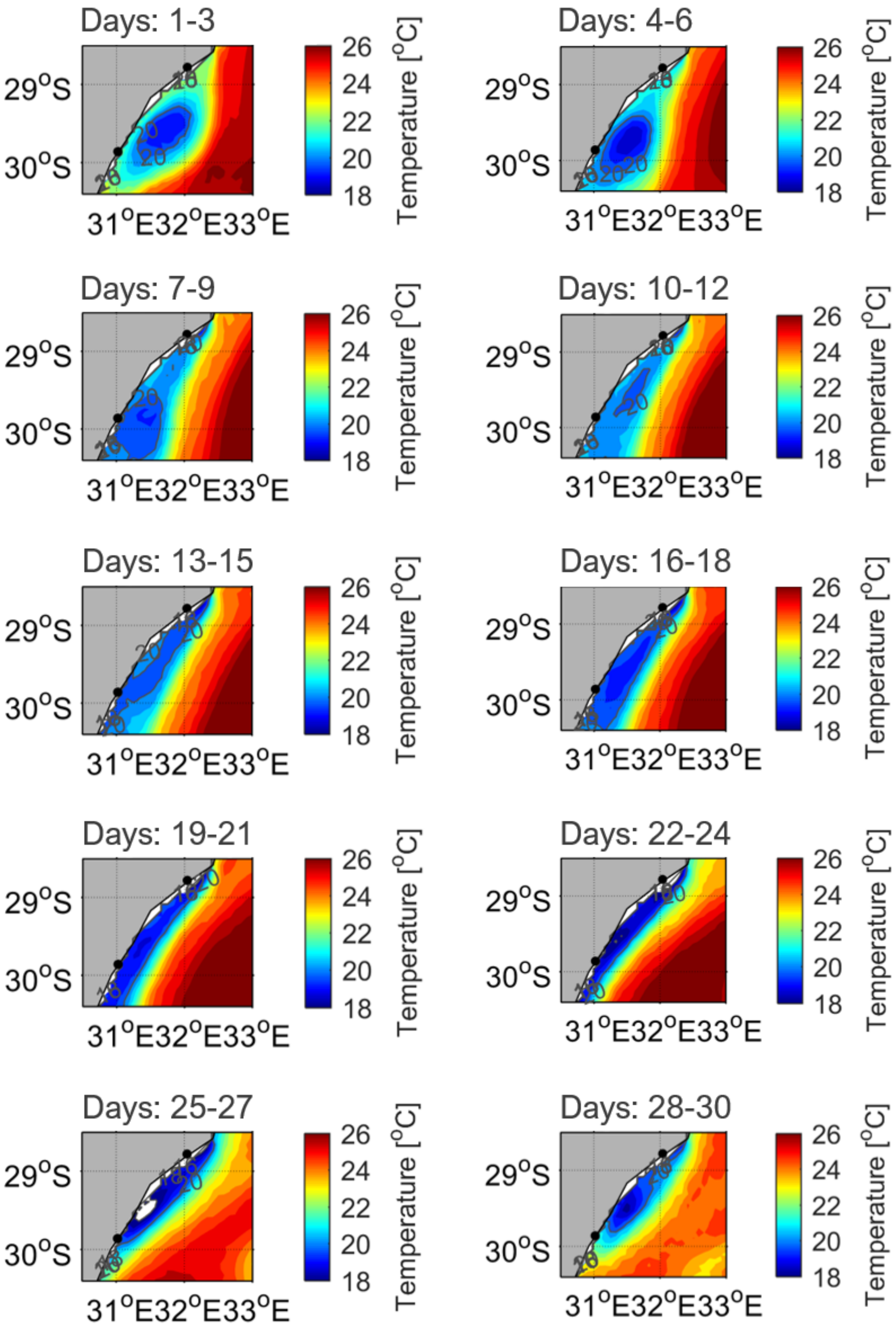


Figure 4-25: The downstream travel of the Natal Pulse in January 1996 plotted in 3-day averages.

5 DISCUSSION

The KwaZulu-Natal Bight (‘the Bight’) has been identified as a key area for protection along the South African east coast as it is a region of larval retention, recruitment and a general nursery area for various marine species (Fennessy et al. 2016b). As a result, two out of 22 new MPAs have been established in the Bight: the uThukela Banks MPA, in the central region of the Bight, and the Aliwal Shoal MPA, south of Durban. The purpose of these MPAs is to protect vulnerable habitats and secure spawning grounds for various marine species, therefore helping to sustain fisheries and ensure long-term benefits important to food and job security (RSA, 2016).

As previously stated, the Bight is a relatively under-sampled region (oceanographically and biologically) (Lutjeharms et al., 2000a; Fennessy et al., 2016a) resulting in a lack of long-term continuous data that can enable us to make inferences about the mean-state of the region. In response to this, the African Coelacanth Ecosystem Programme (ACEP) has been prominent in supporting research on the east coast of South Africa with the purpose of conducting MPA analyses along the Bight through a series of biological and oceanographic studies.

This study aimed to further our understanding of the oceanography of the Bight using oceanographic data collected in 2014-2017 between Richards Bay and Port Edward as well as data obtained from a high-resolution regional ocean model. Temperature and salinity are the two variables that were investigated since they have been identified as vital when refining conservation plans that identify critical areas of biodiversity that require protection (Green, 2015). The in-situ data collected in 2014-2017 were presented in section 3.2 and it was determined that it was too limiting to make conclusions about the mean-structure of the Bight given the sparseness of the in-situ data available. In addition, the data only represents one season, while some areas were not sufficiently sampled and there was no repetition during the sampling campaign. It is for these reasons that a decision to supplement the study with the best available long-term data and was the high-resolution ROMS (~ 9km resolution) simulation (section 3.1) was included.

The objectives of this study were addressed by using the ROMS simulation that provides data at a temporal frequency of 3-days, for the period 1980 to 2010 (30-years). The model was used to build a climatology to present the mean-state of the Bight and investigate the seasonal and annual variability as well as the influence of the Agulhas Current on the shelf. This section will provide a discussion of the results obtained from the model output in section 4.

5.1 MEAN-STATE OF THE BIGHT

5.1.1 Water Masses

TS diagrams allow us to identify the water masses in a region through their temperature and salinity characteristics. In the TS diagrams (Figure 4-2), we see that shelf temperature and salinity characteristics are strongly influenced by the proximity of the Agulhas Current which usually lies seaward of the 200 m isobath (Pearce, 1977). The current has more of a dominant influence north and south of the Bight where it flows close to the coast (Schumann, 1988) and this is evident in the TS diagrams where the Richards Bay and south of Durban profiles are more similar to the upper profile offshore of the Bight (in the general path of the current) than the central Bight profile. The upper Agulhas Current has an influence on surface as well as the bottom waters of the Bight as the Agulhas Current transfers waters onto the shelf which gives the Bight tropical and subtropical characteristics (Schumann, 1988) as seen in Figure 4-2. Warm ITSW, with temperatures ranging between 20 and 25°C and salinities of 34.45-35.65 PSU , were found at the surface of the Bight and are brought onto the shelf by shear edge plumes of the upper water of the Agulhas Current (Grundilingh and Pearce, 1990). Beneath the ITSW were the cooler (15-20°C) and slightly less saline (35.3-35.45 PSU) SSTW. The deepest site out of the points selected within the Bight was the Richards Bay site. As a result the profile show the presence of the much colder and deeper SICW which according to Lutjeharms et al., (2000a) are brought onto the shelf by various upwelling processes. The presence of these water masses was also evident in the maps and vertical sections of temperature and salinity. These maps also enabled us to see at which depths of the Bight they occurred in, this is presented below.

5.1.2 Mean-state of temperature and salinity

Through the maps and vertical sections in section 4.1.2 and 4.1.3, we were able to see temperature and salinity variations spatially and through the water column. Contrary to the findings by Pearce (1978) that stated that seasonal variability in the Bight (more specifically

Richards Bay) were overshadowed by short term variability on the shelf, this study has shown that a temperature and salinity seasonal pattern does exist, especially in the upper 50 m of the water column (Figure 4-4 to Figure 4-7). The path of the warm Agulhas Current is visible to the west of the Bight in temperature maps at all depths (10, 50 and 100 m). Its reported seaward-divergence north of the Bight, due to the broadening of the shelf, and convergence south of Durban, where the shelf becomes narrower again, is also evident. As a result, the current has a dominant influence on shelf waters north and south of the Bight where it flows close to the shelf break (Lutjeharms and de Ruijter, 1996; Schumann, 1988) as also identified in the TS diagrams (Figure 4-2). This means that the Aliwal Shoal MPA, located south of Durban, is more influenced by the Agulhas Current than the uThukela Banks MPA which was further investigated in section 4.3 and discussed later in this section.

The presence of ITSW was seen in the upper 50 m of the water column in the temperature and salinity maps (Figure 4-4 to Figure 4-7). At 100 m we began to see the presence of SSTW (Figure 4-8 and Figure 4-9) which extended down to about 200 m as seen in the vertical sections (Figure 4-10 to Figure 4-13). Furthermore, the vertical sections enabled us to see that the SICW rarely come onto shelf at the two MPAs. However, Roberts et al., (2010) has reported instances where colder waters have been brought up on to the shelf south of Durban to form the feature known as the Durban Eddy. It is driven by the Agulhas Current which moves offshore of a regressing shelf-edge south of Durban. The eddy draws cold, nutrient-rich water upward facilitating biological production (Gustella and Roberts, 2016). The occurrence and strength of this eddy is highly variable (Gustella and Roberts, 2016) and is therefore masked in the climatological maps and vertical sections.

The region of the uThukela Banks was notably 0.5-1°C cooler than the rest of the Bight including the Aliwal Shoal MPA at 10, 50 and 100 m, also observed by Barlow et al., (2008, 2010) and Lamont et al., (2016). This is due to mainly two reasons: the freshwater input of various rivers mainly the Thukela River and the divergence of the Agulhas Current resulting in reduced influence on shelf waters (Pearce, 1977; Schumann, 1988). The effect of freshwater input in the uThukela Bank MPA is also observed in both the 2016 CTD temperature and salinity profiles presented in section 3.2 (Figure 3-6 and Figure 3-7). The casts taken on the Thukela Bank (region of the Thukela River mouth) were cooler and fresher than the casts taken offshore of the bank. These conclusions are in accordance with the observations of Pearce (1978) as well as Lamont et al., (2016).

Seasonal variation over the Bight in temperature was largely restricted to the upper 50 m of the water column as also observed in past studies by Schumann (1988). Summer in the uThukela Banks consists of surface temperatures between 26 and 27°C. In the winter months, sea surface temperatures were cooler at 21-22.5°C (Figure 4-4). Surface temperatures over the Aliwal Shoal MPA in the summer ranged between 26.5 and 27°C and in winter they dropped to 22-23°C (Figure 4-5), sharing similar temperatures to the closely flowing Agulhas Current especially during the winter. Schumann (1988) reported a mean seasonal surface temperature variation along the Bight of about 5°C; this is supported by previous studies by Pearce (1978) who reported a variation of about 4.8°C. Using the temperature ranges stated above, this study found the mean seasonal temperature variation of 4.8°C at the uThukela Banks and 4.3°C at the Aliwal Shoal. Bottom temperatures at both MPAs had a mean seasonal variation of about 3°C.

Since salinity is a more conservative variable, values did not vary by much over the year throughout the water column except for at 50 m where lower salinities were observed in the winter months. Nonetheless, the salinity in the Bight, more so at the uThukela Banks MPA, remained fresher than those observed seaward. Lower salinities can be attributed to increased rainfall (the east coast of South Africa is a summer rainfall region) and riverine input from larger rivers such as the Thukela River (Schumann, 1988; Hutchings et al., 2010). Although there is a difference between the salinity in the Bight and the salinity seaward, there is a lack of strong gradients throughout the water column, in accordance with findings by Pearce (1977) and Lamont et al., (2016). This contrasts with Lutjeharms et al., (2000a) who noted a cross-shelf surface front in salinity over the month of July.

5.2 INTERANNUAL VARIABILITY

Although seasonal variation is evident in the Bight, there were no long-term changes in temperature and salinity over the 30-year period (Figure 4-14, Figure 4-16, Figure 4-18 and Figure 4-20). Wavelet analyses indicated a dominant annual (12-month) cycle in both surface and bottom temperatures (Figure 4-15 and Figure 4-19). However, bottom temperatures displayed a weaker signal than the surface in addition to a slight semi-annual cycle. In contrast, salinity over both MPAS at the surface and bottom displayed no significant cycles (Figure 4-19 and Figure 4-21).

5.3 INFLUENCE OF THE AGULHAS CURRENT ON THE SHELF

The Agulhas Current is known to have a dominant influence on shelf waters in the northern and southern regions of the Bight where it flows close to coast (Schumann, 1988) as noted previously with water masses. Time series comparing temperatures at sites inshore and offshore (in the path of the Agulhas Current) of both MPAs (Figure 4-1) have indicated that although the temperature pattern over the MPAs are similar (inshore and offshore), the Aliwal Shoal MPA's inshore and offshore shared very close temperature values. The temperatures offshore were slightly warmer than temperatures inshore with a mean difference of 0.24°C and 0.32°C at 10 m and 50 m respectively (Figure 4-23). (This contrasted with time series inshore and offshore of the uThukela Banks where temperatures offshore were notably warmer than inshore temperatures. The mean difference between temperatures was 1.19°C and 1.58°C at 10 m and 50 m respectively Figure 4-22.

5.3.1 Anomalous Events

From the bottom temperature time series for both MPAs (Figure 4-21 and 4-22), we were able to identify months of the lowest and highest temperatures (the surface temperature time series did not show any distinct maximum and minimum value months). Temperature distribution maps for those months of interest were plotted (Figure 4-24). A cold body of water (18-20°C) is observed in the Bight in January 1996. This is a feature characteristic of the Natal Pulse, large, cyclonic, lee-trapped eddies known to start in the Bight and travel downstream of the Agulhas Current (Lutjeharms and Roberts, 1988). They have a dimension of about 160 km (about the distance between Richards Bay and Durban), grow laterally as they progress southward at a rate of 20 km/day (Lutjeharms and Roberts, 1988). These are all characteristics of the feature seen in Figure 4-24 and Figure 4-25.

5.4 IMPORTANCE OF THE STUDY AND LIMITATIONS

The geographic distribution of marine species is a result of gradients in the physical environment because different species have different requirements for a range of environmental conditions, primarily temperature (Tittensor et al., 2010; Smit et al., 2013). Findings by Tittensor et al., (2010) indicated that changes in ocean temperature, in conjunction with other human impacts, may ultimately rearrange the global distribution of life in the ocean. The effect of depth on vertical environmental gradients, and hence on species distribution, must be considered when conducting studies on species distribution (Smit et al., 2013) such as those done during MPA analyses. Grantham et al., (2011) state that new methods for conservation planning are emerging and an example is using time-series data of oceanographic variables together with species occurrences to identify important areas for management that are predictable. This would require knowing the mean-state of variables such as temperature and salinity as well as how they vary over time which this study aimed to achieve. Using this information, marine spatial planners would have the tools to identify key areas where management might be required to vary in space and time in response to system dynamics (Grantham et al., 2011).

The challenges of long-term, in-situ monitoring are well-known in the oceanographic community. The main challenge being that it is expensive and requires a long time. With the implementation of the new MPAs around the South African coast and the introduction of new conservation planning methods (RSA, 2016; Grantham et al., 2011), the need of a readily available long-term oceanographic dataset is increasing. Ocean models such as the one used in this study, are able to provide long-term data throughout the water column. However, there is still room for major improvement, most importantly a higher resolution model that takes into account river run-off values specific to the region of interest.

6 CONCLUSION

In this study, the mean-state of temperature and salinity over two newly established MPAs in the KwaZulu-Natal Bight (‘the Bight’): the uThukela Banks MPA and the Aliwal Shoal MPA, are presented. The study uses a high-resolution ROMS simulation that provided data at a temporal frequency of 3-days, for the period 1980 to 2010 (30-years). The model was used to build a climatology to present the mean-state of the Bight and investigate the seasonal and annual variability as well as the influence of the Agulhas Current on the shelf.

The Bight shared the same water masses as the upper Agulhas Current. ITSW (characterised by temperatures <20°C and salinities of 35.45-35.65) were found from the surface down to 100 m. SSTW (15-20°C and 35.3 and 35.45 PSU) occurred below the ITSW extending down to about 200 m at the bottom of the shelf. On the continental slope, bottom waters are dominated by SICW (<15°C and <35.3 PSU). This was applicable to both MPAs throughout the year. Maps and vertical sections of temperature showed seasonal variation over the two MPAs and the entire Bight in the upper 50 m of the water column and that the Bight was cooler and less saline than the surrounding waters. Salinity, a more conservative variable, did not vary by much over the year throughout the water column except for at 50 m where lower salinities were observed in the winter months. Time series for a 30-year period and wavelet analysis showed that a strong annual (12 month) signal was dominant in surface (10 m) and bottom waters (50 m). However, bottom temperatures displayed a weaker signal than the surface in addition to a slight semi-annual cycle. Additional time series, comparing sites inshore and offshore of the two MPAs, indicated that the Agulhas Current influenced the Aliwal Shoal MPA more than the uThukela Banks MPA as they shared similar temperature values (at the surface and bottom) throughout the 30-year period. Inshore the uThukela Banks MPA was cooler compared to the offshore site by 0.5 to 1.5°C at the surface and 1 to 2.5°C at the bottom. These time series also enabled us to identify anomalous features such as the Natal Pulse. Finally, the importance of the results presented for MPA analyses was discussed as well as the advantages and limitations of the model used.

Implications on MPA decision-making

One of the aims of the ACEP Spatial Solutions project was to determine the benthic biodiversity patterns in the Bight and account for observed ecological trends in terms of habitat and process drivers (Fennessy et al., 2016a). Knowledge of the mean shelf environment is vital to account for these ecological trends. Understanding the pattern of temperature and salinity linked with nutrient patterns throughout the water column will help in understanding the migration patterns of resident species and therefore assist in the analysis of MPAs. Knowing the baseline conditions of temperature and salinity throughout the water column will assist in detecting events such as temperature extremes or upwelling events as identified in section 4.3. Since the Bight is an oligotrophic environment, oceanographic processes such as upwelling events and riverine input play an important role in the Bight as they bring about periods of high productivity mainly in the nearshore ecosystem (Omarjee, de Lecea and Smit, 2015).

With the numerous amounts of newly established MPAs around the South African coast, knowledge of the baseline oceanographic environment along the coast is key to MPA analysis. These MPAs are situated in different environments and providing long-term, in-situ measurements for all the areas would be difficult and though they can be used for validation, a baseline of oceanographic conditions should be built for all the MPA regions. Models such as the one used in this study can be used to achieve this, however, to improve the quality of the data, higher resolution models with high resolution bathymetry and river run-off values specific to the region of interest is imperative.

For other further work, other variables such as nutrients and turbidity can be studied in conjunction with temperature and salinity to establish the relationship between these variables and ultimately how they affect ecosystems in the Bight. In addition, the study of the shelf currents is also important to understand the shelf circulation which will also affect the movement of species around the Bight.

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