

# Assessing techniques to successfully monitor the oceanography of the complex uThukela Marine Protected Area

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## List of Abbreviations/Acronyms

ACDP	Acoustic Doppler Current Profiler
ACEP	African Coelacanth Ecosystem Programme
ACLME	Agulhas Current Large Marine Ecosystem
AIMS	Australian Institution of Marine Science
ART	Airborne Radiation Thermometry
BRUV	Baited Remote Underwater Video
CMEMS	Corpernicus Marine Environment Monitoring Service
CTD	Conductivity, Temperature and Depth
DJF	December, January and February
ENSO	El Niño Southern Oscillation
GBR	Great Barrier Reef
GSLWP	Greater ST. Lucia Wetland Park
JJA	June, July and August
KZN	KwaZulu-Natal
KZNSB	KwaZulu-Natal Sharks Board
LME	Large Marine Ecosystem
MHWs	Marine Heatwaves
MODIS	Moderate Resolution Imaging Spectroradiometer
MPA	Marine Protected Area
ONI	Ocean Niño Index
OSTIA	Operational Sea Surface Temperature and Sea Ice Analysis
SST	Sea Surface Temperature
UTR	Underwater Temperature Recorders

## Abstract

Marine Protected Areas (MPAs) are increasingly being established to restore and protect coastal and marine environments. The newly established uThukela Marine Protected Area (MPA), located on the central KwaZulu-Natal Bight along the northeast coast of South Africa, has been identified as a key ecological region. The region provides recruitment and is a general nursery area for marine life on the Bight. Knowledge of the oceanographic dynamics in the region is essential for understanding the functioning of the ecosystem and the effectiveness of the MPA. This study analysed changes in ocean temperatures at 20 sites along the Bight over a 41-year period using *in situ* beach and UTR data, and satellite data. Significant warming of 0.03°C/year occurred at beach sites within and around the MPA. Beach temperatures increased at an average rate of 0.02°C/year across the Bight, during both summer and winter, whereas UTR temperatures warmed by 0.14°C/year during summer and 0.08°C/year during winter. At the event scale, a case study of a persistent decrease in *in situ* temperatures along the entire Bight during summer 2017/2018 was investigated. The decrease in temperatures was hypothesised to be as a result of the combined effects of a La Niña event and a Natal Pulse, which could have significant consequences for temperature-sensitive species. Temperature trends observed in beach temperatures over the 41 years were not reflected in beach temperatures over the past decade, highlighting the importance of large datasets when investigating climate change. Warm biases of up to 2°C observed in satellite-derived temperature measurements, and its failure to replicate trends seen in the beach data, suggests that *in situ* temperature measurements in MPAs are better suited for long-term monitoring efforts. These findings can help assess the success of MPAs and to guide monitoring and research activities within the region.

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I am extremely grateful to Matt Dicken from the KwaZulu-Natal Sharks Board for humbly providing me with the beach and UTR datasets. It takes a lot of hard work and effort to maintain long-term measurements so hats off to all those who contributed.

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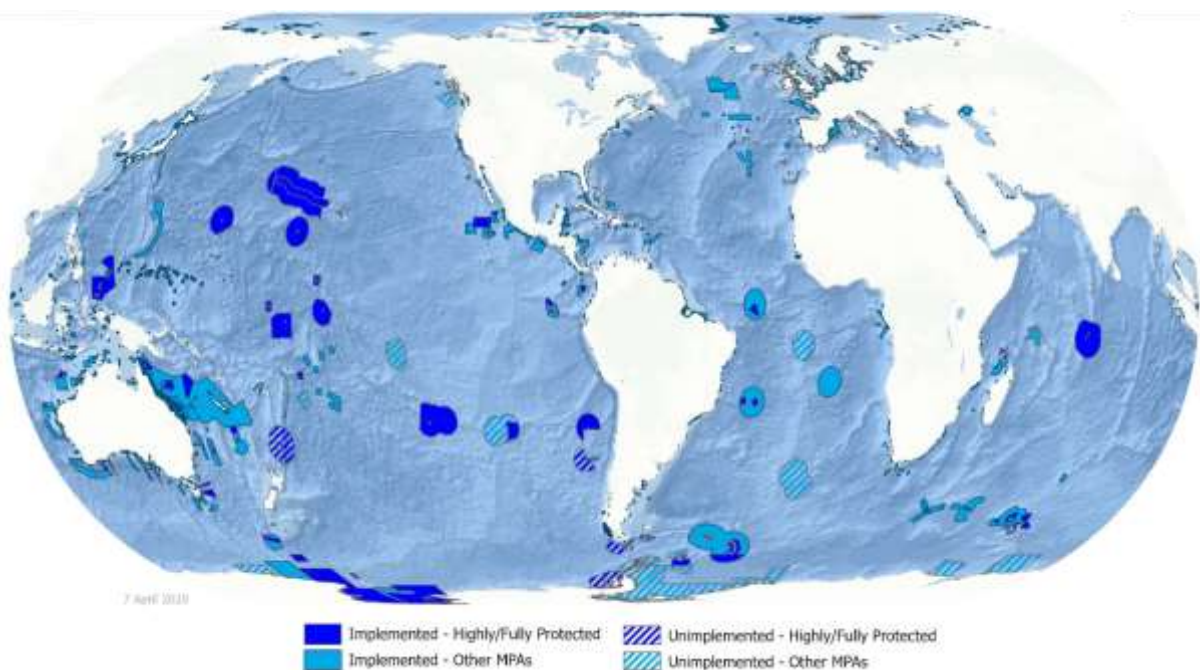
## Chapter 1. Introduction

The oceans cover over 70% of the Earth's surface and contain more than 90% of the living species on our planet (Harris et al., 2012; Sevilla et al., 2020). Ecosystem services provided by marine environments are the greatest contributors to human wellbeing (Harris et al., 2012) by providing us with food, water, sustainable energy, maritime transport, recreational and aesthetic benefits, as well as coastal protection against extreme weather (Sevilla et al., 2020). Nevertheless, the ocean is not indestructible. Marine environments, especially coastal regions, are under great threat as human activities become increasingly concentrated on the coasts (Claudet et al., 2011; Maestro et al., 2019). These environments are vulnerable to anthropogenic disturbances such as overfishing, shipping, ecotourism, industrial dumping and poor water quality due to coastal runoff. In addition to all these stressors, marine environments face pressures exerted by climate change (Couce et al., 2012) including ocean warming, ocean acidification, rising sea levels and change in circulation patterns (Keller et al., 2009; Sevilla et al., 2020). Therefore, it is crucial to protect and conserve natural resources in areas identified as important ecological regions, to secure their long-term viability or to allow populations to recover to more pristine levels (Claudet et al., 2011).

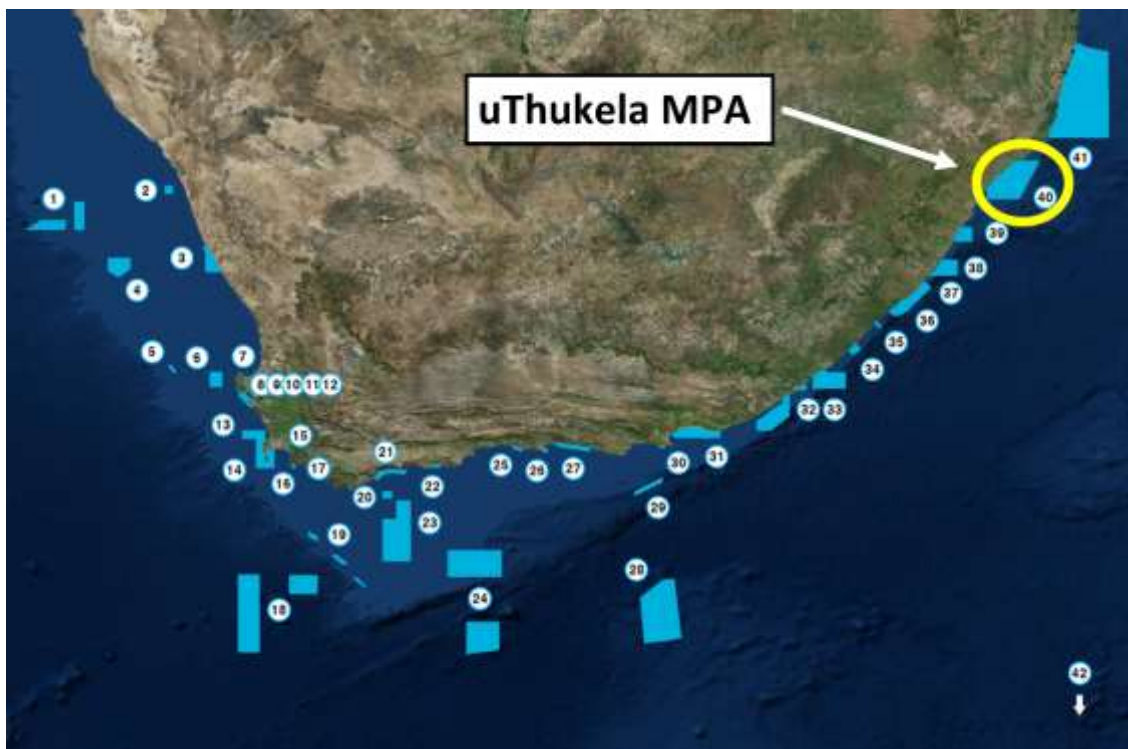
Marine protected areas (MPAs; Figure 1.1) have emerged as one of the most powerful scientific tools for combating the ever-increasing over-exploitation of marine resources and subsequent destruction of our oceans (Manukau, 2019). MPAs are area-based management tools designed to protect marine environments, processes, habitats and biodiversity, thereby contributing to resource restoration and sustainability for social and economic enrichment (Ayers and Scharler, 2011; Villalobos et al., 2021). MPAs come in a variety of shapes and sizes and range from estuaries to coastal regions to the open ocean (Kriegel et al., 2021). In addition to safeguarding the environment within their boundaries, MPAs provide benefits that extend beyond their bounds, such as seawater purification, improved fisheries and the supply of larvae to surrounding exploited regions (Baliwe, 2021). The establishment of MPAs has accelerated in recent years with over 17000 MPAs worldwide (Figure 1.1; Protected Planet, 2022), covering almost 8% of the world's oceans, of which the majority are small and under national jurisdiction (Teschke et al., 2021). Ocean protection in the South African region is far behind compared to most parts of the world (Protected Planet, 2022).

In South Africa, 20 new MPAs were proclaimed in 2019 as part of Operation Phakisa's MPA expansion initiative, protecting a total of 5.4% of ocean territory (Figure 1.2) (Mann-Lang et al., 2021). One of the primary regions identified for protection was the KwaZulu-Natal (KZN) Bight (hereafter referred to as 'the Bight'), on the South African east coast (Figures 1.2 and 2.2), which led to the newly established uThukela MPA (Figures 1.2 and 3.1). This MPA was a key outcome arising

from the South African Department of Science and Innovation's African Coelacanth Ecosystem Programme (ACEP, hosted by the South African Institute for Aquatic Biodiversity; Fennessy et al., 2016). The uThukela MPA is located on the central Bight ecoregion off the uThukela River, the largest river on the KZN coastline (Meyer et al., 2002; Lecea and Cooper, 2016). The Bight is one of the most productive areas along the Subtropical east coast of South Africa (Lamont and Barlow, 2015). This ecosystem comprises a mosaic mud and gravel seafloor with submarine canyons to a lesser extent (Sink et al., 2012; Sink et al., 2019). The region receives freshwater input from 17 catchments along the uThukela river (Lamberth et al., 2009) along with substantial amounts of terrigenous run-off from rivers, which drives the food webs of unique benthic communities along the Bight (Scharler et al., 2016).



**Figure 1.1.** Map showing marine protected areas (MPAs) globally (image: MPAtlas.org).



**Figure 1.2.** Map showing the South African coastline with all 42 proclaimed marine protected areas. The uThukela MPA on the northeast coast of South African has been highlighted (sourced from: <https://www.marineprotectedareas.org.za>).

The Bight and the uThukela River are crucial for a variety of ecological processes, including land-sea connectivity, larval retention, recruitment and the provision of nursery and feeding grounds for native species (Fennessy et al., 2016). Apart from its biological importance, this ecosystem is also considered an oceanographically important area due to its unique dynamic features (Lutjeharms, 2006). The Bight is seaward bound by the powerful western boundary Agulhas Current (Schumann, 1988), therefore offering refuge and playing a significant role in the life history of many native species (Hutchings et al., 2002). Although this region may be considered oligotrophic due to the nutrient-poor Agulhas Current, persistent topographic features induce upwelling which enables marine life on the shelf to thrive (Lutjeharms et al., 2000). The primary source of nutrients is the semi-permanent St. Lucia upwelling cell situated at the northern edge of the Bight (Meyer et al., 2002; Roberts and Nieuwenhuys, 2016), and to a lesser extent, the semi-permanent lee-eddy at the southern extremity of the Bight (Guastella and Roberts, 2016). These oceanographic features strongly influence the functioning of this unique ecosystem.

Despite the ecological importance of this region, it is under great threat. The Bight and the uThukela River are heavily impacted by anthropogenic activities due to their proximity to the highly developed areas around Durban and Richards Bay harbours. Commercial fisheries operating offshore and trawling along the continental shelf (between Durban and Richards Bay) have resulted in substantial habitat loss (Harris et al., 2012). The purpose of the uThukela MPA is to thus protect this ecologically rich ecosystem. However, the mere designation of MPAs does not guarantee that the region would be protected, as many lack adequate management. Effectively managing MPAs requires knowledge of the species and habitats, as well as the rates and scales of environmental and biological change (Oliveira Júnior et al., 2016). To date, only a few features of the Bight are known as the majority of the research data are dated or fragmented (Fennessy et al., 2016). To build a foundation upon which the region's ecosystem structure and functioning can be understood, the ACEP SMART Zone MPA Project is initiating and conducting MPA analysis along the Bight in terms of both biological and oceanographic surveys.

This project focuses on the oceanographic dynamics of the Bight, but more specifically the uThukela MPA in the central region of the Bight, and aims to answer the following questions:

- Has significant warming/cooling occurred across the Bight over the years?
- How do warming/cooling rates compare between the surface beach and subsurface UTR data?
- Is there seasonal variability across the Bight and are there significant changes in temperature during the summer and winter months?
- Are satellite-derived data able to reflect the temperature variability seen in the *in situ* data and resolve features on the Bight?
- Had any noticeable thermal events taken place across the Bight over the years?

Understanding the oceanic environment of a region is important for MPA management. These findings will provide a baseline for a better understanding of ocean dynamics in light of climate change and will guide us in suggesting best-suited techniques for management and monitoring for all MPAs going forward.

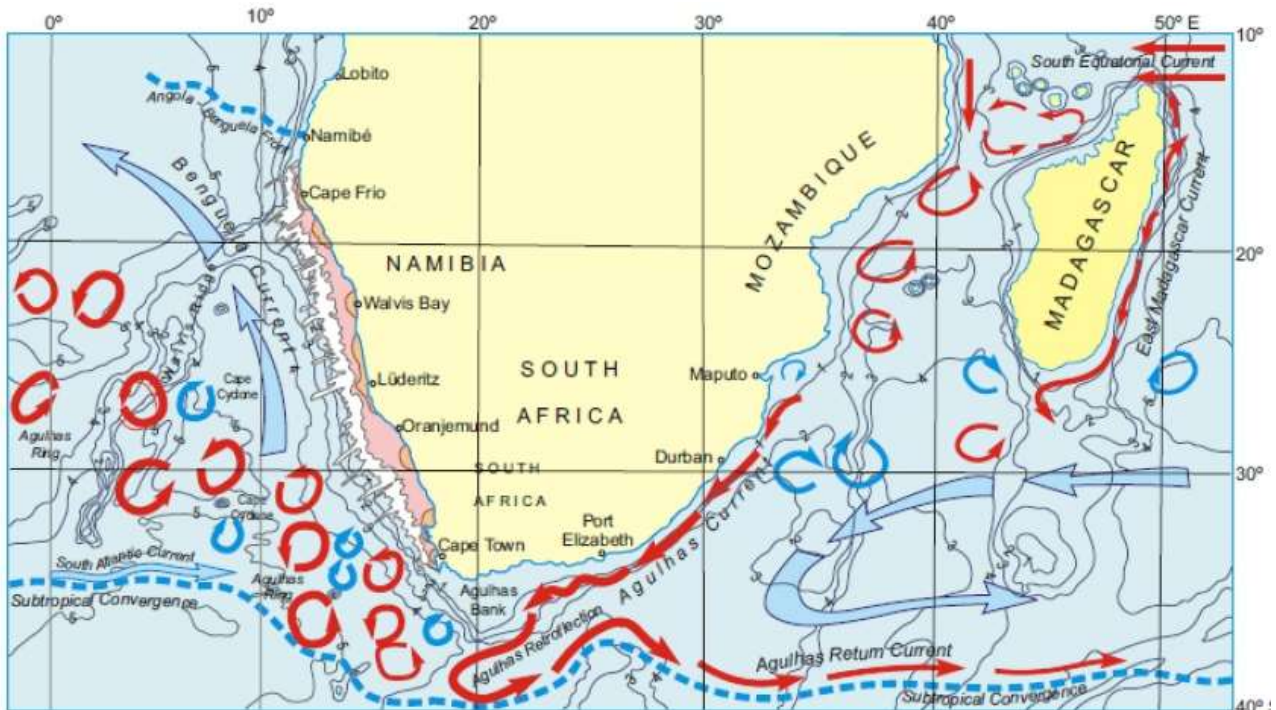
## Chapter 2. Literature Review

### 2.1 The Agulhas Current

The warm Agulhas Current is the largest of the five major western boundary currents in the world (Lutjeharms, 2006). The current is known to have a considerable impact on the weather and climate across the African continent (Rouault et al., 2002) and dominates the coastal ocean off south-eastern Africa (Figure 2.1). It has a core temperature of 24 to 26°C (Roberts et al., 2010) and surface velocities of 1.8 m s<sup>-1</sup> (Beal et al., 2015). The Agulhas current system extends from the tropics southwards to a region adjacent to the Subantarctic (Lutjeharms, 2006). The current has a depth of approximately 2400 m, a width of 90 to 100 km and an average mass transport of approximately 70 Sv (Sv = 1 x 10<sup>6</sup> m<sup>3</sup> s<sup>-1</sup>; Beal and Bryden, 1999; Bryden, Beal and Duncan, 2005; Krug and Tournadre, 2012). There are spatial and temporal variations in the depth, transport, and trajectory of the current, which make the current highly variable resulting in eddies and meanders (Figure 2.3; Donohue et al., 2000; Quartly and Srokosz, 2002). The equatorward border of the current lies at the southern end of the Mozambique Channel (~27 °S) and its poleward border coincides with the termination of the Agulhas Current at the Agulhas Current Retroflection (~40°S), southwest of the southern tip of Africa (Gordon, 1985; Lutjeharms, 2006). The point of retroflection occurs where the Agulhas Current turns on itself, becoming an eastward flow (Figure 2.1). It plays an important role as the Agulhas Current sheds warm-core eddies as it retroflects (Figure 2.3c, thus transporting warm saline Indian Ocean water into the South Atlantic Ocean (Figure 2.1) (Lutjeharms and van Ballegooyan, 1988, Rae, 1991).

The Agulhas Current water originates from three different sources: the recirculation of the South-west Indian Ocean subtropical gyre (Lutjeharms, 2006), The East Madagascar Current and the Equatorial Indian Ocean via the Mozambique Channel (Biaستoch and Krauss, 1999; Ridderinkhof et al., 2013). Eddies in the Mozambique Channel, as well as eddies that spin off the Southeast Madagascar Current (Figure 2.1), transport warm and saline Indian Ocean water southwards into the northern Agulhas Current (Biaستoch and Krauss, 1999; de Ruijter et al., 2004). Water masses trapped on the continental shelf, between the current and the coast, continuously respond to meanders and variations of the Agulhas Current (Pearce, 1977), resulting in Indian Tropical Surface Water and South Indian Subtropical Surface Water (Lutjeharms et al., 2000b) giving the Bight its tropical and subtropical characteristics (Schumann, 1988). The northern portion of the current exhibits remarkable stability in its trajectory as it flows in a southwestward direction due to the steep shelf-slope and narrow continental shelf of southeast Africa (Lutjeharms and van Ballegooyen, 1984; Lutjeharms and De Ruijter, 1996). It detaches from the slope, becoming a free-flowing jet further

south, at the southern edge of the Agulhas Bank (Roberts et al., 2010). The Agulhas Current deviates from the coast at three points along its trajectory (Roberts et al., 2010), one being where the shelf widens along the northern part of the current giving rise to an area known as the KwaZulu-Natal Bight ('the Bight') (Figure 2.2; Lutjeharms et al., 2000b).



**Figure 2.1.** Map of the Greater Agulhas Current System around southern Africa with major circulation features. The Agulhas Current waters are sourced through eddies via the Mozambique Channel and south of Mozambique, and recirculation of the south Indian subtropical gyre. The Agulhas Current retroflexion and leakage into the South Atlantic Ocean are also shown (Morris et al., 2017; Lutjeharms, 2001).

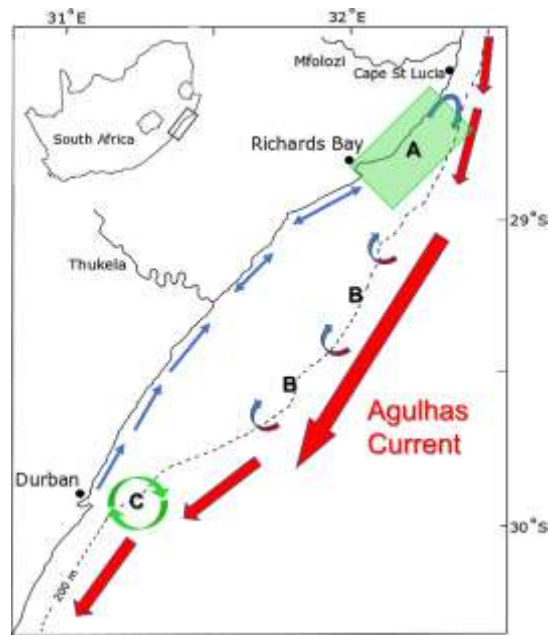
## 2.2 The KwaZulu-Natal Bight

The KwaZulu-Natal Bight is an unusually wide coastal offset, part of a 1300 km coastline, on the northeast coast of South Africa (Figure 2.2; Fennessy et al., 2016). This offset, along with the widening of the east coast shelf, resulted from a tectonic shift of the continental shelf margin from a sheared to a short-rifted section (Martin and Flemming, 1988). The Bight is located between Cape St. Lucia to the north and Durban to the south (Lutjeharms, 2006). It is approximately 160 km long and 50 km wide at its broadest, which is in contrast with the rest of the KZN continental slope which breaks 11 km away from the coast (Schumann, 1988). The center of the Bight is situated just off the Tugela River mouth (Meyer et al., 2002). The Tugela River runoff effects on the Bight have been

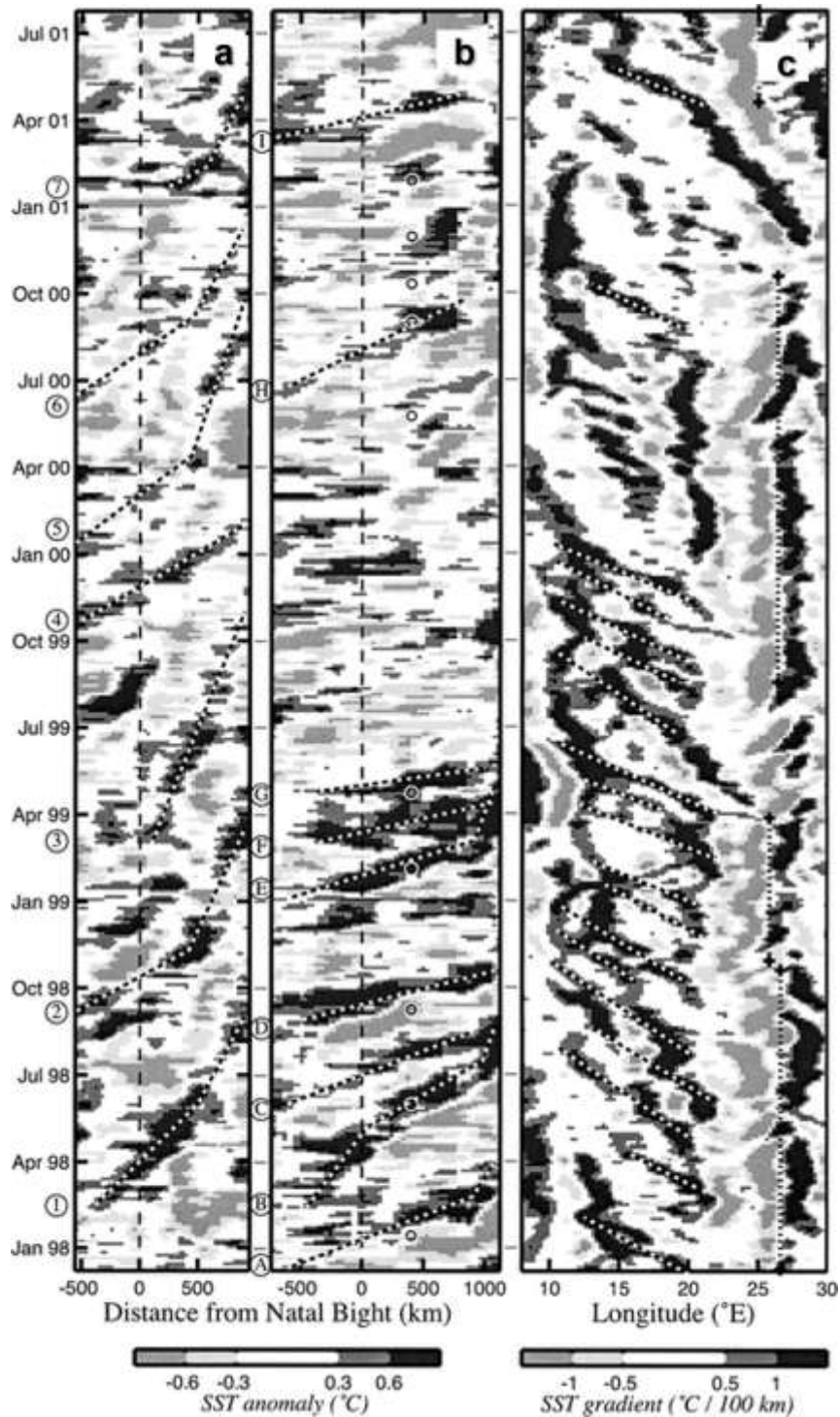
shown to be local and mostly indistinguishable (Meyer et al., 2002; Roberts and Nieuwenhuys, 2016). Interaction with the deep sea is limited due to the strong Agulhas Current along the shelf edge of the Bight enclosing the shelf waters (Lutjeharms et al., 2000b)

The proximity of the swift-flowing Agulhas Current strongly influences the oceanographic variability (Schumann, 1988), as well as encloses shelf waters on the adjacent KZN Bight by deviating seaward at Cape St. Lucia and converging landward at Durban (Schumann, 1988). This concave curvature of the coastline forces the strong Agulhas Current further offshore, resulting in a complex mix of the shelf and coastal currents (Roberts, Nieuwenhuys and Guastella, 2016). This displacement of the Agulhas Current drives an overall cyclonic (clockwise) circulation across the entire Bight (Lutjeharms, 2006), with northward inshore and mid-shelf currents reaching Cape St. Lucia (Figure 2.2). The northward circulation is the strongest in the southern Bight region reaching velocities of approximately  $60 \text{ cm.s}^{-1}$  and has an easterly component. This easterly component, primarily on the outer shelf, highlights the inshore advection and penetration of Indian Tropical Surface Water from the Agulhas Current surface waters (Lutjeharms et al., 2000b; Roberts, Nieuwenhuys and Guastella, 2016). This inflow of surface water diminishes the nutrient content in waters mainly over the southern part of the Bight (Carter and d'Aubrey, 1988; Meyer et al., 2002).

The alongshore wind component plays an important role in the circulation dynamics on the shelf, especially in the central region of the Bight where the Agulhas Current mainly influences the shelf edge only (Schumann, 1988). More recent studies have also shown that favourable alongshore winds during upwelling events inshore of the Agulhas Current cannot be neglected (Leber et al., 2017). Wind-driven, as well as Ekman veering, upwelling along the coastline and inshore edge of the Agulhas Current (Figure 2.2, B) occurs during periods of strong and persistent easterly winds (Schumann et al., 1982). Colder water is upwelled to the surface of the Bight from below the thermocline (Lutjeharms et al., 2000) and onto the shelf near the inshore edge of the Agulhas Current (Schumann, 1986). The Agulhas Current also gives rise to characteristic oceanographic features of the Bight such as the kinematically driven upwelling cell between Richards Bay and Cape St. Lucia (Figure 2.2, A), and a persistent cyclonic eddy off Durban (Figure 2.2, C).



**Figure 2.2.** Map of the KwaZulu-Natal Bight showing the fast-flowing Agulhas current diverging north of the Bight and converging further south, upwelling between Richards Bay and Cape St Lucia (A), inshore edge upwelling (B) and the Durban Eddy (C). The blue lines indicate the movement of water, and the dotted line indicates the 200 m isobath. (Upwelling and circulation adapted from Lutjeharms (2006). Background map and illustration modified from Scharler and Ayers (2019) and Kunnen et al. (2013)).



**Figure 2.3.** Hovmöller diagrams highlighting SST variability of the Agulhas Current adjacent to the KwaZulu-Natal Bight from 1998 to 2001. (a) Spatially averaged SST anomalies between 34.5° and 36.5°E against distance from the Bight (number and dashed lines indicated probable oceanographic features). (b) Spatially averaged SST anomaly in a coastal section (Fig. 2c within Quartly and Srokosz, 2002; circled letters indicate oceanographic events and the circles denote sea surface depressions observed between 29°E, 32°S). (c) The zonal gradient of SST at 38°S (dashed lines emphasis progradations of the Agulhas Retroflexion (Quartly and Srokosz, 2002).

## 2.3 Oceanographic features of the Bight

### 2.3.1 The Cape St. Lucia Upwelling Cell

The Bight is a unique and distinctive part of the South African coastline, where cold nutrient-rich water is upwelled onto the far-northern region of the Bight through the Cape St. Lucia upwelling cell (Figure 2.2, A; Meyer et al., 2002). This persistent upwelling cell is the most important part of the hydrodynamics of shelf waters on the Bight and a fundamental key to understanding the ecosystem (Lutjeharms, 2006). The upwelling cell was first reported by Snyman (1969) using airborne radiation thermometry (ART) surveys (Roberts, Nieuwenhuys and Guastella, 2016). Thereafter, plumes of cold, low salinity water were observed in the area off Richards Bay on numerous occasions (Gründlingh, 1974; Pearce 1977). It has been suggested that the upwelling cell at St. Lucia is topographically and dynamically driven by the passing oligotrophic Agulhas Current as it sweeps over the broadening continental shelf (Lutjeharms et al., 2000b; Lamont et al., 2016). This upwelling occurs during a shoreward shift of the Agulhas Current (Lutjeharms et al., 1989). In contrast to that, Roberts and Nieuwenhuys (2016) showed that almost all the major and minor upwelling events coincided with favourable north-easterly winds, which simultaneously drive the southeastward offshore current. They also found that topographically driven upwelling coexisted with the prevailing winds, resulting in two mechanisms for the upwelling observed at St. Lucia. Wind-driven upwelling was also observed in the inner Bight region, along the coast between Richards Bay and the Thukela River (Roberts and Nieuwenhuys, 2016).

The upwelling cell at St. Lucia is observed to be the main source of nutrients to the Bight, having a substantial influence on the Bight's productivity (Meyer et al., 2002). It creates ideal conditions for phytoplankton to flourish in the northern parts of the Bight, observed by high levels of chlorophyll (Sink et al., 2006). This upwelling may also be beneficial for corals in the Bights ecosystem as upwelling can act as a buffer against coral bleaching (Riegl and Piller, 2003). Colder, saltier and nutrient-rich South Indian Subtropical Surface Water is upwelled, from a depth of 100 m, onto the shelf and transported southwards to the Thukela River (Pearce, 1977; Lutjeharms et al., 2000b; Roberts, Nieuwenhuys and Guastella, 2016). Some of this upwelled water can also reach the southern Bight during intense upwelling events (Meyer et al., 2002). The deepening of the continental shelf from 50 m at Richards Bay to 100 m at Durban leads to the southward movement of upwelled water (Meyer et al., 2002). The southward decrease in nutrient concentrations of the upwelled water may be due to primary production and/or mixing with the low-nutrient Agulhas Current water masses in the central and southern parts of the Bight (Meyer et al., 2002).

### 2.3.2 The Durban Cyclonic Eddy

A semi-permanent, lee-trapped mesoscale cyclonic circulation, referred to as the Durban Eddy, occurs at the southern end of the Bight (Figure 2.2, C), situated 20 to 40 km just off Durban (Gründlingh and Pearce, 1990; Roberts et al., 2010). The Durban Eddy is observed to be driven by the fast-flowing Agulhas Current offshore of the retreating shelf edge just north of Durban (Guastella and Roberts, 2016). The shelf becomes abruptly narrower immediately north of Durban resulting in the Agulhas Current overshooting this offset at the shelf edge and thereafter rejoining the 200 m isobath further downstream (Schumann, 1987). This eddy was first illustrated by Oliff (1969) and has since become a well-recognized part of the circulation regime of the southern Bight off Durban (Pearce et al., 1978; Meyer et al., 2002). In some instances, the cyclonic circulation can be observed to occupy the entire southern half of the Bight (Roberts and Nieuwenhuys, 2016). According to acoustic doppler current profiler (ACDP) data and satellite imagery, the Durban Eddy is present 55% of the time, with a lifespan of 8.6 days and an inter-eddy period of 4 to 8 days. The presence of the Durban Eddy results in strong north-eastward countercurrents reaching a velocity of  $100 \text{ cm s}^{-1}$  inshore (Guastella and Roberts, 2016). The Durban Eddy was found to be highly variable in occurrence, intensity and speed; and showed no seasonal cycle (Guastella and Roberts, 2016). Its lifespan ends as it detaches from the southern Bight region and propagates downstream along the inshore edge of the Agulhas Current (Guastella and Roberts, 2016).

Thermistor arrays deployed in the center of the Durban Eddy, together with conductivity, temperature and depth (CTD) data, indicated an upward doming thermal structure of the eddy (Guastella and Roberts, 2016). The upward dome is associated with cold, nutrient-rich water being upwelled to the surface. This upwelled water has been observed to reach surface depths ranging from 30 to 120 m (Carter and d'Aubrey, 1988; Meyer et al., 2002). Although the Durban Eddy is observed to be cold-cored, Meyer et al. (2002) found the southern Bight water to be nutrient-poor which indicated that the upwelled nutrient-rich water did not reach shallow depths near the surface. It has been suggested that the Durban Eddy may in fact facilitate the intrusion of the warm, oligotrophic Agulhas Current surface waters into the southern Bight region (Meyer et al., 2002). The warm-oligotrophic waters are thereafter transported northwards along the inner- and mid-shelf up until the Thukela River (Roberts, Nieuwenhuys and Guastella, 2016). Contrary to this, some studies state that the upwelling caused by the Durban Eddy is a possible source of nutrients on the Bight (Lutjeharms, 2006) and stimulates primary production as patches of cooler water displayed elevated phytoplankton biomass in the vicinity of the Durban Eddy (Carter and Schleyer, 1988; Barlow et al., 2008; Guastella and Roberts, 2016).

There has also been evidence that the Durban Eddy and nutrient-rich contents aid in the development of a Natal Pulse (Lutjeharms and Roberts, 1988). Natal Pulses are large solitary meanders of the Agulhas Current. They form on the Bight, consisting of cyclonic eddies, and propagate southwards (Lutjeharms et al., 2003). They can also influence the shelf region by inducing localized upwelling of colder nutrient-rich waters (Bryden et al., 2005). Natal Pulses are known to substantially alter the flow of the Agulhas Current and initiate upstream Agulhas Current Retroflexion, thus affecting the exchange of different water masses between the Indian and Atlantic oceans (Lutjeharms and De Ruijter, 1996).

## 2.4 Temperature characteristics of the Bight

The Bight is unique in terms of its temperature as it is seaward bound by the warm Agulhas Current which transports warm tropical and subtropical waters onto the shelf, but the Bight also experiences upwelling events that bring colder, deeper water onto the shelf (Figure 2.2; A, B and C). Table 2.1 is a summary of past studies that have observed temperature ranges across the surface and subsurface depths in various regions of the Bight as well as the seasonal differences. Water on the Bight is largely Indian Tropical Surface Water (Lutjeharms et al., 2000b). Temperature profiles by Barlow et al. (2013) showed a uniform thermal structure in the Bight indicating a fairly well-mixed regime. Observations show that sea surface temperatures off Richards Bay (Cape St. Lucia upwelling cell) are always a few degrees lower (Table 2.1; Gründlingh and Pearce, 1990; Smith et al., 2013). This is due to the upwelling of South Indian Subtropical Surface Water (Lutjeharms et al., 2000b) at the Cape St. Lucia cell that has a core temperature of approximately 16 to 19°C (Lutjeharms et al., 2000b; Meyer et al., 2002). Cooler temperatures are continuously observed off Richards Bay, but the spatial extent of the surface expression varies considerably (Lutjeharms, 2006). Large variability in temperature has been observed in temperatures off Richards Bay, on a short timescale of days (Table 2.1; Carter and Schleyer, 1988). Influences of cold upwelled waters were seen in surface waters along the inner edge of the Agulhas Current as far downstream as Durban as the colder surface waters flow southward as a cool filament (Lutjeharms et al., 1989b). In the absence of upwelling, bottom temperatures on the Bight range between 20.5 and 25.2°C (Roberts and Nieuwenhuys, 2016).

A marked seasonal change in temperature in the upper layers of the Bight has been observed by several studies. The sea surface temperature of the Agulhas Current may exceed 28°C in summer and drop to less than 21°C in winter (Pearce, 1978), which would have subsequent effects on the temperatures observed in summer and winter across the Bight (Table 2.1). Lamont et al. (2016) examined the differences in oceanographic conditions between summer and winter on the Bight and its effects on sea surface temperature (Table 2.1) and found that the temperature distribution

during both seasons showed similar characteristics, with warmer water on the shelf and colder water on the shelf break. A similar pattern was observed during September 2005 and 2007 by Barlow et al. (2008; 2010). The Agulhas Current and the coastal region adjacent to it have significantly warmed up (Rouault et al., 2010; Blamey et al., 2015). Sweijd and Smith (2020) analysed sea surface temperature variability in seven African large marine ecosystems and found that all, including the Agulhas Current large marine ecosystem (ACLME), displayed a general warming trend from 1981 to 2019. The ACLME displayed the lowest overall warming rate of 0.11°C/dec on average, explained by an increase in transport of warmer Agulhas surface waters into the region.

**Table 2.1.** Summary of observed temperature ranges across different regions and depths of the KwaZulu-Natal Bight.

Region along the Bight	Temperature (°C)	References
Surface waters across the Bight.	20 to 23°C	Snyman et al., 1969
Cape St. Lucia upwelling cell surface waters.	Changes of up to 8°C	Carter and Schleyer, 1988
	19 to 22°C	Barlow et al., 2013
Surface waters at Cape St. Lucia during an upwelling event.	19 to 20°C	Robert and Nieuwenhuys, 2016
Cape St. Lucia upwelling cell at 10 m depth.	17.75°C	Lutjeharms et al., 1989
	19 to 22.5°C	Lutjeharms et al., 2000b
Surface waters in vicinity of the Durban Eddy.	24 to 26°C	Barlow et al., 2013
Summer maximum in the upper 100 m.	26°C	Pearce, 1977
Winter minimum in the upper 100 m.	21°C	Pearce, 1987
Surface waters during summer	25°C	Schumann, 1988; Smith et al., 2013.
	22.68 to 28.77°C	Lamont et al., 2016
Sea surface waters during winter	20.5	Schumann, 1988; Smith et al., 2013.
	19.96 to 23.22°C	Lamont et al., 2016

## 2.5 The role of oceanography in MPA management

The importance of considering oceanographic processes has been emphasized when considering the management of MPAs (Grantham et al., 2011). The geographical distribution of marine organisms and the functioning of an ecosystem is driven mainly by gradients in the physical environment (Tittensor et al., 2010). Different groups of organisms require different environmental conditions resulting in their geographical distributions not always coinciding (Smith et al., 2013). The environmental conditions are largely influenced by oceanographic processes. Ocean currents, fronts, eddies and upwelling zones play a significant role in not only distribution but also the production and abundance of marine organisms (Scavia et al., 2002). Eddies, currents, gyres and other forms of circulation enhance the movement of water, and changes in their patterns will influence larval dispersal, recruitment and connectivity among MPAs (Salm and Coles, 2001; Harley et al., 2006; Lima et al., 2021). Rapid currents also aid in flushing harmful toxins from the water column, reducing the effects of pollution. Nutrients that are necessary for phytoplankton production are made available through mixing processes that occur in upwelling or tidally influenced regions (Soto et al., 2002). The main environmental variable that has a direct influence on population connectivity, community structure and biogeographical patterns in ecosystems is the seawater temperature (O'Connor et al., 2007; Smith et al., 2013). Seawater temperature has a controlling effect on the reproduction and survival of marine organisms and hence the patterns in the evolution and ecology of biodiversity at regional scales are well established (Smith et al., 2013).

Changes in seawater temperature modify the stratification and mixing of the water column (Scavia et al., 2002), which controls the rate of fundamental biochemical processes (O'Connor et al., 2007). Temperature affects the metabolic rates and physiological processes of species, which subsequently affects their growth and survival (Ray et al., 1992; Soto et al., 2002; Harley et al., 2006). Temperature changes and shifts in ranges could result in new species and new biological interactions (Keller et al., 2009). The warming of the ocean is one of the most pervasive threats to marine ecosystems and is expected to have wide-ranging ecological consequences (Selig et al., 2012). As ocean temperatures rise as a result of climate change, marine species' range, migration, and abundance will fluctuate according to their thermal tolerance and ability to adapt (Sagarin et al., 1999; Harley et al., 2006; Bartsch et al., 2012). This potentially compromises the efficacy of MPAs as conservation tools (Soto et al., 2002). Negative effects of temperature increases have resulted in widespread coral bleaching (Harley et al., 2006; Bruno et al., 2018). Bleaching events have resulted in major loss and possible extinction of coral habitats (Salm and Coles, 2001); and have changed the structure of coral inhabiting ecosystems, which has the potential to critically influence the conservation of biodiversity

in these regions. Bleaching has also resulted in subsequent reductions in reef health, including coral illnesses, reef framework failure, and the loss of vital habitats for reef fish and other biotas. (Baker et al., 2008; Keller et al., 2009). Furthermore, a chain reaction can be triggered by a change in one environmental variable. For example, temperature changes can influence changes in salinity, dissolved oxygen, pH, nutrient concentrations and ocean currents (Carr et al., 2017).

### 2.5.1 Techniques used worldwide for MPA management

Clear research and monitoring are needed to understand the impacts of changes in temperature on marine ecosystems and strategize on ways to mitigate harmful effects where feasible (Baker et al., 2008). This adds an important tool for the management of MPAs. Studies have used both remote sensed observations together with coupled ocean-atmosphere climate models in an effort to monitor bleaching events and track dispersal trajectories (Baker et al., 2008; Lacharité and Brown, 2019). It is suggested that temperatures should be measured continuously using *in situ* data loggers and spot-checked at times of surveys using calibrated thermometers (Salm and Coles, 2001). The loggers should be deployed in arrays extending throughout the water column to define long-term depth profiles for a given site to establish baselines and monitor hydrological changes (e.g., ocean warming, heatwaves, stratification). Loggers are being used to monitor climate-related responses in the Mediterranean MPAs (Garrabou et al., 2018; Bensoussan et al., 2019). Hourly data from loggers since 1994 was also used for temperature measurements in the Greater St. Lucia Wetland Park (GSLWP), and a series of eight environmental moorings were installed as part of the Integrated Marine Protected Area System Plan for Seychelles, to study changes in the reef ecosystem (Wilkinson et al., 2003).

Baited remote underwater video (BRUV) technology was used for long-term monitoring of changes in biodiversity and community structure in the Stilbaai MPA in the Western Cape, South Africa (Figure 1.2; De Vos, 2012). Loggers were attached to the BRUV tripod, which measured water temperature every 5 mins. A simple linear interpolation monitoring tool was created by using *in situ* logger temperature data from four western Australian MPAs and satellite data. It was suggested that this interpolation approach will be used for near real-time temperature estimates for broadscale MPA monitoring across Western Australia (Baldock et al., 2014). The availability of accurate spatio-temporal variation in seawater temperature at small spatial scales, over a broad regional extent, will aid in improving our understanding of marine ecosystem responses and enable informed management decisions for MPAs (Baldock et al., 2014). A combination of data from echosounders, a conductivity-temperature probe and underwater cameras were used to monitor the El Bajo Espiritu

Santo Seamount, located in an MPA in the southwest Gulf of California (Figure 1.1; Villalobos et al., 2021). The integration of acoustic, optical and oceanographic data could give descriptions of the bathymetry, oceanographic habitat and distribution of biota. These technologies provide information at depths difficult for divers to access.

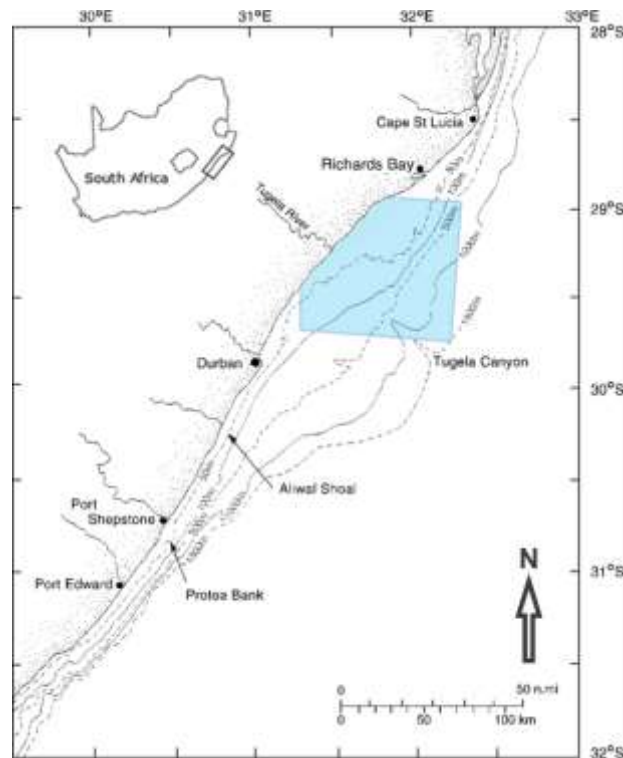
The Great Barrier Reef (GBR) Marine Park off the coast of northeast Australia (Figure 1.1) is an important ecoregion whose reef ecosystems are under great threat due to climate change. The Australian Institution of Marine Science (AIMS) has deployed a variety of instruments to monitor the change in various environmental variables (<https://www.aims.gov.au/measuring-change>). A network of weather stations, from Torres Strait in the north to Heron Island at the southern reef, record water temperatures that represent the best long-term on-reef record of temperature changes in the region. Some stations have been in operation for over 30 years. Oceanographic moorings and loggers have also been deployed at selected sites in the GBR for monitoring temperature, salinity, turbidity and chlorophyll at multiple depths (Gruber et al., 2019). The moorings are deployed as pairs with one on the outer continental shelf and the other in deeper waters further offshore. This technique aids in understanding the connection between the continental shelf and the deep ocean and tracks upwelling processes. Arrays of wireless sensor networks allow for the streaming of real-time data, which provides fine-scale information on how parts of the reef function. These networks provide a platform for a range of oceanographic sensors including temperature, salinity, pH and light. Cameras can also be attached for underwater videos and images of the reef. Sea-gliders are also being used for profiling the water column, especially in remote areas such as the far northern GBR and the Coral Sea. Near real-time information allows researchers to respond to conditions as they occur. These monitoring techniques serve as a baseline for the respective MPAs and for researchers to continue studying the MPA ecosystems (Villalobos et al., 2021).

The uThukela MPA (Figures 1.2 and 3.1) is a region of biological importance but there is poor understanding of the oceanographic dynamics within this region due to a lack of data. The proclamation of this MPA has increased the urge of understanding a creating a baseline of the oceanographic environment as this largely controls the biology of the region. Based on previous studies, MPA management techniques are not entirely region dependent but based on instruments that can accurately capture the desired oceanic properties. The best monitoring technique used for majority of the MPAs has been through observational data collected from in situ instruments such as loggers, moorings and CTDs, over a long period of time. Efforts should therefore be made in extending in situ monitoring platforms for the management of MPAs worldwide.

## Chapter 3. Data and Methodology

### 3.1 Study area

This study focuses on the KwaZulu-Natal Bight ('the Bight'), an unusually wide coastal offset off the northeast coast of South Africa. The newly established uThukela MPA is located at the center of the Bight, just offshore of the uThukela River (Figure 3.1).



**Figure 3.1.** Map showing the boundaries and zonation of the newly established uThukela Marine Protected Area (blue) located on the KwaZulu-Natal Bight off the northeast coast of South Africa. Solid and dotted lines off the coast indicate isobaths (background map adapted from Meyer et al. (2002) and Scharler and Ayers (2019)).

### 3.2 *In situ* temperature data

#### 3.2.1 KZN Sharks Board beach temperature data

Surface temperature data were obtained from 12 beach sites between Richards Bay and Durban along the KZN coastline (Figure 3.3 as circles) over a period ranging from 1980 to 2021. The temperature was measured daily (Monday to Friday, weather dependent) by the KZN Sharks Board (KZNSB) meshing teams, who are a team of people that go out and measure the temperature along

the KZN coastline using hand-held thermometers at approximately 20 cm below the sea surface. There were no changes in the methodology for temperature measurements except in September 2020, when the thermometer make/model was changed from analogue to digital with an accuracy of  $\pm 0.80^{\circ}\text{C}$ . The daily beach temperature measurements were averaged into monthly and annual means. Summer and winter climatologies were computed using the averages of December, January and February (DJF); and June, July and August (JJA), respectively for each year.

The KZN Bight can be geographically divided into the north, central and south of the Bight, as each region has a characteristic feature that could influence the temperatures there. The northern region of the Bight is dominated by the upwelling cell, the central region is located off the Thukela River mouth and the southern region is dominated by the Durban Eddy. For this study and to compare the temperature variability amongst these three regions, the temperature data were divided into the north, central and south (Table 3.1).

**Table 3.1.** *The geographical separation of the temperature measurement locations based on the north, central and south of the KwaZulu-Natal Bight.*

North	Central	South
Richards Bay	Zinkwazi	Salt Rock
	Blythedale	Thompson's Bay
	Tinley Manor	Ballito
		Westbrook
		La Mercy
		eMdloti
		uMhlanga Rocks
		Durban

### 3.2.2 Underwater Temperature Recorders

Subsurface temperature data were obtained from four electronic Star ODDI mini Underwater Temperature Recorders (UTRs; Figure 3.2) attached to shark avoidance nets offshore. These devices have a thermal precision of  $0.001^{\circ}\text{C} \pm 0.025^{\circ}\text{C}$  (<http://www.star-oddi.com>). The UTRs are installed and maintained by divers. Servicing of the UTRs can take place between 3 to 4 months, during which new ones are installed if required. The UTRs used in this study were located at Richards Bay, Zinkwazi, Ballito and Durban, at a depth of approximately 3 m and a distance of approximately 300 m offshore (Figure 3.3 as triangles) from the beach sites. The hourly temperature measurements were recorded in degrees Celsius ( $^{\circ}\text{C}$ ) over a period ranging from September 2013 to June 2021. The data from the four sites were combined into one dataset and averaged into monthly and annual

means. Summer and winter climatologies were computed using the averages of December, January and February (DJF); and June, July and August (JJA), respectively for each year.



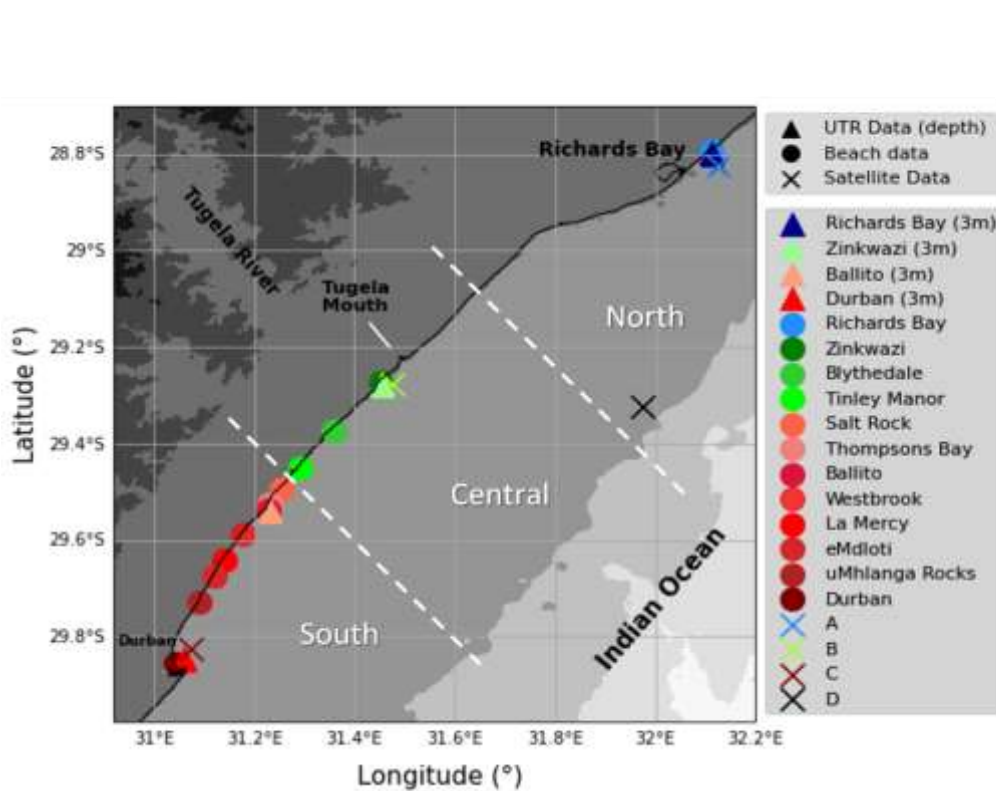
**Figure 3.2.** Image of the electronic Star ODDI mini Underwater Temperature Recorder (UTR) used in this study (image: <http://www.star-oddi.com>).

The UTRs dataset is not only shorter than that of the KZN Sharks Board temperature dataset (9 years in comparison to 40 years) but also contains missing values due to various technical or weather-dependent reasons. Monthly climatological means were calculated and the missing monthly values in the dataset were replaced by the respective monthly climatological means. Thereafter annual means were computed, allowing for continuous observation of temperature over the years.

### 3.3 Satellite Sea Surface Temperature data

The Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA) product was used for sea surface temperature (SST) along the Bight. The OSTIA product (Good et al., 2020) is provided by the Copernicus Marine Environment Monitoring Service (CMEMS, <https://marine.copernicus.eu/>), implemented and operated by Mercator Ocean International, which is a European Union service. The data provided by CMEMS are of three orders: reprocessed, near-real-time and forecasts. The OSTIA global sea surface temperature reprocessed product used in this study is a level 4 product that provides daily gap-free maps of sea surface temperature at a horizontal grid resolution of  $0.05^{\circ} \times 0.05^{\circ}$ , using *in-situ* and satellite data. The Bight is strongly influenced by missing data as it experiences cloud cover the majority of the time due to the adjacent flowing warm Agulhas Current, therefore a level 4 product is best suited (Carr et al., 2021). A recent study (Meneghesso et al., 2020) compared level 4 satellite data to *in situ* data at 42 different coastal locations worldwide and found that the OSTIA product overestimated coastal water temperatures the least. It had the lowest positive bias of  $0.43^{\circ}\text{C}$ . This was in comparison to 10 other level 4 temperature products, including higher spatial resolution products. This reassures the use of the OSTIA product in analysing sea surface temperature in a coastal region such as the Bight.

The satellite-derived SST used was for the period from January 1982 to December 2020. SST data was downloaded for the Bight (32.3°E, 31°W, 28.88°S, 30°S) and three grid points of SST were extracted at the closest location to *in situ* data points at the northern (A), central (B) and southern (B) part of the Bight, and one single grid point of SST was extracted at the edge of Bight (D) (Figure 3.3 as crosses). The daily satellite-derived SST data were averaged into monthly and annual means. The SST data for the three points (northern, central and southern) were compared to the three closest located *in situ* data points. To evaluate the change in the Bights' temperature over a varying period ranging from 1981 to 2021, linear regressions (temperature °C) as a function of time (annually) were fitted. From the set of linear regressions, a range of summary statistics relating to the annual rates of temperature change were reported, including its standard error, correlation coefficient (r-value) and p-value (95% level of significance).



**Figure 3.3.** Map showing sites along the KZN Bight where the temperature was measured using underwater temperature recorders (UTRs), hand-held thermometers (Beach data), and points from which satellite-derived temperature was extracted. The white dashed line indicates the separation of the Bight into the Northern, Central and Southern regions.

## Chapter 4. Results

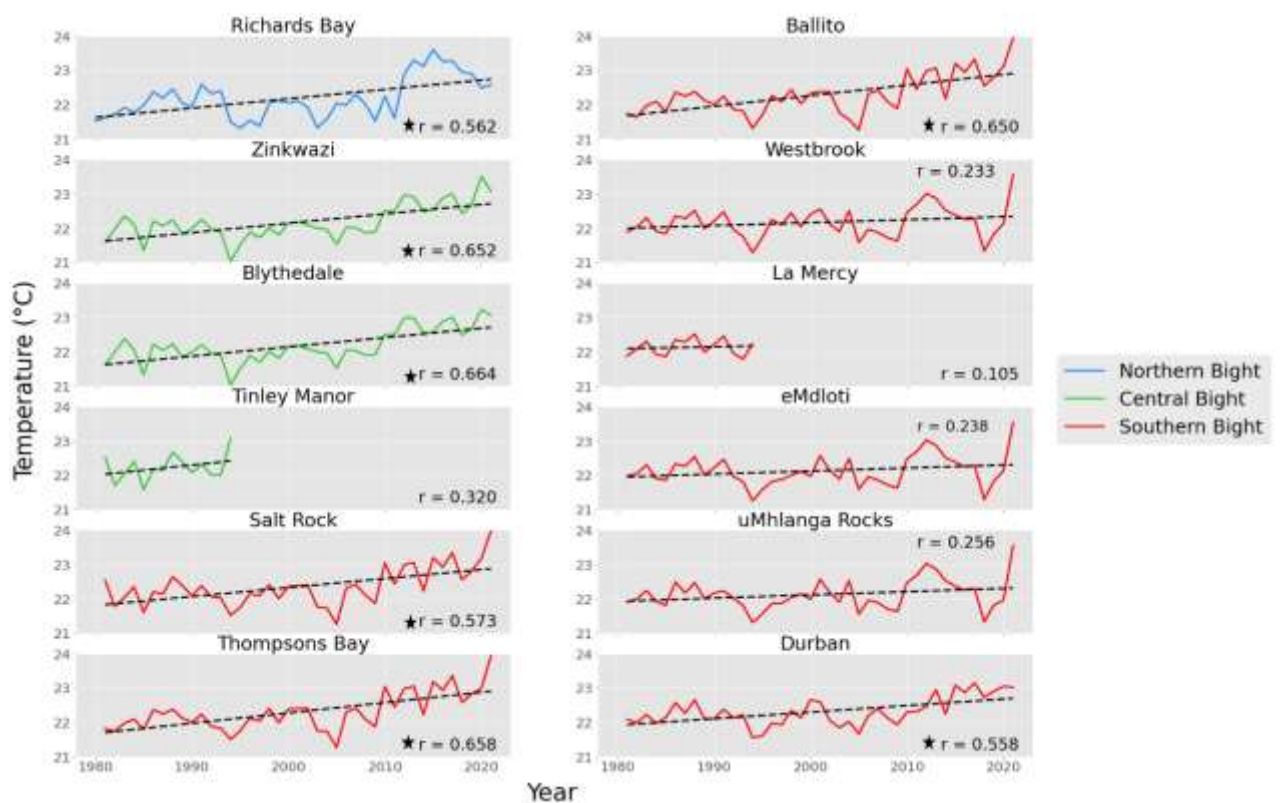
Understanding the oceanographic environment of the KwaZulu-Natal Bight ('the Bight') is essential for MPA management as it enables scientists and managers to make more informed decisions in MPA planning (Chapter 2). Despite the biological importance of the Bight, there is a paucity of seawater temperature climatologies for the South African coastal regions (Smit et al., 2013) and minimal analyses of existing data have taken place. This study focuses on temperature as it is a key oceanographic variable known to largely influence marine ecosystems and the life within. This chapter uses *in situ* data from beach recordings and UTRs, together with OSTIA satellite data (Chapter 3), to analyse changes in annually-averaged surface and subsurface temperatures over an extended period. In this chapter, beach temperature data from the KwaZulu-Natal Sharks Board is referred to as beach temperatures, UTR data is referred to as UTR temperatures and satellite-derived data is referred to as satellite sea surface temperature (SST).

### 4.1 Beach temperature variability

Coastal beach sites along the Bight are highly impacted by various human activities as well as run-offs from several catchments, which influences ocean temperature along the coastal zones (Claudet et al., 2011). Beach temperatures were analysed at 12 beach sites along the Bights' coastline over a period ranging from 1980 to 2021 (Chapter 3 and Figure 4.1). The shortest temperature recording period (1981 to 1994) was for Tinley Manor and La Mercy in the central and southern regions, respectively. The Bight is geographically separated into three regions, which are color-coded with blue representing the northern site, green representing the central sites and red representing the southern sites (Figure 3.3). The full names of the sites in each region are given in Table 3.1. All beach sites displayed significant warming (positive) trends over the years. The northern region is highly influenced by the almost constant upwelling of cold South-Indian Subtropical Surface waters (Lutjeharms et al., 2000b) and hence a difference in temperature variability is expected. However, this expected difference in temperature variability was not observed. Beach temperatures in the northern Bight ranged from 21.31 to 23.60°C with a significant ( $p < 0.05$ ) warming rate of 0.03°C/year (Table 4.1). This range of temperature does not coincide with temperatures  $< 19^{\circ}\text{C}$  suggestive of cold waters being upwelled (Lutjeharms et al., 2000b; Meyer et al., 2002).

Beach temperatures in the central Bight ranged from 21.03 to 23.51°C. A similar averaged amount of warming, as compared to the northern Bight, occurred at Zinkwazi and Blythedale at a significant ( $p < 0.05$ ) rate of 0.03°C/year. The warming rate at Tinley Manor, from 1981 to 1994, was the same as the northern and central sites on the Bight where temperature recordings were for a much longer

period (41 years) (Table 4.1). Beach temperatures in the southern regions of the Bight ranged from 21.26 to 23.98°C. Salt Rock, Thompson’s Bay and Ballito displayed the same significant warming rate of 0.03°C/year, whereas Westbrook, eMdloti and uMhlanga Rocks displayed the same nonsignificant rate of 0.01°C/year (Figure 4.1). La Mercy warmed at the same rate (0.01°C/year), from 1981 to 1994, as nearby sites (Westbrook and eMdloti) despite the latter being over a longer period (41 years). The warming rates were > 0.01°C/year at Salt Rock, Thompson’s Bay, Ballito and Durban (Table 4.1). The fastest warming rates, in the southern Bight, occurred at Salt Rock, Thompson’s Bay and Ballito with a significant warming rate of 0.03°C/year. The warming rates > 0.01°C/year were statistically significant with a strong positive trend over time, except for Tinley Manor in the central Bight region (Table 4.1). In contrast to previous observations, beach temperatures off Richards Bay in the north were not a few degrees lower in comparison to the whole region (Gründlingh and Pearce, 1990; Lutjeharms, 2006).

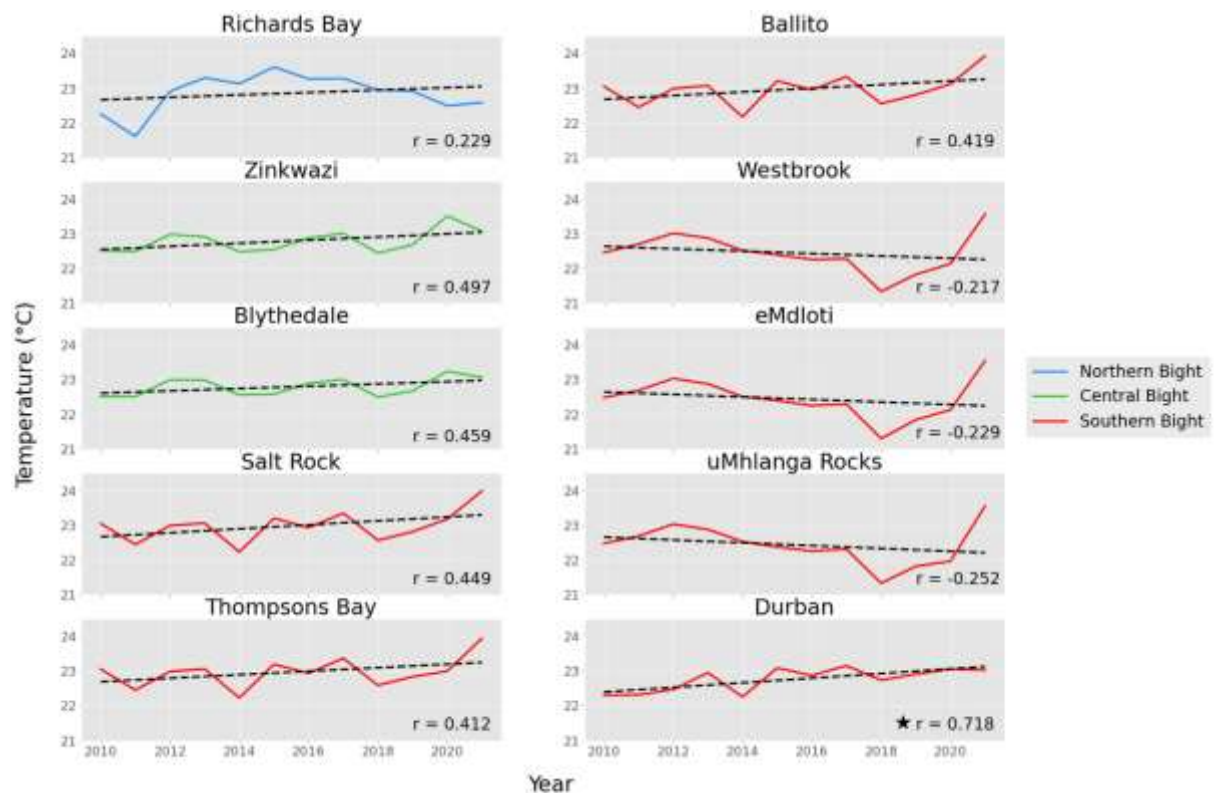


**Figure 4.1.** Time series of annual mean beach temperatures measured at 12 beach sites along the KwaZulu-Natal Bights’ coastline (Figure 3.3), over 41 years. Beach sites correspond to positions in Figure 3.3. The sites are colour-coded with blue representing the northern Bight, green representing the central Bight and red representing the southern Bight. The trendlines (dashed black line) and the correlation coefficients ( $r$ ) are indicated. \* Significant trends are indicated by stars next to the  $r$ -values.

**Table 4.1.** Linear regression results of annual mean beach temperatures measured at 12 beach sites along the Kwa-Zulu-Natal Bights' coastline, over 41 years. Shown are the sites, region on the Bight, the rate of warming/cooling (rate °C/year), standard error (Std. error), correlation coefficient (r-value) and the corresponding probability (p-value). The highlighted p-values are statistically significant ( $p < 0.05$ ).

Site	Region on Bight	rate (°C/year)	Std. error (°C)	r-value	p-value
Richards Bay	North	0.03	0.01	0.56	p < 0.01
Zinkwazi	Central	0.03	0.01	0.65	p < 0.01
Blythedale	Central	0.03	0.01	0.66	p < 0.01
Tinley Manor	Central	0.03	0.03	0.32	0.26
Salt Rock	South	0.03	0.01	0.57	p < 0.01
Thompson's Bay	South	0.03	0.01	0.66	p < 0.01
Ballito	South	0.03	0.01	0.65	p < 0.01
Westbrook	South	0.01	0.01	0.23	0.14
La Mercy	South	0.01	0.02	0.10	0.72
eMdloti	South	0.01	0.01	0.24	0.13
uMhlanga Rocks	South	0.01	0.01	0.26	0.11
Durban	South	0.02	0.01	0.56	p < 0.01

Interestingly, the largest rate of warming appeared to occur from 2010 onwards at the central Zinkwazi and Blythedale sites and southern Salt Rock, Thompson's Bay, Ballito and Durban sites (Figure 4.1). Further analysis of the beach temperature for the last decade (Figure 4.2) showed that only Durban had a significant warming rate of 0.07°C/ year ( $p < 0.05$ ) and a strong positive trend over time ( $r = 0.72$ ). Although the other sites displayed faster warming rates (Table 4.2), Westbrook, eMdloti and uMhlanga Rocks displayed a cooling trend over the 11 years (2010 to 2021) of approximately -0.04°C/year, in contrast to the 41 years. The standard errors associated with the rates for the past decade were also larger by a maximum of 0.04°C (Tables 4.1 and 4.2). Tinley Manor and La Mercy were excluded in this analysis as there were no beach data available for the last decade.



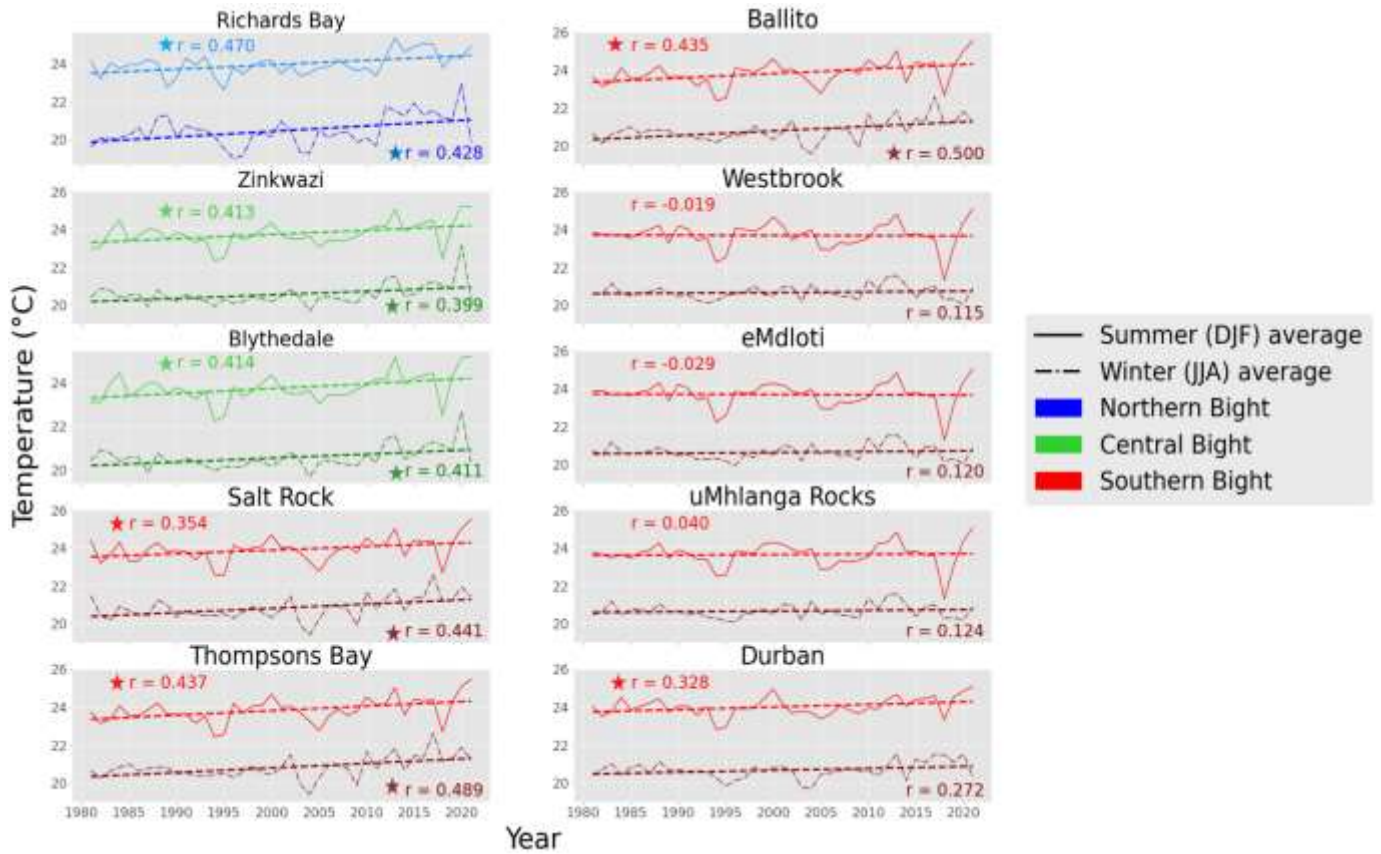
**Figure 4.2.** Time series of annual mean beach temperatures measured at 10 beach sites along the KwaZulu-Natal Bights' coastline for the last decade (2010 to 2021). The sites are colour-coded with blue representing the northern Bight, green representing the central Bight and red representing the southern Bight. The trendlines (dashed black line) and the correlation coefficients ( $r$ ) are indicated. Significant trends are indicated by stars next to the  $r$ -values.

**Table 4.2.** Linear regression results of annual mean beach temperatures measured at 10 beach sites along the Kwa-Zulu-Natal Bights' coastline for the last decade (2010 to 2021). Shown are the sites, region on the Bight, the rate of warming/cooling (rate °C/year), standard error (Std. error), correlation coefficient ( $r$ -value) and the corresponding probability ( $p$ -value). The highlighted  $p$ -values are statistically significant ( $p < 0.05$ ).

Site	Region on Bight	rate (°C/year)	Std. error (°C)	$r$ -value	$p$ -value
Richards Bay	North	0.06	0.05	0.35	0.29
Zinkwazi	Central	0.04	0.02	0.50	0.10
Blythedale	Central	0.03	0.02	0.46	0.13
Salt Rock	Central	0.06	0.04	0.45	0.14
Thompson's Bay	South	0.05	0.04	0.41	0.18
Ballito	South	0.05	0.04	0.42	0.18
Westbrook	South	-0.04	0.05	-0.22	0.50
eMdloti	South	-0.04	0.05	-0.23	0.47
uMhlanga Rocks	South	-0.04	0.05	-0.25	0.43
Durban	South	0.07	0.02	0.72	$p < 0.01$

Analysing long-term temperature changes in a region is crucial but understanding the seasonal signal and the long-term temperature changes between seasons is just as important, especially for marine species whose migration patterns are season dependent. Annual beach temperatures for summer (DJF) and winter (JJA), at the ten beach sites, were analysed for changes in temperature during the two seasons (Figure 4.3). Tinley Manor and La Mercy were excluded due to a lack of data. Seasonal differences were evident at each site as expected with warmer temperatures in summer (Lutjeharms, 2006; Lamont et al., 2015). Beach temperatures were on average 3.50°C, 3.19°C and 3.06°C warmer in summer than in winter across the northern, central and southern regions of the Bight respectively. A larger difference with central Bight beach temperatures being 4.8°C warmer in summer than in winter were also observed using a high-resolution model simulation (Malange, 2018). Significant warming occurred at all northern and central sites and only at Salt Rock, Thompson's Bay and Ballito in the southern region during summer and winter (Table 4.3). Significant warming at Durban only occurred during summer. Maximum summer beach temperatures of approximately 25°C were cooler than the maximum surface temperatures of 28.76°C observed by Lamont et al. (2015) in January 2010.

Beach temperatures in the northern Bight warmed faster during winter compared to summer, with a warming rate of 0.029°C/year compared to 0.023°C/year, respectively. Summer beach temperatures at Richards Bay were > 22°C in contrast to temperatures that ranged from 19° to 22°C observed in the vicinity (Barlow et al., 2013). Zinkwazi and Blythedale, in the central Bight, both warmed at an approximate rate of 0.022°C/year during summer and 0.019°C/year and 0.018°C/year during winter, respectively (Table 4.3). The warming rates in the northern and central Bight regions were statistically significant ( $p < 0.05$ ). The fastest warming of beach temperatures in the southern region of the Bight occurred at Thompson's Bay and Ballito during summer and winter, which warmed at a rate of 0.024°C/year. Winter beach temperatures across all regions of the Bight agreed with ranges found by Barlow et al. (2013). During winter, the Agulhas Current was located further offshore inducing active upwelling of colder water (Barlow et al., 2013). All sites displayed weak trends over time (Figure 4.3; Table 4.3) and warming rates > 0.01°C/year were found to be significant ( $p < 0.05$ ), except for the warming rate at Durban during winter. A persistent drop in beach temperatures of approximately 3°C occurred during the summer of 2017/2018 at sites (Figure 4.3). The decrease in temperature is however less prominent at Richards Bay in the north and Durban in the south. Considering the entire Bight, beach temperatures warmed by an average rate of 0.02°C/year during both summer and winter.



**Figure 4.3.** Time series of annual summer (DJF) and winter (JJA) beach temperatures measured at 10 beach sites along the KwaZulu-Natal Bights' coastline over 41 years. The sites are colour-coded with blue representing the northern Bight, green representing the central Bight and red representing the southern Bight. Solid lines show the mean summer temperatures and dashed-dot lines show the mean winter temperatures. The trendlines (dashed line) and the correlation coefficients ( $r$ ) are indicated. Significant trends are indicated by stars next to the  $r$ -values.

**Table 4.3.** Linear regression results of annual summer (DJF) and winter (JJA) beach temperatures measured at 10 beach sites along the Kwa-Zulu-Natal Bights' coastline over 41 years. Shown are the sites, the season, the region on the Bight, the rate of warming/cooling (rate °C/year), standard error (Std. error), correlation coefficient (r-value) and the corresponding probability (p-value). The highlighted p-values are statistically significant ( $p < 0.05$ ).

Site	Region on Bight	Season	rate (°C/year)	Std.error (°C)	r-value	p-value
Richards Bay	North	DJF	0.023	0.007	0.47	p < 0.01
Richards Bay	North	JJA	0.029	0.010	0.43	p < 0.01
Zinkwazi	Central	DJF	0.022	0.008	0.41	p < 0.01
Zinkwazi	Central	JJA	0.019	0.007	0.40	p < 0.01
Blythedale	Central	DJF	0.022	0.008	0.41	p < 0.01
Blythedale	Central	JJA	0.018	0.006	0.41	p < 0.01
Salt Rock	South	DJF	0.019	0.008	0.35	0.02
Salt Rock	South	JJA	0.023	0.007	0.44	p < 0.01
Thompson's Bay	South	DJF	0.024	0.008	0.44	p < 0.01
Thompson's Bay	South	JJA	0.024	0.007	0.49	p < 0.01
Ballito	South	DJF	0.024	0.008	0.43	p < 0.01
Ballito	South	JJA	0.024	0.007	0.50	p < 0.01
Westbrook	South	DJF	-0.001	0.009	-0.02	0.90
Westbrook	South	JJA	0.004	0.005	0.12	0.47
eMdloti	South	DJF	-0.002	0.009	-0.03	0.86
eMdloti	South	JJA	0.004	0.005	0.12	0.46
uMhlanga Rocks	South	DJF	0.002	0.009	0.04	0.80
uMhlanga Rocks	South	JJA	0.004	0.005	0.12	0.44
Durban	South	DJF	0.013	0.006	0.33	0.04
Durban	South	JJA	0.010	0.006	0.27	0.09

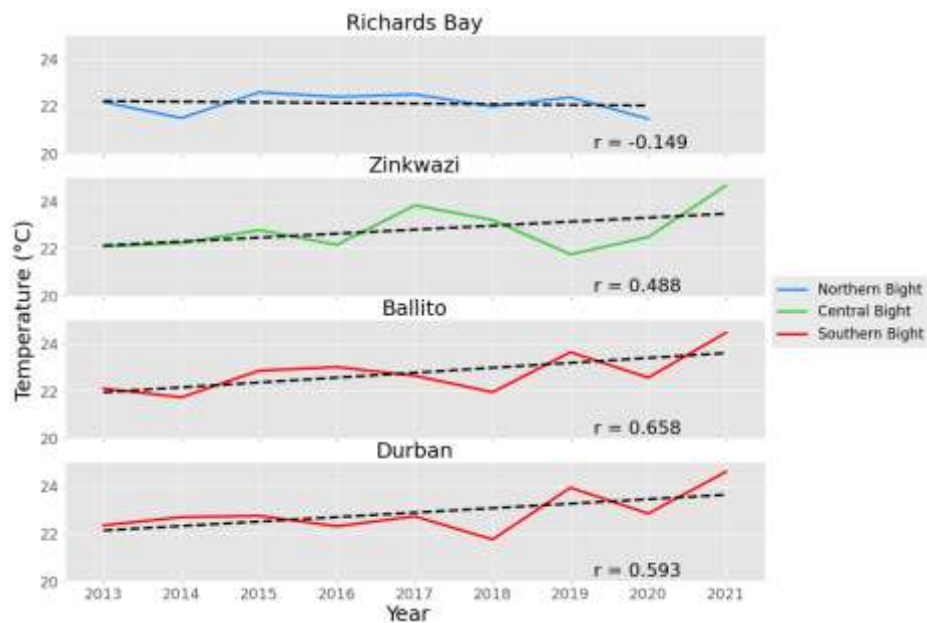
This section analysed changes in surface beach temperatures along the coastal zones of the Bight. However, with MPA analysis and being able to make informed management decisions about an area, surface temperature variability is not sufficient. It is important to understand the structure, dynamics and changes that occur below the surface (Malange, 2018) as the majority of the ecology is either pelagic or benthic.

#### 4.2 UTR temperature variability

UTRs temperatures were analysed at located at Richards Bay, Zinkwazi, Ballito and Durban, at a depth of approximately 3 m and a distance of approximately 300 m offshore from the beach sites (Figure 3.3) over 9 years (2013 to 2021) and are presented as an annual mean time series (Figure 4.4). All sites displayed a warming trend over the years except for Richards Bay, which displayed a weak negative trend over time (Table 4.4). This difference in temperature variability in comparison

to the rest of the Bight is expected as mentioned before due to the persistent upwelling that occurs in the northern region of the Bight (Meyer et al., 2002). UTR temperatures at Richards Bay ranged from 21.46 to 22.58 °C on average, with a cooling rate of -0.03°C/year (Table 4.4). These temperatures fall within the range of those observed during upwelling events at a depth of 10 m (Lutjeharms et al., 2000b).

The central and southern regions of the Bight showed much warmer temperatures. UTR temperatures at Zinkwazi ranged from 21.76 to 24.66 °C on average, with a warming trend of 0.17°C/year. UTRs in the southern region ranged from 21.74 to 24.60 °C on average between the two sites. Ballito, however, had a higher warming rate of 0.21°C/year compared to Durban, which had a warming rate of 0.19°C/year. Sites in the central and southern regions of the Bight show fairly strong positive trends over time ( $r > 0.4$ ; Figure 4.4; Table 4.4). The most amount of warming occurred in 2021, where UTR temperatures in the central and southern regions of the Bight were approximately 2°C warmer than the climatological mean. Warming rates increased from north to south, along the subsurface depths of the Bight, although none of the rates were significant ( $p > 0.05$ ; Table 4.4).



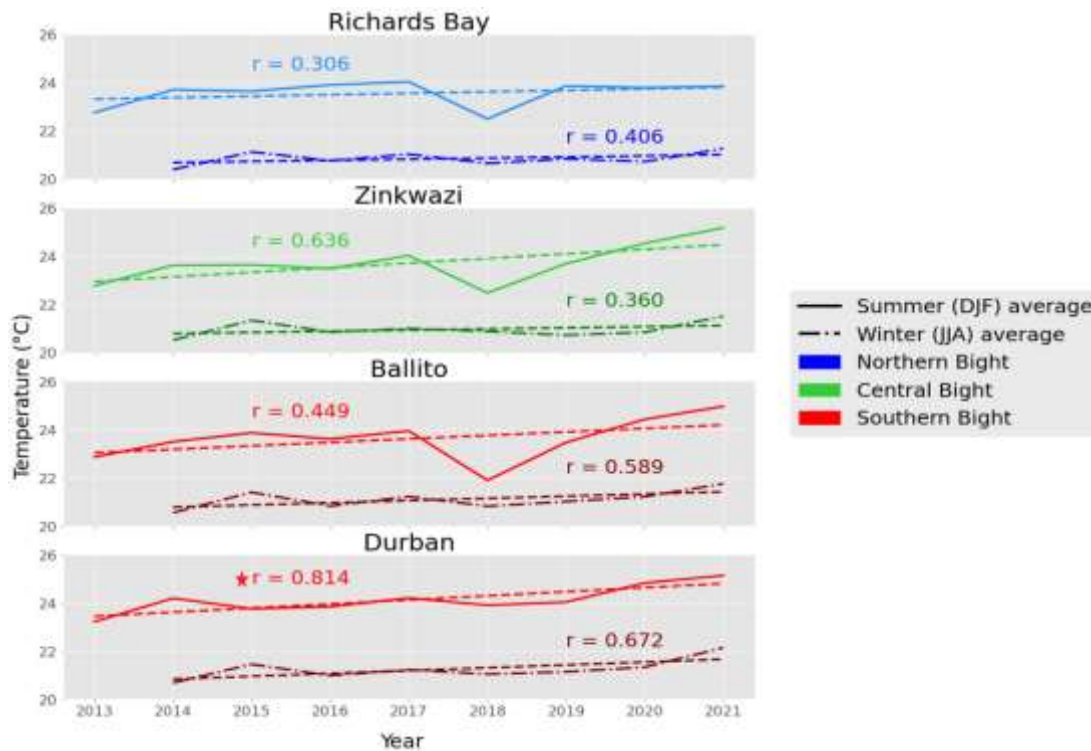
**Figure 4.4.** Time series of annual underwater temperature recorder (UTR) temperatures measured at 4 sites along the KwaZulu-Natal Bights' coastline (Figure 3.3) from 2013 to 2021. The sites are colour-coded with blue representing the northern Bight, green representing the central Bight and red representing the southern Bight. The trendlines (dashed black line) and the correlation coefficients ( $r$ ) are indicated. Significant trends are indicated by stars next to the  $r$ -values.

**Table 4.4.** Linear regression results of annual underwater temperature recorder (UTR) temperatures at 4 sites along the KwaZulu-Natal Bights' coastline from 2013 to 2021. Shown are the sites, region on the Bight, the rate of warming/cooling (rate °C/year), standard error (Std. error), correlation coefficient (r-value) and the corresponding probability (p-value). The highlighted p-values are statistically significant ( $p < 0.05$ ).

Site	Region on Bight	rate (°C/year)	Std.error (°C)	r-value	p-value
Richards Bay	North	-0.03	0.07	-0.15	0.72
Zinkwazi	Central	0.17	0.11	0.49	0.18
Ballito	South	0.21	0.09	0.66	0.05
Durban	South	0.19	0.10	0.59	0.09

Similar to beach temperatures, understanding the long-term temperature changes below the surface during different seasons is important. Annual summer (DJF) and winter (JJA) UTR temperatures at the four sites were analysed for changes in temperature during the two seasons (Figure 4.5). The expected seasonal difference was evident at each site. UTR temperatures were on average 2.71°C, 2.76°C and 2.70°C warmer in summer than in winter across the northern, central and southern regions of the Bight respectively. All regions of the Bight displayed a warming trend during both seasons, with summer months warming at a faster rate (Table 4.5). Interestingly, Richards Bay warmed during both seasons but displayed an overall cooling trend during the study period (Figure 4.4). However, the warming rates during both seasons were the slowest when compared to the central and southern regions of the Bight, where summer months warmed at 0.06 °C/year and winter months warmed at 0.05 °C/year. The summer warming rate at Richards Bay was a tenth of a magnitude less than the other beach sites (Table 4.5).

The fastest warming occurred at Zinkwazi and Durban in the central and southern regions during summer with rates of 0.19 and 0.17 °C/year, respectively. Strong positive trends over time also occurred at these two sites ( $r > 0.5$ ; Table 4.5), and significant warming occurred only at Durban during summer ( $p < 0.05$ ; Table 4.5). Similar to beach temperatures (Figure 4.3), a persistent drop in UTR temperatures of approximately 2 °C was seen during the summer of 2017/2018 at all sites except for Durban (Figure 4.5). Considering the entire Bight, UTR temperatures warmed by 0.14°C/year during summer and 0.08°C/year during winter. These rates were, however, not significant ( $p > 0.05$ ). The UTR warming rates during winter increased from north to south along the Bight (Table 4.5).



**Figure 4.5.** Time series of annual summer (DJF) and winter (JJA) underwater temperature recorder (UTR) temperatures measured at 4 sites along the KwaZulu-Natal Bights' coastline from 2013 to 2021. The sites are colour-coded with blue representing the northern Bight, green representing the central Bight and red representing the southern Bight. Solid lines show the mean summer temperatures and dashed-dot lines show the mean winter temperatures. The trendlines (dashed line) and the correlation coefficients ( $r$ ) are indicated. Significant trends are indicated by stars next to the  $r$ -values.

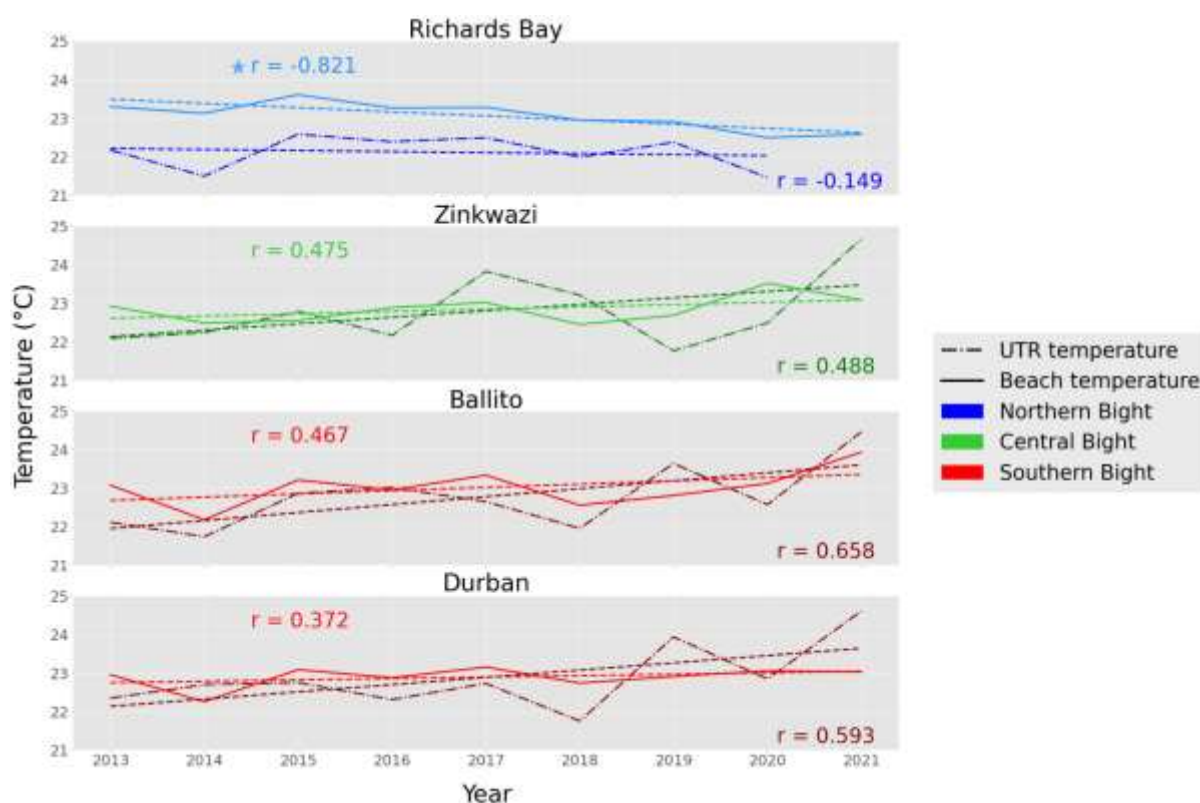
**Table 4.5.** Linear regression results of summer (DJF) and winter (JJA) underwater temperature recorder (UTR) temperatures at 4 sites along the KwaZulu-Natal Bights' coastline from 2013 to 2021. Shown are the sites, the season region on the Bight, the rate of warming/cooling (rate °C/year), standard error (Std. error), correlation coefficient ( $r$ -value) and the corresponding probability ( $p$ -value). The highlighted  $p$ -values are statistically significant ( $p < 0.05$ ).

Site	Region on Bight	Season	rate (°C/year)	Std.error (°C)	r-value	p-value
Richards Bay	North	DJF	0.06	0.07	0.31	0.42
Richards Bay	North	JJA	0.05	0.04	0.41	0.31
Zinkwazi	Central	DJF	0.19	0.09	0.64	0.07
Zinkwazi	Central	JJA	0.05	0.05	0.36	0.38
Ballito	South	DJF	0.14	0.11	0.45	0.23
Ballito	South	JJA	0.09	0.05	0.59	0.12
Durban	South	DJF	0.17	0.05	0.81	p < 0.01
Durban	South	JJA	0.12	0.05	0.67	0.07

### 4.3 Comparison between beach and UTR temperature variability

A comparison between the annual beach and UTR temperatures was analysed between the four UTR sites: Richards Bay, Zinkwazi, Ballito and Durban; and the four comparable beach sites (Figure 4.6). The beach temperatures at each site had to be subsetting from 2013 to 2021 for comparative purposes with the UTR dataset. Table 4.6 only shows the linear regression results for the beach temperatures as the UTR temperature results remain the same as Table 4.1. Daily temperatures between the beach and UTR data were correlated to investigate the relationship between the two at a higher resolution (not shown). Significant strong positive correlations were found between the beach and UTR sites at Richards Bay, Zinkwazi, Ballito and Durban with correlation coefficients ( $r$ ) of 0.87, 0.91, 0.90 and 0.92 respectively ( $p < 0.01$ ). This indicates a strong relationship between the beach and UTR temperatures across the Bight. A clear difference of up to 2°C is evident between the beach and UTR temperatures (Figure 4.6). Beach temperatures at Richards Bay (Figure 4.6) were warmer than UTR temperatures (Figure 4.6) as expected due to the surface layers being directly exposed to solar radiation. The beach temperatures at Richards Bay cooled at a negative significant rate of -0.11°C/year; in contrast to the significant warming rate of 0.03°C/year observed over the 41 years (Figure 4.1).

Beach temperatures at Zinkwazi, Ballito and Durban are on average warmer than UTR temperatures but at times the UTR temperatures are warmer than beach temperatures. It is however important to note that beach and UTR sites are not at the same geographical location (Figure 3.3). The warming rates of beach temperatures at Zinkwazi, Ballito and Durban (0.06°C/year, 0.08°C/year and 0.04°C/year, respectively) were faster than those observed during the 41 years (Table 4.1), however, none were significant ( $p > 0.05$ ). Comparing the warming/cooling rates of beach and UTR temperatures (Table 4.4 and Table 4.6) show that beach temperatures are cooling by -0.08°C/year faster than UTR temperatures at Richards Bay; and UTR temperatures are warming by 0.11°C/year, 0.13°C/year and 0.15°C/year faster than beach temperatures at Zinkwazi, Ballito and Durban, respectively. Given the lack of significance of the warming/cooling trends observed in the UTR data due to the short time series, the strong correlations between the beach temperature and corresponding UTR temperatures give us some confidence in the use of beach temperatures for the region.



**Figure 4.6.** Time series of the comparison between annual beach and underwater temperature recorder (UTR) temperatures measured at 4 beach and 4 UTR sites, respectively, along the KwaZulu-Natal Bights' coastline from 2013 to 2021. The sites are colour-coded with blue representing the northern Bight, green representing the central Bight and red representing the southern Bight. The trendlines (dashed line) and the correlation coefficients ( $r$ ) are indicated. Significant trends are indicated by stars next to the  $r$ -values.

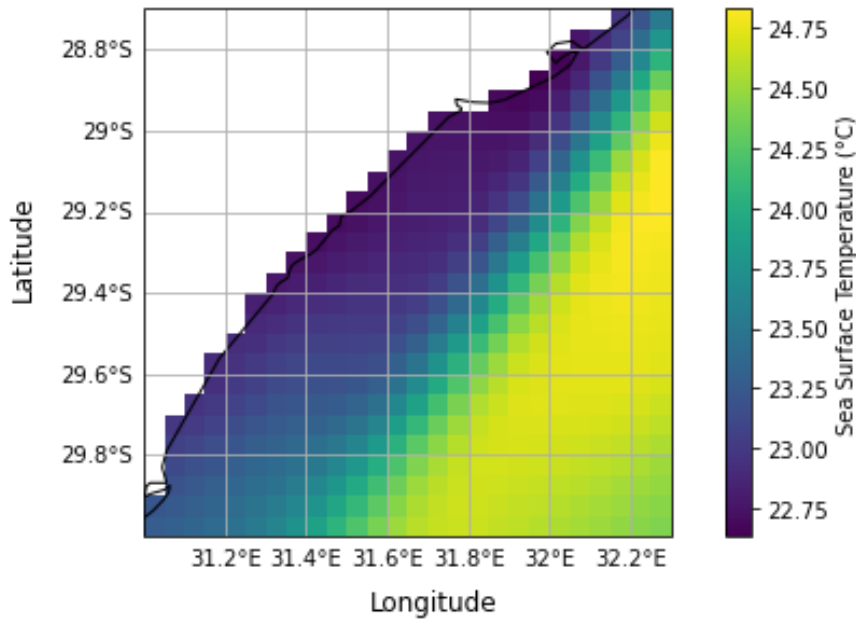
**Table 4.6.** Linear regression results of annual beach temperatures measured at 4 beach sites along the Kwa-Zulu-Natal Bights' coastline from 2013 to 2021. Shown are the sites, region on the Bight, the rate of warming/cooling (rate °C/year), standard error (Std. error), correlation coefficient ( $r$ -value) and the corresponding probability ( $p$ -value). The highlighted  $p$ -values are statistically significant ( $p < 0.05$ ).

Site	Region on Bight	rate (°C/year)	Std.error (°C)	$r$ -value	$p$ -value
Richards Bay	North	-0.11	0.03	-0.82	0.01
Zinkwazi	Central	0.06	0.04	0.47	0.20
Ballito	South	0.08	0.06	0.47	0.21
Durban	South	0.04	0.03	0.37	0.32

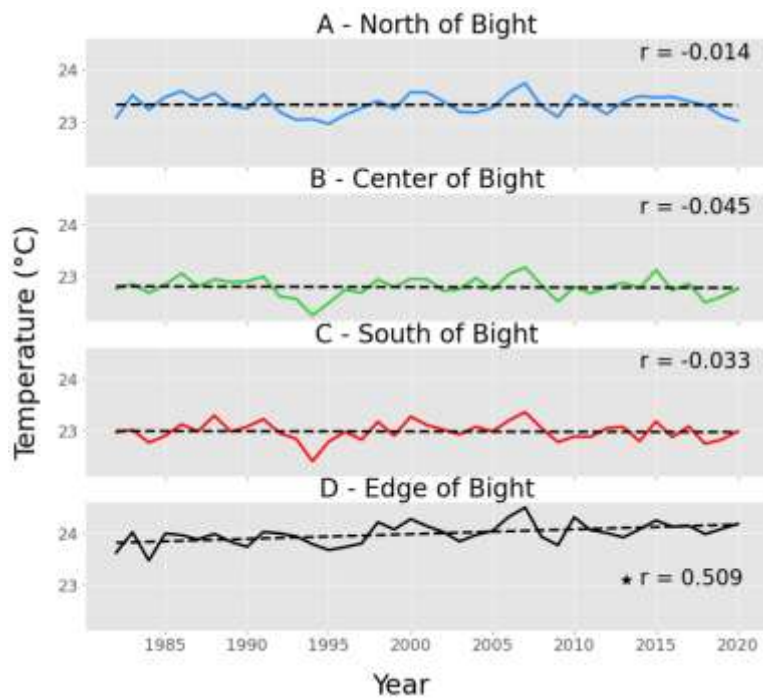
#### 4.4 Satellite Sea Surface Temperature variability

Many modern studies rely on satellite products for various purposes as it covers a wide region and often over long periods (Smith et al., 2013; Sweijd and Smith, 2020). However, there can be known inaccuracies and it is important to evaluate the performance of satellite products with existing *in situ* data (Carr et al., 2021). A map of annual satellite sea surface temperature (SST) used in this study for 2020 is shown in Figure 4.7. Warm waters indicative of the Agulhas Current and cold water in the northern region of Bight, extending southwards, was seen. Satellite SST was analysed at four sites across the Bight over 38 years (1982 to 2020) and are presented as annual mean time series (Figure 4.8). It was noted in Chapter 3 section 3.4 that there are constraints in using satellite data in this region, especially in proximity to the coast. The plots are colour-coded according to the geographical distribution of the Bight (Figure 3.3, crosses), with blue (A) representing a northern site, green (B) representing a central site, red (C) representing a southern site and black (D) representing a site at the edge of the Bight (Figure 4.8). The edge of the Bight is in proximity to the Agulhas Current and hence a site in this region could give insight as to how the influence of the Agulhas Current differs from the inshore regions of the Bight.

Satellite SST at site A ranged from 22.95 to 23.73°C with a weak trend over time and a low cooling rate of -0.0002°C/year (Table 4.7). Satellite SST at site B ranged from 22.23 to 23.16°C with also a weak trend and low cooling rate of -0.0007°C/year. Similar results were seen at site C, where satellite SST ranged from 22.40 to 23.34°C, the trend was weak and cooling occurred at -0.0005°C/year (Figure 4.8; Table 4.7). Satellite SST at site D ranged from 23.46 to 24.49°C. These temperatures displayed a strong positive trend over time and site D was the only site where significant ( $p < 0.05$ ) warming occurred at 0.0092°C/year (Table 4.7). A pattern in surface warming could not be identified across the Bight nor between inshore and offshore sites as the trends in all the inshore sites (A, B, and C) lacked significance.



**Figure 4.7.** Map of the annual OSTIA (Good et al., 2020) satellite sea surface temperature (SST) for the KwaZulu-Natal Bight region for 2020. The data are provided by the Copernicus Marine Environment Monitoring Service (CMEMS, <https://marine.copernicus.eu/>).



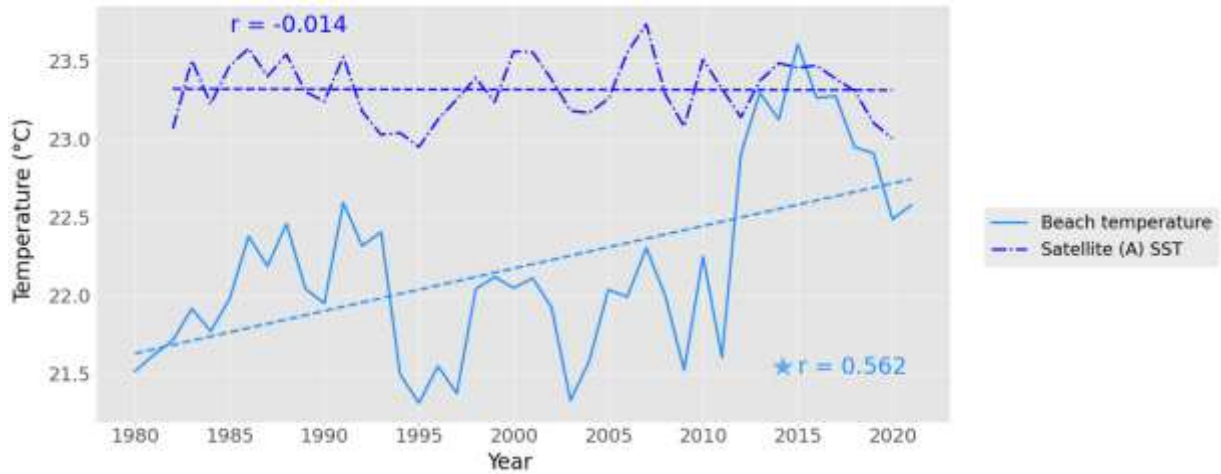
**Figure 4.8.** Time series of annual OSTIA satellite sea surface temperature (SST) for 4 sites (A, B, C and D) across the KwaZulu-Natal Bight from 1982 to 2020. The sites are colour-coded with blue representing the northern region, green representing the central region, red representing the southern region and black representing the edge of the Bight. Trendlines (dashed black) and correlation coefficients ( $r$ ) are indicated. Significant trends are indicated by stars next to the  $r$ -values.

**Table 4.7.** Linear regression results of annual OSTIA satellite sea surface temperature (SST) measured at 4 sites across the Kwa-Zulu-Natal Bight from 1982 to 2021. Shown are the sites, region on the Bight, the rate of warming/cooling (rate °C/year), standard error (Std. error), correlation coefficient (r-value) and the corresponding probability (p-value). The highlighted p-values are statistically significant ( $p < 0.05$ ).

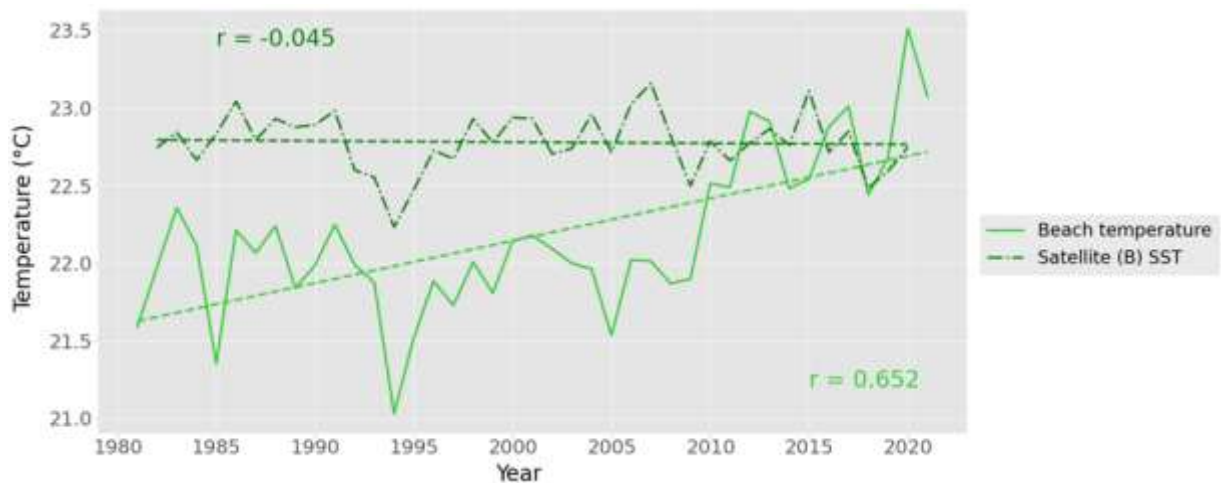
Site	Region on Bight	rate (°C/year)	Std.error (°C)	r-value	p-value
A	North	-0.0002	0.003	-0.014	0.934
B	Central	-0.0007	0.003	-0.045	0.784
C	South	-0.0005	0.003	-0.033	0.841
D	Edge	0.0092	0.003	0.509	<b>p &lt; 0.01</b>

Sites A, B and C were selected to coincide with the nearest *in situ* beach temperature site in the northern, central and southern regions of the Bight (Figure 3.3). Comparisons between the satellite SST and beach temperatures were analysed (Figures 4.9, 4.10 and 4.11). Site A was compared to beach temperatures at Richards Bay, site B to beach temperatures at Zinkwazi and site C to beach temperatures at Durban. Figures 4.9, 4.10 and 4.11 all show that satellite SST overestimates *in situ* beach temperatures at all sites across the Bight. Weak but significant ( $p < 0.05$ ) correlations were found between the beach temperatures and satellite SSTs at Richards Bay and Zinkwazi with correlation coefficients ( $r$ ) of 0.34 and 0.24 respectively. A fairly strong and more significant ( $p < 0.01$ ) correlation was found between the two datasets at Durban with a correlation coefficient of 0.42.

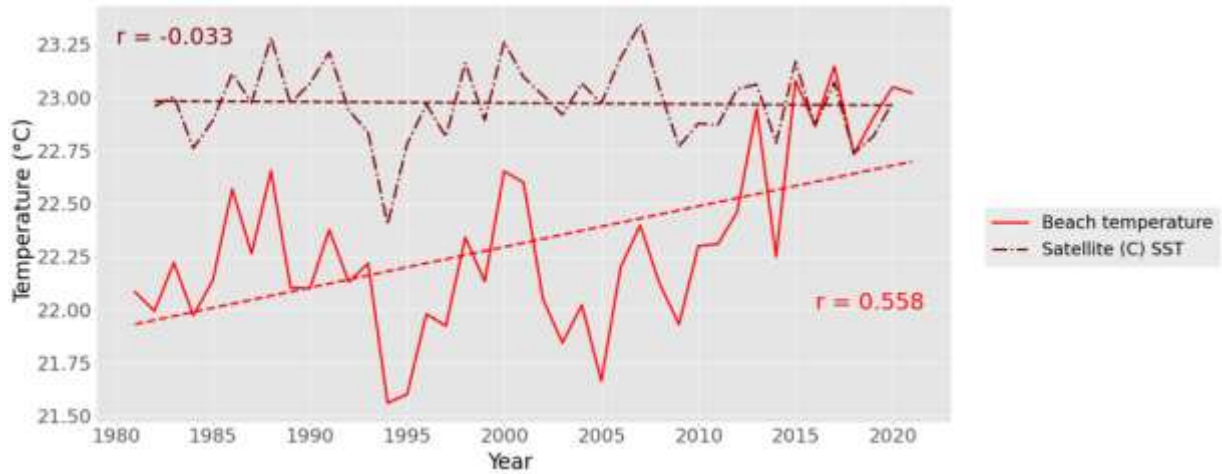
Satellite SST displays a warm bias of 1.11°C, 0.62°C and 0.67°C on average in the northern, central and southern regions of the Bight, respectively. A higher warm bias of up to 6°C was found by Smith et al. (2013) in the Bight by using Moderate Resolution Imaging Spectroradiometer (MODIS) Terra and Pathfinder SST products. The satellite SST also fails to replicate the trends observed in the *in situ* data. The linear regression results and warming/cooling rates are the same as those presented in Tables 4.1 and 4.6. The warming rates observed by the beach temperatures at the respective sites were of a magnitude of 10 times greater than those observed by the satellite SST indicating that satellite SST underestimated the warming rate at each site. These results are extremely important, especially for studies that rely on satellite SST to observe long-term changes in coastal regions. This section not only shows that satellite SSTs overestimate beach temperatures but also underestimate the warming rates over time. This is important as most MPAs are located in coastal regions and hence satellite SSTs for MPA monitoring need to be used with caution.



**Figure 4.9.** Comparison between annual beach temperatures at Richards Bay and OSTIA satellite sea surface temperature (SST) in the northern region of the Bight. Trendlines (black dashed line) and correlation coefficients ( $r$ ) are indicated. Significant trends are indicated by stars next to the  $r$ -values.



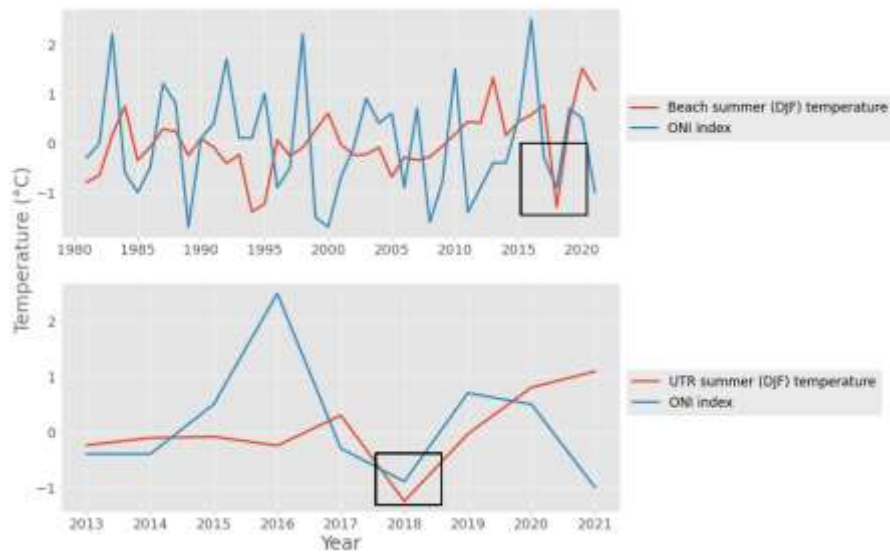
**Figure 4.10.** Comparison between annual beach temperatures at Zinkwazi and OSTIA satellite sea surface temperature (SST) in the central region of the Bight. Trendlines (black dashed line) and correlation coefficients ( $r$ ) are indicated. Significant trends are indicated by stars next to the  $r$ -values.



**Figure 4.11.** Comparison between annual beach temperatures at Durban and OSTIA satellite sea surface temperature (SST) in the southern region of the Bight. Trendlines (black dashed line) and correlation coefficients ( $r$ ) are indicated. Significant trends are indicated by stars next to the  $r$ -values.

#### 4.5 Interannual variability – A case study

The persistent decrease in both beach and UTR temperatures observed during the summer of 2017/2018 (Figures 4.3 and 4.5) coincided with a strong La Niña year. A similar but weaker decrease was also seen in satellite SSTs (Figure 4.8). The El Niño Southern Oscillation (ENSO) is an ocean-atmospheric phenomenon that affects weather conditions and seawater temperatures along the east coast of Africa (Tourre and White, 1995; Rouault et al., 2010; Holbrook et al., 2020). For further investigation, a comparison between the beach and UTR summer temperature anomalies in the central Bight (Zinkwazi) with the summer averages of the Oceanic Niño Index (DJF; [https://origin.cpc.ncep.noaa.gov/products/analysis\\_monitoring/ensostuff/ONI\\_v5.php](https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php).) was analysed (Figure 4.12). Sea surface temperature anomalies that are equal to or greater than  $0.5^{\circ}\text{C}$  indicate an ENSO warm phase (El Niño), whereas anomalies equal to or less than  $-0.5^{\circ}\text{C}$  indicate an ENSO cool phase (La Niña). The analysis showed a good correlation between the temperatures and the ONI in 2017/2018 (Figure 4.12). These results should be interpreted with as not all the ENSO events coincide with changes in the temperature, such as the drop in temperatures in 1994/1995 that coincided with a strong El Niño event (Rouault et al., 2010). However, it is well known that the ENSO signal is often not linear and the interactions with regional coastal temperatures are likely to be complex and driven by coastal phenomena such as local wind mixing (Smith et al., 2013; Nhesvure, 2020)



**Figure 4.12.** Comparison of summer (DJF) anomalies between beach and UTR temperatures at the central regions of the KwaZulu-Natal Bight (Zinkwazi) with the Oceanic Nino Index (ONI). The point where both datasets correlated are highlighted by a black box.

This chapter analysed long-term beach and UTR temperatures in the northern, central and southern regions of the Bight; and compared beach temperatures to satellite-derived SSTs. Significant warming/cooling rates were found in all regions of Bight as well as an anomalous event during the summer of 2017/2018. These findings are crucial in understanding the environmental changes occurring within and around the uThukela MPA; and the reasons as to why these changes may be occurring.

## Chapter 5. Discussion

The KwaZulu-Natal Bight ('the Bight'), a coastal offset on the northeast coast of South Africa (Figure 2.2), has been identified as a key area for protection against anthropogenic influences. The Bight is important for marine ecology as it serves as a region of larval retention, recruitment and a general nursery and foraging area for several native species (Fennessy et al., 2016). The newly established uThukela MPA serves as a tool to protect, restore and conserve the biodiversity in this region. The uThukela MPA is located in the center Bight ecoregion off the uThukela River (Figure 3.1; Meyer et al., 2002) and is considered an area of oceanographic interest (Lutjeharms, 2006). The Bight is seaward bound by the swift-flowing oligotrophic western boundary Agulhas Current (Schumann, 1988), which encloses the shelf waters of the Bight, thereby providing refuge to marine species (Hutchings et al., 2002). Apart from the Agulhas Current, other unique oceanographic features shape the ecosystem of this region (Chapter 2).

As mentioned, only some of the oceanographic features of the Bight are known as the majority of the data is out dated or fragmented (Fennessy et al., 2016). To build a foundation upon which the region's ecosystem structure and functioning can be understood, the ACEP SMART Zone MPA Project is conducting biological and oceanographic surveys along the Bight. To complement this, this study aims to analyse historic oceanographic data (temperature) to assess if there have been any significant changes within the northern, central and southern regions of the Bight (Table 3.1), which will guide us in suggesting best-suited techniques in monitoring the effectiveness of this MPA going forward. Three datasets were used in this study: *in situ* beach temperatures from 12 beach sites along the KZN coastline (Richards Bay to Durban), *in situ* UTR temperature and OSTIA satellite-derived SST from 4 sites across the Bight, for a period ranging from 1980 to 2021 (Chapter 3 and Figure 3.3). With the ongoing climate changes our oceans are experiencing, the effect global warming has on warming/cooling trends across the Bight cannot be ignored (Seager et al., 2019; Pisano et al., 2020; Ruela et al., 2020). From 1950 to 2018, global SSTs have warmed at an average rate of 0.01°C/year (Lumpkin, 2019). This chapter provides a discussion of the results (Chapter 4) and aims to address the key questions that were highlighted for this study at the end of Chapter 1.

### 5.1 Has significant warming/cooling occurred across the Bight over the years?

The lack of significance observed in the warming/cooling rates at the UTRs sites across the Bight makes it difficult to suggest possible explanations for these findings. However, the strong correlation found between the UTRs sites and comparable beach sites provides assurance in using beach sites to measure temperatures. In general, beach temperatures warmed significantly across the northern, central and southern regions of the Bight, with the exception of some southern beach sites (Figure

4.1). The warming rates decreased from north ( $0.03^{\circ}\text{C}/\text{year}$ ) to south ( $0.01^{\circ}\text{C}/\text{year}$ ) except at Durban, where significant warming occurred at  $0.02^{\circ}\text{C}/\text{year}$ . A study analysing changes in SST in seven African large marine ecosystems (LMEs) also found that the majority of LMEs, including the Agulhas Current LME (ACLME), which the Bight forms part of, displayed warming trends from 1981 to 2019, with the ACLME warming the slowest at a significant ( $p < 0.01$ ) rate of  $0.01^{\circ}\text{C}/\text{year}$  (Sweijid and Smit, 2020). The fastest warming, at a rate of  $0.03^{\circ}\text{C}/\text{year}$ , occurred at all northern and central sites on the Bight as well as three out of the eight southern sites. This indicates that significant warming has occurred within and around the uThukela MPA. The same rate ( $0.03^{\circ}\text{C}/\text{year}$ ) was observed in SSTs for 71.6% of coastal locations worldwide, which significantly warmed from 1982 to 2010 (Lima and Wetthey, 2012).

The hydrography of the Bight is dominated by the warm Agulhas Current due to the steep continental slope (Lutjeharms, 2007) and proximity of the current, especially towards the northern and southern regions (Schumann, 1988). It has been reported that parts of the Agulhas Current have warmed faster than 90% of the world's ocean over the past few decades (Kelly et al., 2019). Rouault et al. (2010) found a positive warming rate of up to  $0.06^{\circ}\text{C}/\text{year}$  in most parts of the Agulhas Current from 1982 to 2009. They attributed warming in the KZN region to the Agulhas Current intensifying as a result of a poleward shift of westerly winds and stronger trade winds in the South Indian Ocean. Thus, warming of shelf surface waters on the Bight may be potentially driven by an increase in the advection of warmer Agulhas waters by shear edge plumes (Gründlingh and Pearce, 1990; Rouault et al., 2009). A key influence of the Agulhas Current on the Bight is the persistent topographically driven upwelling in the northern region (Figure 2.2, A; Roberts and Nieuwenhuys, 2016), which is known to be the primary source of nutrients for biodiversity on the Bight (Meyer et al., 2002). It is a fundamental key to understanding the ecosystems present (Lutjeharms, 2006); and significant warming in this region could be of major concern.

The upwelled waters are cold nutrient-rich South Indian Subtropical Surface waters of approximately  $19^{\circ}\text{C}$  (Meyer et al., 2002). Throughout this study, temperatures at Richards Bay were  $> 20^{\circ}\text{C}$  except during winter (Figure 4.3). The frequency and intensity of upwelling events may be affected by the physical changes in the Agulhas Current (Hutchings et al., 2010). Also, the global increase in SST enhances stratification (Lamont et al., 2016) and prevents the upwelled waters from reaching the surface layers of the Bight. Stratification decreases the wind-driven surface mixing depth (Austin and Lentz, 2002) and subsequently the upward movement of cooler nutrient-rich waters to the mixed layers (Dunstan et al., 2018), which may have resulted in the warming observed. The upwelling events have also been associated with north-easterly winds, which drive the southeastward offshore current (Roberts and Nieuwenhuys, 2016). Changes in the prevailing wind conditions will therefore

influence the nature of upwelling occurring in, not only the northern region, but also the wind-driven upwelling, along with currents observed in the inner regions from the northern to the central Bight (Roberts et al., 2010; Roberts and Nieuwenhuys, 2016).

The upwelled cold nutrient-rich waters spread southwards throughout the water column (Lutjeharms et al., 2000b; Hutchings et al., 2010) where it sustains the food web near the Thukela River at the center of the Bight. The central Bight is richer in nutrient content and is more biologically active in comparison to the northern and southern regions (Scharler et al., 2016). Warming of beach temperatures in the northern region would result in warmer waters transported to the central Bight, supplying the central Bight with fewer nutrients than the region normally receives from upwelled waters. A reduction in nutrients and enhanced stratification will negatively affect marine life and the food webs that thrive in these waters and across the entire Bight.

The other source of nutrients to Bight is the Durban Eddy (Figure 2.2, C). Beach temperatures  $< 22^{\circ}\text{C}$  suggest the influence of Durban eddies, but there is uncertainty as eddies aren't annual features of the Bight (Guastella and Roberts, 2016) and upwelled waters do not always reach surface depths (Meyer et al., 2002). Also, the coarseness of the data (annual instead of monthly) or the proximity of the sites to the shore is unable to capture the thermal signal. The slower warming rates observed in the southern region, in comparison to the northern and central regions, are of interest as this region experiences less frequent upwelling and warmer water being advected by the Durban Eddy on the Bight has been observed (Fennessy, Roberts and Barlow, 2016), thus a faster warming rate should be expected.

Warming identified in the beach temperatures from 2010 onwards (Figure 4.1) mainly occurred at sites in the central and southern regions of the Bight. Further investigation of warming/cooling trends over the last decade (2010 to 2021; Figure 4.2) showed faster warming rates as expected due to the short time series, (Table 4.2) but only Durban showed strong significant warming at a rate of  $0.07^{\circ}\text{C}/\text{year}$ . The same warming rate was found for the Agulhas Current by Rouault et al. (2009) but was computed since the 1980s. In contrast to the 41 years, standard errors for the warming/cooling rates were higher and some southern sites (Westbrook, eMdloti and uMhlanga Rocks) indicated cooling rates of  $-0.04^{\circ}\text{C}/\text{year}$ . The difference between these analyses highlights the importance of using a long-term dataset when investigating climate variability in a region. Long-term datasets reduce uncertainty and facilitate the understanding to support adaptive decision-making and also optimize model outputs (Hassani et al., 2019)

## 5.2 How do warming/cooling rates compare between the beach and UTR data?

In order to make comparisons between beach and UTR temperature trends, beach temperature data had to be subset to analyse both datasets over the same period (2013 to 2021; Figure 4.6). As mentioned previously, strong and significant correlations were observed between each UTR site and the comparable beach site, indicating strong positive relationships between the two. However, it is important to note that the beach and UTR sites do not have the same geographical location on the Bight (Figure 3.3). A difference of up to 2°C was evident between beach and UTR temperatures with the former being warmer on average. Surface temperatures are expected to be warmer due to direct exposure to incoming solar radiation (Sætra et al., 2008). Colder beach temperatures in comparison to the corresponding UTR could be an indication of wind-driven mixing of upper layers on the shelf (Lamont et al., 2016). Mixing of the upper layers would most likely be expected in the northern region due to the near-continuous upwelling of cold nutrient-rich waters, but temperature ranges between the beach and UTR temperatures at Richards Bay do not coincide as the UTR site is at a depth of 3 m (Figure 3.3).

Warming occurred in all central and southern regions of the Bight, whereas cooling was observed in the northern region. Significant rates were only observed in beach temperatures in the northern Bight where waters cooled at a rate of  $-0.11^{\circ}\text{C}/\text{year}$ . On average, UTR temperatures were observed to warm at faster rates than beach temperatures, which will have subsequent impacts on the biodiversity that thrive below the surface (Kelly et al., 2019). The difference in warming/cooling rates can be attributed to the beach sites, along the inner Bight, experiencing wave action which causes mixing (Moum and Smyth, 2001). Ocean mixing homogenizes the temperature profile of the water column by brining cooler water to the surface, thus slowing the surface warming rates. The beach sites also experience the most amount of anthropogenic influence as it is a region of land-sea connectivity (Fennessy et al., 2016). The coastal region is also directly exposed to riverine runoff from several catchments but this has greater effects on salinity and chemical composition (Lamont et al., 2016) and minimal effects on seawater temperature. The lack of significance of the warming/cooling rates observed at all but one site adds uncertainty to these findings, however, it does create awareness of whether waters at bottom depths are also warming and at what rate. The warming/cooling of the water column not only affects stratification but can influence bottom Ekman veering, which brings cold water to the surface, and hence warming/cooling can alter the circulation on the Bight (Roberts, 2010; Kelly et al., 2019).

It important to note that the time series presented in this study are of annual means and therefore there are limitations to this type of statistical analysis. Annual means remove daily and monthly

thermal signals that are important for understanding the oceanography of this region. Analysis of the daily/monthly means would give a more meaningful understanding of how temperature has changed in the St. Lucia upwelling region (Figure 2.2; A) and if there have been changes in the frequency of the Durban Eddy. In addition to this, removing the seasonal pattern from the overall trend may be more informative of warming/cooling over the years. A more detailed analysis is therefore essential for understanding surface and subsurface temperature variability of this region.

### 5.3 Is seasonal variability evident across the Bight and are there significant temperature changes during summer and winter?

Understanding the changes in seasonal signals is crucial, especially for regions of ecological importance. Many species depend on seasonal variability for processes such as breeding, spawning and migration (Kelly et al., 2019). A clear and expected difference was evident in both beach and UTR temperatures between the summer (DJF) and winter (JJA), agreeing well with previous studies (Lutjeharms, 2006; Smith et al., 2013; Lamont et al., 2016). Significant warming occurred at all northern, central and southern beach sites during both seasons except for four southern beach sites (Figure 4.3; Table 4.3). Durban showed significant warming at both beach and UTR sites only during summer at rates of 0.013 and 0.17°C/year respectively. The difference in magnitude is largely due to the difference in the length of the observational period (Chapter 3). Significant warming occurred the fastest at the northern beach site (0.029°C/year) during winter and the slowest at the southern beach site (0.013°C/year) during winter. Rouault et al. (2010) observed a significant warming rate of 0.025°C/year in the KZN region during summer, which agrees with summer warming rates observed in the northern and central Bight. The MPA experiences significant warming within and around it during both seasons at an average rate of 0.02°C/year. However, the central regions of the Bight show faster warming (0.002°C/year) in summer than in winter. These results could be explained by the frequency at which the Agulhas Current shifts offshore in winter, inducing active upwelling of colder water (Barlow et al., 2013). The warming rates on average decreased from north to south during both seasons agreeing with Smith et al. (2013) who found that average temperatures decreased from north to south during both seasons.

The main mechanism driving seasonal variation of ocean temperatures is the annual variation of solar insolation together with the prevailing wind conditions (van Aken, 2010; Lamont et al., 2016). The increase in surface heating during summer enhances stratification and enables the development of intense thermoclines and shallower mixed layer depths, with the opposite occurring during winter (Schumann et al., 1995; Lamont et al., 2016). Shallow mixed layer depths during summer may also be due to increased input of Tropical Surface Waters from the Agulhas Current (Blastoch et al.,

1999). Over the Bight, both upwelling-favourable north-easterly winds and downwelling-favourable south-westerly winds occur approximately 50% of the time (Schumann and Martin, 1991). These observations agreed with Lamont et al. (2016) who observed that there was no difference in wind conditions in the northern region, with both north-easterly and south-westerly winds occurring during both seasons. This is suggestive of no clear seasonal pattern in the prevailing wind conditions over the northern region of the Bight. The extent of upwelled waters near Richards Bay together with nutrient distributions display no clear seasonal patterns (Carter and d'Aubrey, 1988; Lutjeharms et al., 1989). No detectable seasonal cycle was found in the Durban Eddy occurrences either (Guastella and Roberts, 2016). Therefore, there seems to be no distinct mechanism that drives seasonal variations in the temperatures besides solar heating of surface waters and the variability of the Agulhas Current along the shelf edge.

#### 5.4 How does satellite data compare with in situ data across the Bight?

Satellite products have become widely used in many fields of study. Many studies rely on satellite-derived data for understanding coastal regions and regions that are unsampled (Sweijd and Smith, 2020). SST trends close to zero were observed between 2002 and 2019 near Durban (Krug, 2020; Ocean and Coasts) and agreed with warming rates in the northern, central and southern sites. Significant warming only occurred at the edge of the Bight at a rate of  $0.0092^{\circ}\text{C}/\text{year}$  (Table 4.7). The warming rate at the edge of the Bight is slower than some of the warming that occurred at the beach temperature sites (Table 4.1). This contradicts findings by Varela et al. (2018) who observed slower warming at inshore coastal locations in comparison to offshore locations over the period 1982 to 2015. They suggested that these differences were due to coastal upwelling acting as a buffer to ocean warming. The slower warming observed at the edge can be attributed to shelf edge upwelling due to Ekman veering as a result of the swift-flowing Agulhas Current adjacent to it (Lutjeharms et al., 2000). This however was not seen in beach temperatures at the northern Bight possibly because the oceanic dynamics occurring at the edge of the Bight, due to the Agulhas Current, allows upwelled waters to reach surface layers (Figure 2.2, B).

A comparison between the three satellite points (A, B and C) with comparable *in situ* beach temperature sites (Figures 4.10, 4.11 and 4.12) enabled the evaluation of the satellite product in near-shore coastal regions. Significant correlations were observed between the respective sites. However, the satellite SSTs failed to reflect patterns in the beach data. Satellite SSTs overestimated the *in situ* beach temperatures and underestimated the warming rates by a magnitude of 10 at all sites across the Bight (Table 4.1 and 4.6). Warm biases of up to  $1.11^{\circ}\text{C}$  were found with lower biases in the central and southern regions. These biases are less than those found by Smith et al. (2013) of

up to 3°C on the east coast by using higher-resolution satellite products (4 km compared to 5.5 km). They found that warm biases were reduced in the Bight region in comparison to warm biases of up to 6°C along the rest of the South African coastline.

It is well known that temperatures derived from satellite products differ from *in situ* measured temperatures (Carr et al., 2021), which in the case of this study, were measured at ~20 cm below the water surface. Several factors in coastal regions also contributed to the biases observed such as the source of data, proximity to the shore and presence of upwelling. These features occur at small scales resulting in satellite products failing to capture the thermal signals (Smith et al, 2013). Missing pixels at the land-sea edge also influence the data (Pearce, Faskel and Hyndes, 2006). Therefore, *in situ* data is best for understanding changes occurring within ecologically important coastal regions.

## [5.5 Had any noticeable thermal events occurred across the Bight over the years?](#)

A striking feature throughout the seasonal analysis for both beach and UTR temperatures; and to a lesser extent satellite SSTs, was the persistent decrease in temperatures of approximately 3°C during the summer of 2017/2018 (Figures 4.3, 4.5 and 4.8). The decrease in temperature was evident at all central and southern beach sites and all UTR sites, except at Durban. This indicated that some oceanographic feature/phenomenon was at play as the decrease in temperature was evident along the coastline and shelf waters, as well as in the surface layers of the Bight. The years 2017/2018 were identified as a strong La Niña year (Zhang et al., 2019). El Niño and La Niña events are known as the El Niño Southern Oscillation (ENSO), which is a well-known ocean-atmospheric phenomenon. ENSO strongly affects weather systems and subsequently ocean temperature around the world, including Southern Africa (Reason et al., 2000). Around South Africa, El Niño years are associated with warmer than normal ocean temperatures and La Niña years are associated with colder than normal ocean temperatures (Rouault et al., 2010).

ENSO-related extremes in ocean temperatures can result in periods of prolonged marine heatwaves (MHWs) or marine cold spells, which have major implications for biodiversity as they can severely impact coral, kelp, seagrass and various other ecosystems (Holbrook et al., 2020). These extremities, especially MHWs, are of considerable interest due to their significant increase in frequency and duration (Oliver et al., 2018). The decrease in temperatures evident in this study coincided with the 2017/2018 La Niña event, indicated by the negative anomaly of the Oceanic Niño Index (ONI) for summer (Figure 4.12). However, not all ENSO events coincided such as the 1995/1996 and 2007/2008 La Niña event, and the 1994/1995, 1997/1998 and 2015/2016 El Niño event (Nhesvure,

2020); making it uncertain if ENSO is the actual driving force of the drop in temperature observed. Although, the complexities driven by coastal processes (upwelling and wind-driven mixing) and oceanic variability are likely to mask relationships between ENSO and coastal temperature.

Complexities in coastal regions cannot rule out the influence of other coastal features that could have influenced the decrease in temperature. When the Agulhas Current moves further offshore (150 to 300 km offshore), the instability in the core triggers large meanders known as the Natal Pulses (de Ruijter et al., 1999; Lutjeharms et al., 2000b). Natal Pulses are also formed as the Agulhas Current interacts with deep-sea anticyclonic eddies (Tsugawa and Hasumi, 2010). The Bight serves as a formation region for these large solitary episodic meanders (Lutjeharms and Roberts, 1988), where they grow in amplitude as they propagate downstream (Roberts et al., 2010). Natal Pulses are cyclonic cold-cored meanders (Roberts, Nieuwenhuys and Guastella, 2016) that significantly influence the shelf waters by inducing intensive localized upwelling of cold nutrient-rich water (Bryden et al., 2005; Rouault et al., 2010). Therefore, ocean variability i.e. Natal Pulses appear to be a more likely reason for the drop in temperature observed. Further in-depth investigation is required to identify the cause of these cooling events and how they will respond to climate change.

## Chapter 6. Importance of findings and recommendations for MPA management

The warming observed at most beach and UTR sites within and around the uThukela MPA over the last few decades will have moderate to severe biogeographical implications within the region (Kelly et al., 2019). Changes in ocean temperature can also potentially drive alterations in the currents and circulation that will prompt the spatial and temporal shifts of some species (Tittensor et al., 2010), with warmer temperatures causing a poleward shift in their distribution (Lloyd, 2012). The recruitment, spawning and larval dispersal across the Bight will also be affected as many fish that spawn in this region rely on the coastal currents to transport their eggs and larvae (Beckley and Connell, 1996). Marine animals such as leatherback sea turtles, which have been listed as an endangered species (Nel and Casale 2015), aggregate off the beach in the northern KZN region during their nesting seasons (van der Bank et al., 2019) and depend on circulation features to travel to distant areas (Luschi et al., 2003). Changes in the circulation patterns will therefore alter their movements and seasonal changes may affect their nesting patterns. Within MPAs along the KZN coast, Leatherback turtle populations have not yet shown signs of growth, however, Loggerhead turtles have been shown to benefit from coastal MPAs (Nel et al., 2013). The famous annual KZN sardine run is also seasonal as sardines move northwards along the east coast during winter. Winter warming of coastal regions will provide unfavourable conditions for this species that prefer cooler water and could lead to a cessation of the run (Hutchings et al., 2010; Augustyn et al., 2018).

Apart from altering the currents and circulation patterns of the Bight, the health of the ecosystem could potentially deteriorate. Warming of ocean temperatures will affect the abundance, physiology and catchability of South Africa's marine species (DEA 2013; Potts et al., 2015; Whitfield *et al.* 2016); and will have far-reaching economic impacts (Kelly et al., 2019). The impacts that warming has on biodiversity and ecosystem functioning will continue to intensify and thus effective management of MPAs are crucial. An increase in research accompanied by extensive and uninterrupted monitoring is needed to understand the environmental stressors that influence this region together with the interactions they may have with other pressures (Kelly et al., 2019). The large biases in satellite data suggest that *in situ* observations are most reliable and better suited for understanding temperature change in coastal regions. Increases in observational data are encouraged, especially for UTRs, as they have higher instrumental accuracy than beach readings (0.001°C compared to 0.8°C). This improves our understanding of temperature change across the Bight, allowing effective monitoring of the MPA. The effect of depth on temperature variability and species distribution, together with other physical variables such as salinity, must be considered during MPA analysis. These variables

should be considered over a long period (long-term datasets) as highlighted in this study. Hence, a long-term monitoring programme should be put into place with sites covering the majority of the Bight if feasible and eco-friendly. A long-term dataset will help in identifying the frequency of eddies and other oceanic phenomena and how it affects the ecology. Understanding wind and upwelling variability, especially in the northern Bight are also recommended as the entire Bight depends on this region for survival (Roberts, 2016).

## Chapter 7. Conclusion

This study analyses long-term changes in temperature across the KwaZulu-Natal Bight ('the Bight') on the northeast coast of South Africa, to recommend monitoring techniques for the newly established uThukela MPA in the central region. The study used *in situ* beach temperature data from 12 beach sites along the coast, UTR temperature data from 4 sites across the Bight, and OSTIA satellite-derived SST data extracted from 4 points across the Bight. Annual time series were analysed over an extensive period ranging from 1980 to 2021. UTR temperature data were only available since 2013 resulting in a shorter time series and subsequently a lack of significance in the warming/cooling trends. However, the strong correlations between the UTR and beach data displayed confidence in the beach temperature trends. The Bight was geographically separated into the northern, central and southern regions. Warming was observed at all beach sites with rates ranging from 0.01 to 0.03°C/year, with significant warming within and around the MPA region. A possible reason for the warming across the Bight was the increased advection of the warmer Agulhas Current surface waters. The warming in the north, where persistent upwelling takes place, was attributed to enhanced stratification preventing upwelled waters from reaching and cooling surface waters. Large warming was observed in the majority of beach temperatures from 2010 onwards but further analysis showed significant warming only at Durban. This highlighted the importance of using large datasets over an extended period of time when investigating temperature variability for MPA analysis.

Clear seasonal differences were seen in summer and winter averages for beach and UTR temperatures. On average, both beach and UTR temperatures displayed warming during summer and winter. Beach temperatures warmed at an average rate of 0.02°C/year during both seasons. The majority of the warming at beach sites, especially in the northern and central regions, was significant and ranged from 0.013 to 0.029°C/year, whereas UTR temperatures warmed significantly only at Durban during summer at a rate of 0.17°C/year. An anomalous event where temperatures decreased by 2°C was evident in summer 2017/2018 across all beach and UTR sites. Ocean-atmospheric phenomena such as ENSO or the regional Natal Pulse have the potential to drive such decreases in temperature, but further investigation is needed. Warm biases of up to 1.12°C were observed in satellite SSTs in comparison to *in situ* data. Satellite SST trends failed to replicate trends observed in the beach data and largely underestimated warming trends. These differences emphasized the importance of directly measuring temperature in coastal regions. Given that the world's oceans and especially coastal systems are subject to change caused by anthropogenic influences, the spatio-temporal variability of this change is important to understand and consider for MPA analysis, if the impacts on the functioning of the ecosystem is to be effectively managed.

## Chapter 8. References

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