Comparing *in situ* and satellite temperature data on the Agulhas Bank to understand changes in anchovy (*Engraulis encrasicolus*) distribution

Submitted in partial fulfilment of the requirements for the degree of

MASTER OF SCIENCE

(by coursework and dissertation)

in Applied Marine Science

Department of Biological Sciences

University of Cape Town

By

ROBERT WILLIAM SCHLEGEL

February 2014

Marine Research Institute

Supervisors

A/Prof Coleen Moloney (UCT), Dr. Mike Roberts (DEA), Dr. Carl van der Lingen (DAFF)

Plagiarism Declaration

I know the meaning of plagiarism and declare that all of the work in this dissertation, save for that which is properly acknowledged, is my own.

______________________________ ______________________

Signature Date

Table of Contents

Acknowledgements

I would like to thank the Department of Environmental Affairs for the UTR and CTD data provided for this study and the Department of Agriculture Forestry and Fisheries for the use of the CalVET net data. Special thanks go to Janet Coetzee for use of the pelagic spawner biomass survey data.

Most importantly I must thank my supervisors, without whose heroic efforts this dissertation would not have made it far out of its larval stage. Many thanks to Professor Moloney for her attention to formatting and being so blindingly fast at returning proofs of my dissertation, as well as ensuring the correct use of statistical analyses statistics. My paper is much stronger now because of it.

Thanks to Dr. Roberts for his editing and input on the physical oceanography side of things. He gave me some much needed perspective on how I should be saying what I was trying to say and the importance (or lack thereof) of it all.

And lastly, thank you Dr. van der Lingen for both of your edits and for helping my biology along. And thank you for reminding me what the focus of the whole thing was, preventing me from spinning wildly out of hand on random tangents.

Abstract

Satellite data have high spatial/ temporal resolution, extensive coverage and are easily accessible, making them a common part of many studies on the oceans. One such important study to use satellite data found a relationship between the cross-shelf SST difference on the Agulhas Bank and the relative distribution of anchovy (*Engraulis encrasicolus*) spawner biomass east of Cape Agulhas. However, other studies have shown that nearshore satellite data may not be as accurate as originally believed. Using the relationship observed in the aforementioned study as a test, I compared time series' from two types of *in situ* temperature data to satellite SST data. A combined CTD/CalVET (PISCTD) data set was used for *in situ* data on the coastal and offshore regions of the Agulhas bank whereas a data set with two UTRs was used for inshore *in situ* data. None of the data sets correlated significantly with each other, save the two UTRs. Both *in situ* data sets showed a negative relationship between the size of the cross-shelf temperature difference on the Agulhas bank and the increase in anchovy biomass there, whereas the satellite data showed a positive relationship. This was largely due to the pattern of decadal warming observed in the *in situ* data whereas the satellite data showed decadal cooling. Even though it was found that the difference in sampling methodology between the satellite and *in situ* data sets prevented them from being accurately compared, the difference in the annual and decadal patterns between these two types of data do support other findings showing discrepancies between remotely-sensed and *in situ* data for nearshore environments.

Chapter 1
General Introduction and Literature Review

Along roughly 2,700km of coastline, the small pelagic fish of South Africa must survive within two distinctly different ecosystems. As part of an Eastern Boundary Upwelling System (EBUS), the Benguela Current on the west coast of South Africa is a cold water system (Hutchings et al. 2009), whereas the Agulhas Current on the east and south coasts brings a warm supply of subtropical water south from the equator (Roberts 2004). These two massive oceanographic features interact south of Africa, making the ocean environment dynamic with poorly understood impacts on marine organisms (Hutchings et al. 2009). Coastal upwelling provides an environment conducive to plankton production (Cury et al. 2000), which is one of the reasons small pelagic fishes have lifecycles that predispose them to success in regions of strong upwelling (Miller et al. 2006). Anchovy (*Engraulis encrasicolus*) and sardine (*Sardinops sagax*) are two such omnivorous small pelagic fish species that live, spawn and die off the coast of South Africa (van der Lingen et al. 2006b). The biomass of these species began to decrease in the traditional fishing grounds on the west coast during the mid 1990s while increasing on the south coast (Roy et al. 2007, Coetzee et al. 2008). The change in relative biomass to the east of Cape Agulhas had a negative impact on the purse seine fishery as well as the Benguela ecosystem (Hutchings 2009). The hypotheses that have been proposed to explain this relative increase in biomass to the east are covered in more detail in this chapter. Previous research into this phenomenon using satellite data has found a link between environmental variability in the Agulhas Bank region and the relative increase in anchovy spawner biomass to the east (Roy et al. 2007). In this dissertation, the question of why this relative increase has occurred is re-investigated using inshore, coastal and offshore *in situ* temperature data.

Oceanography

The Benguela ecosystem has a strong upwelling zone that stretches from Cape Agulhas to Cape Frio (Hutchings et al. 2009) and the offshore current associated with this zone moves northwards at 0.25-0.50m.s^{-1} (Roberts 2004). The Angola Current flows south into the northern boundary of the Benguela ecosystem at roughly 17°S (Hutchings et al. 2009). The Benguela ecosystem is predominantly oriented North - South, changing to East - West at 34°S on the Agulhas Bank where it meets the Agulhas Current, which forms the southern boundary (Hutchings et al. 2009). The broad South Atlantic gyre forms a rough outer boundary to the Benguela ecosystem (Hutchings et al. 2009). A particularly strong upwelling cell at Lüderitz (26°S) partially separates the northern and southern Benguela ecosystems (Hutchings et al. 2009), creating two largely separate regions. The southern region affects the west and south coasts of South Africa.

The pulsed, seasonal, wind-driven upwelling in the southern Benguela ecosystem peaks in austral summer to autumn and causes short-term variability in phytoplankton production and fish recruitment (Hutchings et al. 2009). The strong interannual and decadal signals in this system make long term trends difficult to detect (Hutchings et al. 2009), though winds may have increased over the last 100 years, particularly since 1950 (Coetzee et al. 2008). The Benguela jet (Figure 1.1), with a maximum velocity of ~0.75m.s^{-1} and transporting 1-7Sv (Roberts 2004), acts as a natural transport for the eggs and larvae of marine organisms spawning to the west of Cape Agulhas (Hutchings et al. 2009).

The Agulhas Current starts below Madagascar, at roughly 25°S (Lutjeharms 2006), and flows south along the east coast of southern Africa transporting 70-135Sv of water at ~$2m.s^{-1}$ (Roberts 2004), making it a much larger, faster body of water than the Benguela Current. Upon reaching the eastern Agulhas Bank, the Agulhas Current has a volume transport of 60 – 80Sv at $0.2\text{-}0.3m.s^{-1}$, before it retroflects back into the South Indian Ocean (Figure 1.1) (Roberts 2004).

The strongest wind-driven coastal upwelling observed in the Agulhas Bank system occurs on the inner shelf at roughly 22°E (Figure 1.1) (Roberts 2004). It has been inferred that this upwelling occurs near Port Alfred and the upwelled water flows westward, moving shoreward of the Agulhas Current (Roy et al. 2007). The easterly (alongshore) wind, which favours upwelling, occurs from November to April (Roberts 2004, Roy et al. 2007) whereas westerlies dominate in the winter, preventing upwelling (Roberts 2004). The highest levels of primary production occur inshore near Mossel Bay, Tsitsikamma and Algoa Bay (Roberts 2004).

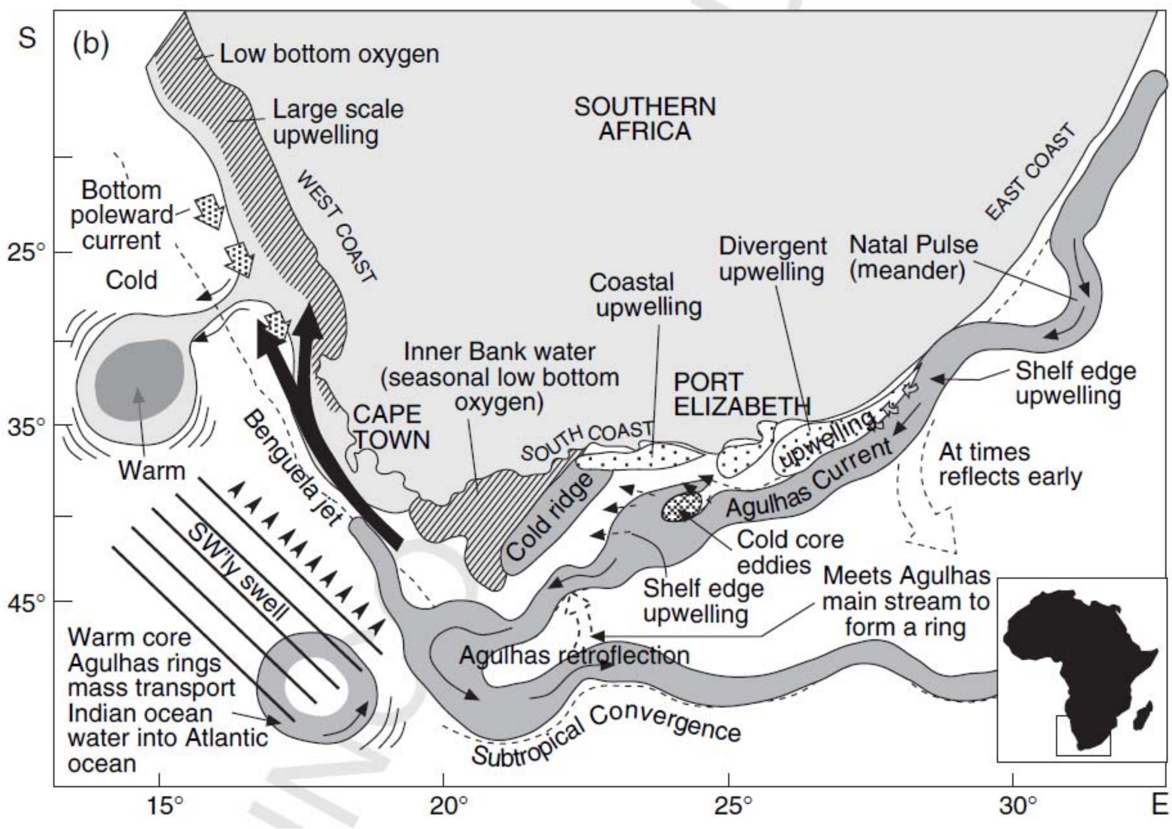


Figure 1.1: Map of southern Africa illustrating many of the locations and phenomena mentioned in the text (after Roberts 2004)

An important, though not fully understood phenomenon occurring in the Agulhas Bank system is the "cold ridge" (Figure 1.1) (Roberts 2004, Hutchings et al. 2009). Likely originating from the wind-driven coastal upwelling cell at roughly 22°E, this tongue of cold water usually lasts for several days to weeks at a time and extends 10-40km offshore with surface temperatures reaching 11-15°C (Roberts 2004). In the absence of offshore advective forces, such as prevailing winds, the ridge is not formed (Roberts 2004). The cold ridge borders the inner shelf flow and outer Agulhas flow along the 100m contour (Roberts 2004). Studies by Miller et al. (2006) and Roberts (2004) have found that the cold ridge may aid in the retention of ichthyoplankton and squid paralarvae on the south coast. This has widespread implications for the impact this feature may have on the lifecycles of other organisms in this ecosystem, specifically small pelagic fish such as anchovy.

Life Cycle

One of the primary spawning grounds for anchovy and sardine, which constitute most (~80%) of the catch for the purse seine fishery in South Africa, is in the ocean bordering the south west corner of the country, between Cape Point and Cape Agulhas (Coetzee et al. 2008). The Benguela jet that moves from here up the coast towards the St. Helena Bay nursery ground is readily available to transport the larvae to where they have historically thrived, making this an ideal spawning ground for adult fish (Coetzee et al. 2008). The larvae that are transported inshore after surviving the 500km voyage to the nursery ground (Huggett et al. 2003) must then contend with fluctuating predation rates, uncertain food availability and uncertain abiotic conditions, such as low oxygen events and warm Agulhas or Angolan water incursions (Hutchings 1998). The larvae that survive to juveniles then make their way back down the coast towards the same spawning grounds that their parents utilized, to begin the cycle anew. This process lasts roughly one year, with anchovy spawning occurring largely from October to February, larvae moving inshore on the west coast during austral autumn and recruitment occurring six to seven months later at a mean caudal length (CL) of 6–9cm (Barange et al. 1999). The recruitment variability and natural mortality in this system are still not well understood (Hutchings et al. 2009) because many variables may affect recruitment success (Hutchings et al. 1998, Huggett et al. 2003). Juvenile and adult anchovy show diel migrations from deeper in the water column during the day up to the top 35 metres of the water column at night where they spread out to feed (van der Lingen et al. 2003).

The small pelagic fish larvae that recruit predominantly to the area near St Helena Bay are successful because of the high abundance of food available there, making this nursery ground important to the success of small pelagics (Hutchings et al. 2009). However, a model created by Miller et al. (2006) showed that two distinct nursery grounds, one on the west coast and one on the south, could potentially be used for recruitment. The west coast nursery ground was identified from the Orange River to Cape Columbine out to the 500m isobath and the south coast nursery ground was identified as the region between Cape Infanta to Plettenberg Bay out to the 500m isobath (Miller et al. 2006). This supports the idea that successful recruitment of small pelagic fish may occur on the Agulhas Bank, even if it is believed to be less productive than the St. Helena Bay nursery ground (Hutchings et al. 1998).

The Agulhas Bank ecosystem is not as productive as the Benguela ecosystem, though it does have less inter-seasonal variability (Roberts 2004). This more stable ecosystem is one in which the large copepod, *Calanus agulhensis*, a key forage item for anchovy, may thrive (Huggett and Richardson 2000). As the most dominant species of large copepod on the Agulhas Bank, *C. agulhensis* represents 53 – 82% of the total copepod biomass found there (Huggett and Richardson 2000). C*alanus agulhensis* reproduces continuously throughout the year and develops faster than other *Calanus* species, with growth rates influenced more by food consumption than ambient temperature (Huggett and Richardson 2000). This species covers a wide range of the Agulhas shelf, though it is continuously being advected to the west and then north, where the old stages are most often found (Huggett and Richardson 2000). The cold ridge, where cyclonic circulation is thought to aid in retention, keeps a large number of *C. agulhensis* over the mid-shelf, where their concentration on the south coast is highest (Huggett and Richardson 2000).

In periods when the cold ridge is weak or non-existent, increased concentrations are found on the west coast (Huggett and Richardson 2000).

The squid *Loligo vulgaris reynaudii* spawns between Plettenberg Bay and Port Alfred (Roberts 2004). The survival of this species depends on the success of the paralarvae, which feed mainly on copepods such as *Calanus agulhensis* (Roberts 2004), the same primary food item for anchovy. A strong link has been found between the strength of the cold ridge in summer, when the paralarvae are developing, and autumn squid biomass (Roberts 2004). This implies that the cold ridge may have a similar positive impact on the success and retention of small pelagic fish larvae on the Agulhas Bank.

Fishery

Knowing what biotic and abiotic variables may affect the success of small pelagics off the coast of South Africa is important because the purse seine fishery employs over 10,000 people, supports 100 purse-seine vessels, has eight fish meal plants, six canning factories and over 40 bait-packing facilities (van der Lingen et al. 2011). The fishery started in the 1940s when fishermen first started targeting sardine off the west coast (van der Lingen et al. 2006a) and escalated quickly until the 1960s when the fishery collapsed, possibly due to overfishing (Coetzee et al. 2008). After the sardine stock collapsed in the 1960s they were replaced by anchovy as the primary catch from 1974 to 1995 (Figure 1.2) (van der Lingen et al. 2006a). The pelagic purse seine fishery in South Africa is responsible for approximately two thirds of all fish landings in the country (Barange et al. 2009). Over the past 50 years the fishery has landed approximately 375,000 tons of fish each year (Fairweather et al. 2006) and is worth approximately US$80 million annually (Barange et al. 1999). Factories that process small pelagic fish began forming around the 1940s (Coetzee et al. 2008), with the majority of the industry that supports the purse seine fishery located near St. Helena Bay (van der Lingen et al. 2011).

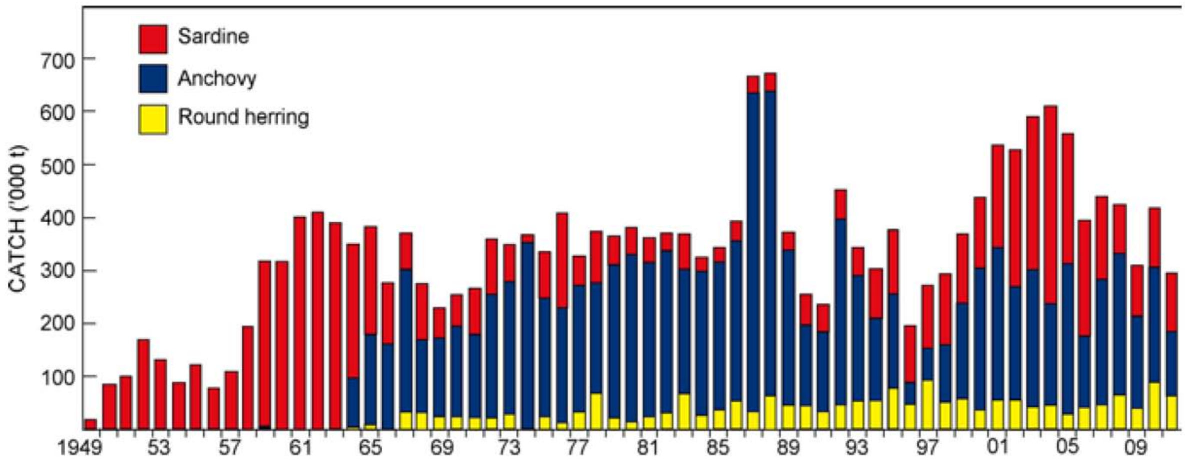


Figure 1.2: Annual catches of South Africa's purse seine fishery for sardine, anchovy and round herring from 1949-2011 (after DAFF Status Report 2012)

The good status of the purse seine fishery is important because of the number of people that derive their livelihood from it, as well as the animals that rely on small pelagics to survive. Sardine, and anchovy to a lesser extent, are an important prey item in the diet of the African penguin (*Spheniscus demersus*) (Sherley et al. 2013), Cape fur seals (*Arctocephalus pusillus pusillus*), Cape gannets (*Morus capensis*) (Hutchings et al. 2009) Cape cormorants (*Phalacrocorax capensis*) (Cury et al. 2000) and many other species. For this reason the southern Benguela ecosystem is sometimes labelled as "wasp-waist" (Cury et al. 2000), meaning that small pelagics exert bottom-up control on their predators while simultaneously exerting top-down control on their prey (Cury et al. 2000). This means that any fluctuations in the populations of small pelagics can have a large impact on the entire food web, rather than just one or two other species (Cury et al. 2000).

Distribution Change

The distribution of anchovy spawner biomass off the coast of South Africa experienced just such a fluctuation when a sudden and dramatic relative increase in spawner biomass to the east of Cape Agulhas occurred in 1996 (Figure 1.3) (Roy et al. 2007). Sardine followed a similar pattern of shifting eastward over the next few years, though the possible causes for this are less clear (Coetzee et al. 2008). For this reason only the geographical change in relative biomass of anchovy is being investigated in this dissertation. Since the initial 1996 change, an average of two thirds of the total anchovy spawner biomass recorded off the coast of South Africa during the annual pelagic spawner biomass acoustic surveys has been found east of Cape Agulhas.

Of the species that rely most heavily on small pelagic fish, the relative increase to the east appears to have had the largest negative impact on African penguins. They have a narrower dietary range than other predators that prey on small pelagics as well as being less mobile during the breeding season, generally being restricted to a nesting island and therefore central place foraging (Sherley et al. 2013). It has also been found that seabird populations in general have been declining while fur seal populations have been increasing (Hutchings et al. 2009). Even though the relative increase of small pelagics to the east of Cape Agulhas has had a large impact on a multitude of species, it is likely that many other factors are also contributing to the health of these populations.

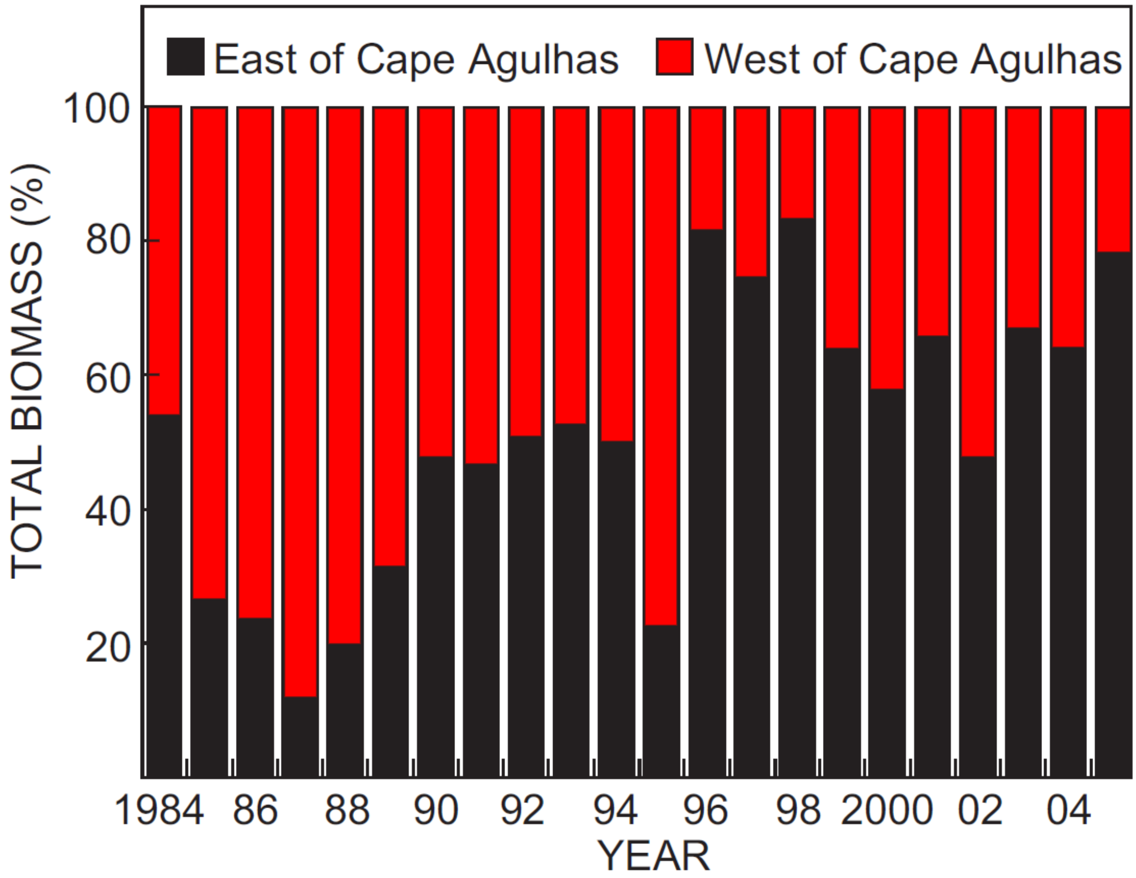


Figure 1.3: The total percentage of anchovy spawner biomass, as detected from the annual pelagic spawner biomass survey, located to the east and west of Cape Agulhas from 1984-2005 (after Roy et al. 2007)

Hypotheses

There are several hypotheses to explain the shift in relative biomass distribution for small pelagic fish. Foremost of these are: fishing pressure, behavioural responses, discrete stocks and environmental variability (Cury 1994, Roy et al. 2007, Coetzee et al. 2008 and van der Lingen 2011). Of these hypotheses, environmental variability is the most likely to have affected anchovy (Roy et al. 2007). However, behavioural mechanisms could also have played a role in attracting and retaining anchovy spawners east of Cape Agulhas.

Well known taxa that exhibit the behavioural mechanisms known as “natal homing”, which causes animals to return to the site of their birth to reproduce, are sea turtles and salmon (Cury 1994). This phenomenon is very common in the animal kingdom and it is believed that anchovy may also experience the urge to return to the conditions in which they were spawned (Roy et al. 2007). Philopatry is the term used to define the process of natal homing over generations, with organisms choosing to reproduce in the same geographic location/ environmental condition (Cury 1994). However, the optimal conditions in which an organism should reproduce are not passed on via a genetic link, but rather through teleonomic imprinting at birth (Cury 1994). The hypothesis known as the “school trap” states that when different schools of fish are shoaling together, the dominant school will direct the shoal (Cury et al. 2000). This would allow dominant schools of fish to alter the philopatry of other, smaller schools.

Large scale abiotic shifts, such as temperature change, have been hypothesized as an important driver for the observed changes in distribution of anchovy spawner biomass (Roy et al. 2007). A study conducted by Blamey et al. (2012) detected significant shifts in wind strength and increases in upwelling strength along the west coast and western Agulhas Bank, using three different statistical methods to identify regime shifts (Blamey et al. 2012). Eastward shifts in the rock lobster *Jasus lalandii* and breeding pairs of the bank cormorant *Phalacrocorax neglectus* were also detected (Blamey et al. 2012). Many of the significant regime shifts detected by Blamey et al. (2012) occurred around a similar time frame as the relative increase in anchovy spawner biomass east of Cape Agulhas. There is also evidence that suggests the prey species composition for small pelagics may change when regimes shift (van der Lingen et al. 2006b). Measuring the lipid content of small pelagics as a metric for condition, van der Lingen et al. (2002)

found that the anchovy to the east of Cape Agulhas had higher lipid content than their western counterparts, implying that the ambient food environment was better east of Cape Agulhas (Roy et al. 2007).

The persistence of the relative increase of anchovy spawner biomass to the east may be due to natal homing, which would have kept the new south coast anchovies returning to their natal homing sites, rather than spawning on the west coast (Roy et al. 2007). This behaviour could have been accelerated by the "school trap" (Cury et al. 2000). As more anchovy were spawned on the south coast, more large schools may have been present to entrap anchovy that would have normally spawned on the west coast. The presence of the cold ridge on the Agulhas Bank may also be a factor in the retention of anchovy spawners on the south coast.

The primary objective of a study conducted by Roy et al. (2007) was to assess the possibility of environmental variability contributing to the relative eastward increase in anchovy spawner biomass that occurred in 1996. The researchers found that a significant shift of roughly 0.5°C in the difference between sea surface temperature (SST) on the inshore and offshore regions of the Agulhas Bank occurred in 1996 and persisted until the end of the time series in 2006 (Roy et al. 2007). This temperature shift was found to have a significant relationship with the increase in relative anchovy spawner biomass east of Cape Agulhas that occurred in the same year (Roy et al. 2007). It was postulated that wind-induced coastal upwelling led to coastal cooling and an increase in favourable conditions to the east, and that this minor change mediated a drastic shift in relative anchovy biomass distribution (Roy et al. 2007). The temperature values used in Roy et al.'s (2007) study were taken from the Optimally Interpolated Sea Surface Temperature (OISST.v2) analysis.

Remotely-sensed Data

OISST.v2 is an ocean temperature data set composed of remotely sensed satellite data and *in situ* buoy and ship data and is made freely available for online download via the NOAA website. The remotely sensed portion of these data are first obtained via the Advanced Very High Resolution Radiometers (AVHRR) aboard the NOAA polar-orbiting satellites (Reynolds et al. 2002). The OISST.v2 algorithm then uses a method of optimal interpolation in which a first-guess, based on the previous week's data, is made before *in situ* data are used to make any necessary corrections (Reynolds and Smith 1994). These *in situ* data, which are drawn from the Comprehensive Ocean–Atmosphere Data Set (COADS) from 1981 to 1997 and the Global Telecommunication System (GTS) from 1998 to present (Reynolds et al. 2002), are subjected to a series of quality controls and weighting before being used (Reynolds and Smith 1994). However, uncertainties and biases in the *in situ* data complicate the processing of the remotely-sensed data (Reynolds et al. 2002). For the *in situ* data used in OISST.v2, the global average error for ship data is 1.3°C, whereas that for buoy data is 0.5°C, making buoys more valuable for the interpolation process (Reynolds et al. 2002). Thanks to the current global effort to expand *in situ* coverage of the oceans, the presence and number of buoys have been increasing, whereas ships' data have decreased (Reynolds et al. 2002). A minimum of five *in situ* data points per 2° longitude/ latitude grid are required for the data to be flagged as good (Reynolds and Marsico 1993). The final product is a "bulk" surface temperature as it reflects the ocean temperature of the upper 0.5 metres (Reynolds et al. 2002).

Whereas OISST.v2 is a very powerful tool, it does have its weaknesses. Even though the data are available at a daily temporal resolution (Reynolds and Smith 1994), most research is conducted with the weekly or monthly mean products. This ensures a more complete analysis of the 1°x1° gridded product by filling gaps caused by interference from cloud cover and other atmospheric aerosols, which may lead to significant biases (Smith et al. 2002). High error regions are usually found within western boundary currents. However, the coast of southern Africa, with the Agulhas Bank at its centre, is one of the regions of greatest error on the planet, with an average error of 0.5°C (Reynolds and Smith 1994), potentially due to the lack of ARGO floats in this region. Besides this potential source of error, OISST.v2 also has a slight bias of -0.05°C, which comes mostly from a strong negative bias found from 30-60°S (Reynolds et al. 2002).

Even though the OISST.v2 algorithm may have difficulty detecting sharp gradients and short term mesoscale features, it has repeatedly been found to be more accurate than other remotely-sensed data sets, specifically MODIS (Terra and Aqua), HadISST and EFRSST.v3 (Smith et al. 2002, Hurrell et al. 2008, Hughes et al. 2009, Smale and Wernberg 2009). Recent studies have shown that, besides the aforementioned difficulties, these remotely-sensed data sets also struggle with coastal temperature measurements (Kilpatrick et al. 2001, Hughes et al. 2009, Smale and Wernberg 2009, Castillo and Lima 2010, Hutchings et al. 2012, Smit et al. 2013). It is for this reason that many of these authors strongly recommend the use of *in situ* data when investigating the effect of temperature on coastal ecosystems even though *in situ* data may show potential biases towards local phenomena at the point of measurement.

Several studies have compared remotely-sensed data sets with varying types of *in situ* data with varying focuses. A study conducted by Donlon et al. (2002) compared *in situ* ship data to hull-mounted AVHRRs. They found that a wind speed of at least 6m.s^{-1} strengthened the correlation between these two measurements because water temperatures can vary by up to 2°C within the first several meters from the surface. Hughes et al. (2009) noted that, whereas the gridded OISST.v2 data set has much better global resolution than any *in situ* data set alone, the larger the temperature variability within a 1°x1°gridded area the less it correlated with single *eulerian in situ* measurements from the same region. Smale and Wernberg (2009), using an Australian derivation of AVHRR data, found the remotely-sensed data to be significantly warmer than the nearshore *in situ* data by 1 to 2°C. A study conducted by Castillo and Lima (2010), in which the authors matched the times of their remotely-sensed data (MODIS Aqua/ Terra) to their *in situ* data, found that the remotely-sensed data were significantly colder by 1°C. These studies help to illustrate the fact that few consistent results are to be found in the literature concerning the comparison of remotely-sensed and *in situ* data. What is clear, however, is that using *in situ* data in studies of temperature change in coastal ecosystems to verify the remotely-sensed data set used is an important step that is often overlooked. It is the aim of this project to provide this *in situ* verification of the study conducted by Roy et al. (2007).

Project

There are many tools used to collect *in situ* data in South Africa. Underwater temperature recorders (UTRs) produce high temporal, low spatial resolution data, and several have been deployed along the coast and used since the early 1990s. There are two UTRs located in the region where upwelling is believed to link to the cold ridge.

These have been producing data at an hourly rate from the early 1990s, more or less consistently, until the present day. The data produced by these UTRs can be averaged into monthly means to be used as a measurement for inshore *in situ* temperature, providing an indication of temperatures at the primary upwelling site on the Agulhas Bank (Roberts 2004).

The annual small pelagic spawner biomass survey has been carried out from Hondeklip Bay to Port Alfred since 1984 (Coetzee et al. 2008). Many *in situ* measurements are made during these surveys and a detailed description of the methods employed can be found in Barange et al. (1999). CTD measurements, which are known to be very accurate though sparse, can be used to correct the more numerous, less accurate temperature data generated by the temperature probe mounted on California Vertical Egg Tow (CalVET) nets. Once standardized, these two *in situ* data sources can be combined to form a predicted *in situ* CTD (PISCTD) data set of high spatial resolution to more accurately depict the changing temperatures of the coastal and offshore Agulhas Bank region. These PISCTD data are created from *in situ* temperature data taken from the same cruise that generates the data used to calculate the relative distribution of anchovy spawner biomass along the coast of South Africa.

The Agulhas Bank is a complex region and it is difficult to extract strong abiotic signals from the background noise (Hutchings et al. 2009). In addition, it is possible that sardine and anchovy are influencing each other via school traps (van der Lingen 2006b), leading to a shift in natal homing (Cury 1994), or vice versa. Given these multiple levels of complexity, it can be difficult to identify which variables are affecting the increase of relative anchovy spawner biomass east of Cape Agulhas (Roy et al. 2007) and which hypotheses developed to explain the phenomenon are most plausible. The results of Roy et al. (2007) show that an abiotic shift may be responsible for, or at least related to, this eastward distribution shift. However, their results were generated using satellite data that have since been shown to be less accurate than previously believed (Kilpatrick et al. 2001, Hughes et al. 2009, Smale and Wernberg 2009, Castillo and Lima 2010, Hutchings et al. 2012, Smit et al. 2013). It is for this reason that this project aims to use UTR and PISCTD data to verify the findings of Roy et al. (2007).

Chapter 2
Project

Comparing *in situ* and satellite temperature data on the Agulhas Bank to understand changes in anchovy (*Engraulis encrasicolus*) distribution

Introduction

For almost three decades satellite data have been commonly used in studies to understand the oceans and in particular have been used to compare the performance of models and generate long term data time series (e.g. Rouault et al. 2010). A major advantage of satellite measurements is that they quickly cover the globe almost synoptically unlike *in situ* measurements, which rely on ships, gliders and buoys that are very slow and limited in their spatial coverage. Consequently satellite data have become indispensable. Recent studies however have shown that, in coastal regions and areas of strong upwelling, the algorithms that are used to process satellite data often show significantly warmer or cooler temperatures when compared against *in situ* data, implying a bias in the data and leading many authors to conclude that these data should be used with caution and compared to *in situ* data when possible (Hughes et al. 2009, Smale and Wernberg 2009, Castillo and Lima 2010, Dufois et al. 2012, Smit et al. 2013).

In particular, Smit et al. (2013) have shown that, when comparing Pathfinder v5.2 sea surface temperature (SST) data against underwater temperature recorder (UTR) data along the entire coast of South Africa, the satellite data were almost always significantly warmer than the UTRs, with the warm bias on the Agulhas Bank almost reaching 3.5°C. Other studies comparing different types of *in situ* data to several different remotely-sensed data sets around the world have similarly found warm or cold biases, with the only commonality between the investigations being that Reynolds Optimally Interpolated Sea Surface Temperature (OISST.v2) data correlated the strongest with the different *in situ* data sets used (Hurrell et al. 2008, Hughes et al. 2009, Smale and Wernberg 2009, Castillo and Lima 2010)

Roy et al. (2007), using OISST.v2 data, found a significant positive relationship between the size of the cross-shelf SST difference (offshore – inshore) of the Agulhas Bank and the relative anchovy (*Engraulis encrasicolus*) spawner biomass east of Cape Agulhas. These findings have not been validated with *in situ* temperature data. Understanding what could have contributed to this increase in relative biomass east of Cape Agulhas is important because the shift happened so quickly and has persisted for almost 20 years.

I hypothesized that the decadal-scale increase in the cross-shelf SST difference on the Agulhas Bank displayed in the OISST.v2 data, as described in Roy et al. (2007), would also be observed with *in situ* data from the same region and that the *in situ* data would also show a positive relationship with the eastward shift in anchovy spawner biomass. It was also hypothesized that, whereas the *in situ* data sets used in this study would not show the exact same trends as the OISST.v2 data, they would be expected to be well correlated.

Three separate sources of *in situ* temperature data were used for this study: CTD, California vertical egg tow (CalVET) nets and UTRs at Knysna (UTR K) and Tsitsikamma (UTR T). None of these sources alone have the temporal and spatial consistency of OISST.v2 data, but can be used together to show coastal and nearshore temperatures on the Agulhas Bank. Using these data sets, I investigated the cross-shelf temperature difference of the Agulhas Bank to the east of Cape Agulhas and how it related to the change in relative distribution of anchovy spawner biomass.

Material and Methods

Study Area

Following Roy et al. (2007), the Agulhas Bank was divided into four different subdomains (Figure 2.1).The coastal subdomains in this study extend from 34 to 35°S The western Agulhas Bank coastal (WABC) subdomain is situated between 19 to 20°E, the central Agulhas Bank coastal (CABC) subdomain extends from 20 and 22°E and the eastern Agulhas Bank coastal (EABC) subdomain from 22 to 23°E. The central Agulhas Bank offshore (CABO) subdomain covers the area between 35 to 36°S and 20 to 22°E. It was necessary to divide the Agulhas Bank into 1°x1° blocks for analysis as this was the finest resolution at which the OISST.v2 data were available.

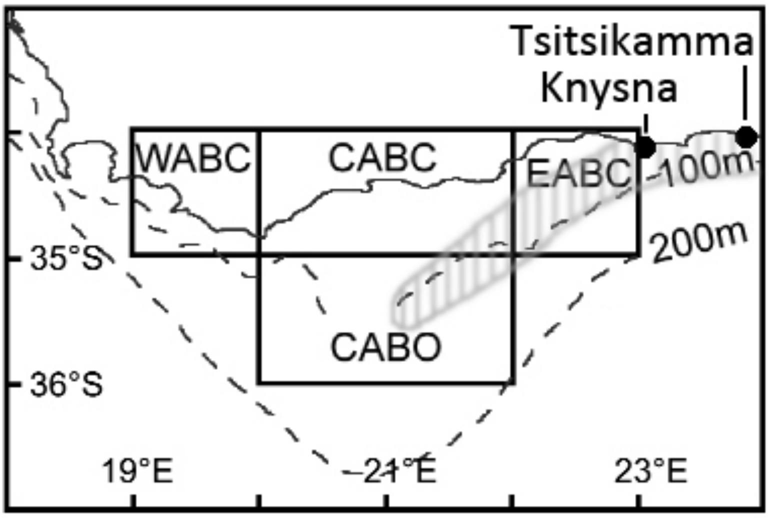


Figure 2.1: The study area on the Agulhas Bank. The UTRs at Knysna (UTR K) and Tsitsikamma (UTR T) are represented with black dots with the cold ridge roughly outlined in grey (modified after Roy et al. 2007)

Abiotic Data

The remotely-sensed temperature data used in this study are the NOAA OISST.v2 monthly product that can be downloaded from the National Centers for Environmental Prediction (NCEP) Climate Prediction Center (Reynolds and Smith 1994, Reynolds et al. 2002). These data are available in a weekly format from November 1981 to one month before the present date at a global 1°x1° resolution. The weekly data are then used to produce a monthly product (Reynolds et al. 2002). One day resolution and 1/4° grid products are also available. However, for the purposes of better verifying the results obtained by Roy et al. (2007) the monthly 1°x1° resolution data were used.

The CTD and CalVET net data were collected during the annual pelagic spawner biomass surveys that are conducted in spring (late October to early December) by the Department of Agriculture, Forestry and Fisheries (DAFF; formerly Marine and Coastal Management (MCM)). These surveys conduct randomly-placed cross-shelf transects from inshore (roughly 20m depth) to the edge of the continental shelf (200m) and occasionally beyond (Coetzee et al. 2010). A description of the methods for using hydroacoustics along these transects to estimate fish abundance can be found in Barange et al. (1999). Environmental data are collected along some, but not all transects, every 10 nautical miles by deploying CTD and/ or CalVET nets with temperature sensors attached (van der Lingen and Huggett 2003, Coetzee et al. 2010).

For the study area of the Agulhas Bank, most years have 30–40 stations in which CTD temperatures are taken at 5m depth, with 2001- 2003 having upwards of 100 per year. Generating temperature recordings to the third decimal place, these data are considered to be the most accurate of all the *in situ* data generated in South Africa and, though sparse, are used as a metric against which the CalVET net data are compared. The values used to create the temperatures for each subdomain were chosen from the 5m depth because the CTD is no longer influenced at this depth by surface disturbances such as waves and chop experienced during its deployment.

A CalVET net is used during the annual pelagic spawner biomass survey to conduct an ichthyoplankton survey (van der Lingen and Huggett 2003). This instrument has a mounted temperature recorder that is accurate to the first decimal place. These temperature data are collected on most stations during the annual pelagic spawner biomass cruise with each year having roughly 300 temperature profiles recorded within the study area of the Agulhas Bank. These data are taken from the same 5m depth as the CTD data and are used to generate a higher spatial resolution data set of surface temperatures on the Agulhas Bank than provided by the CTD temperature data alone.

The two UTRs used in this study are located at Knysna (34°01'22"S, 23°53'58"E, 7m depth) and Tsitsikamma (34°04'34"S, 23°03'36"E, 10m depth). The UTRs are monitored and serviced by the Department of Environmental Affairs (DEA) at least annually. The data from UTR K start in January 1990 and those from UTR T start in July 1991. The data are collected hourly and have been averaged into days and then months. These two sites are located in a region of the Agulhas Bank where coastal wind-driven upwelling is strongest (Roberts 2004). A summary of the abiotic data used in this study can be found in Table 2.1.

The period of study for the change in distribution of anchovy spawner biomass is 1986 to 2005. This 20-year period evenly covers the observed shift, which occurred in 1996 (Figure 2.2). Analysing the data in this way allows for the decades before and after the shift to be compared. The annual OISST.v2 and UTR time series used in this study are available from January – December (hereafter Jan-Dec) whereas the *in situ* data generated during the annual pelagic spawner biomass survey are only available from late October to early December. To make up for this inconsistency, mean temperatures for the months of October – December (hereafter Oct-Dec) have been estimated from the OISST.v2 and UTR time series.

All three of these data sets measure the ocean in different ways so it is important to keep in mind that a direct comparison is ill advised. The OISST.v2 data represent a broad, though synoptic picture of the Agulhas Bank. The resolution is low but the consistency is high, due to the monthly means and broad synoptic sampling. The PISCTD data provide a high spatial resolution image of the Agulhas Bank, whereas the temporal resolution is low. It must also be considered that it may take more than two months to collect the data used to show the temperature on the Agulhas Bank and that while sampling mesoscale features may have a disproportionately large impact on the final mean. The UTRs give a long term annual *in situ* reading of the areas in which they are moored, but these areas are very shallow, well inshore from the typical spawning and hunting grounds of anchovy, and the readings are highly exposed to effects from local temperature phenomena. It is important to understand the strengths and weaknesses of these different data sets to fully understand the relevance they have towards the question of an environmentally mediated shift in anchovy spawner biomass.

Table 2.1: An overview of the three different data sets used in this study. Note the years of "Available Data" for UTR K and UTR T

Data Type	Frequency	Time of Year	Values/ 1°x1° grid	Precision of Measurement	Available Data
OISST.v2	Monthly	January - December	1	0.01°C	1986 – 2005
PISCTD	Daily	October – December	4 – 35	0.1°C	1986 – 2005
UTR	Hourly	January - December	1	0.01°C	K: 1990 – 2005 T: 1991 – 2005

Biotic Data

The anchovy spawner biomass data used in this study were obtained from the same annual acoustic spawner biomass surveys from which the CTD and CalVET net temperature data were obtained; the time period for these data sets match exactly each year. Details of the methods employed to create the spawner biomass estimates can be found in Barange et al. (1999). These biotic data contain spawner biomass in five or six strata (i.e. geographic ranges) depending on the year. The boundaries of these strata have been consistent since the 1988 spawner biomass survey, and for years 1986 and 1987 I used the notes attached to the data to find which strata were correct to match the rest of the data set. The first three strata (Hondeklip Bay to Cape Agulhas) have been combined to represent the percentage of anchovy spawner biomass to the west of Cape Agulhas while the fourth and fifth strata (Cape Agulhas to Port Elizabeth/ Port Alfred) have been combined to represent the percentage of relative spawner biomass to the east of Cape Agulhas (Figure 2.2).

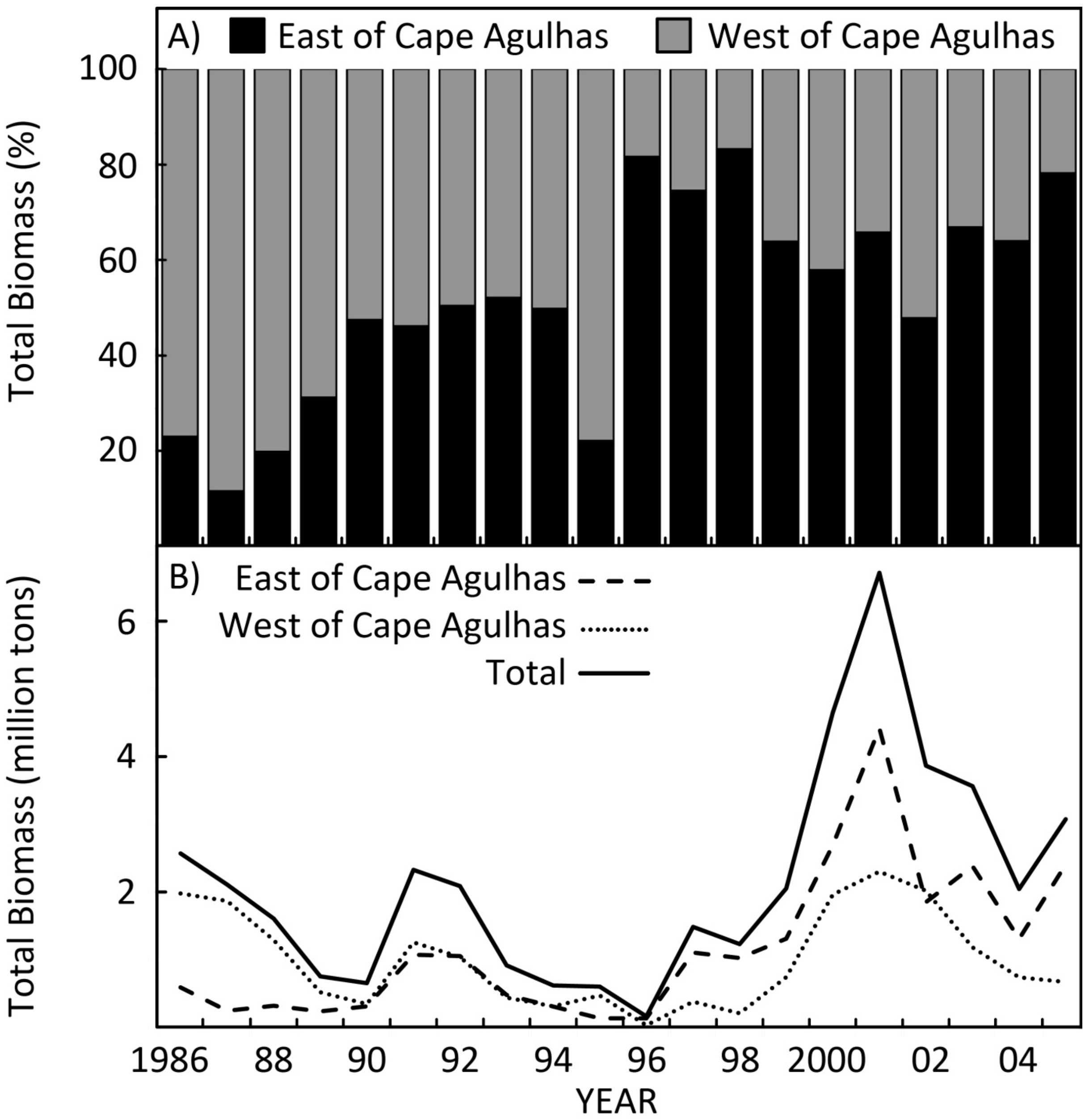


Figure 2.2: A) The percentage of anchovy spawner biomass east (black bars) and west (grey bars) of Cape Agulhas estimated from the annual pelagic spawner biomass surveys conducted from 1986 to 2005, B) The biomass (metric tons) of anchovy along the coast of South Africa with the dashed line representing the biomass of anchovy detected east of Cape Agulhas, the dotted line representing the biomass detected to the west of Cape Agulhas and the solid line representing the total biomass detected along the entire coast (data courtesy J. Coetzee, DAFF)

Methods

The temperature data collected with the CalVET net were compared to the CTD temperature data from the same stations (both within and outside the study area of the Agulhas Bank) at 5m depth to create a common data set for fitting a GLM, correcting the CalVET net data to the more accurate CTD data with one common line of best fit with individual intercept corrections for each year. The corrected CalVET net data were then merged with the CTD data to create a larger "predicted *in situ* CTD" (PISCTD) data set. All data points within this new data set were divided into the appropriate subdomains of the Agulhas Bank (Figure 2.1) using their longitude/ latitude flags and averaged to produce one mean temperature value for each subdomain per year.

A standard t-test comparing temperatures in the first (1986-1995) and second (1996-2005) decade of the time series was used for each subdomain from each data set to examine whether a shift in temperature had occurred. The Oct-Dec mean temperatures for the OISST.v2 data set were compared against those for the PISCTD data set to measure correlation between these two types of data. The UTR data were only correlated with temperatures from the EABC for the other two data sets as this is the closest subdomain to the two UTRs. The cross-shelf difference for each dataset was calculated by subtracting the mean temperatures in each year for the inshore subdomain from the offshore subdomain (e.g. CABO-WABC, etc.). The Oct-Dec mean values for the UTR and OISST.v2 data sets, rather than the Jan-Dec means, were used to calculate this difference. These values were then correlated with relative anchovy biomass (%) east of Cape Agulhas to calculate the strength and direction of the relationship between temperature and biomass.

Results

Temperature Corrections

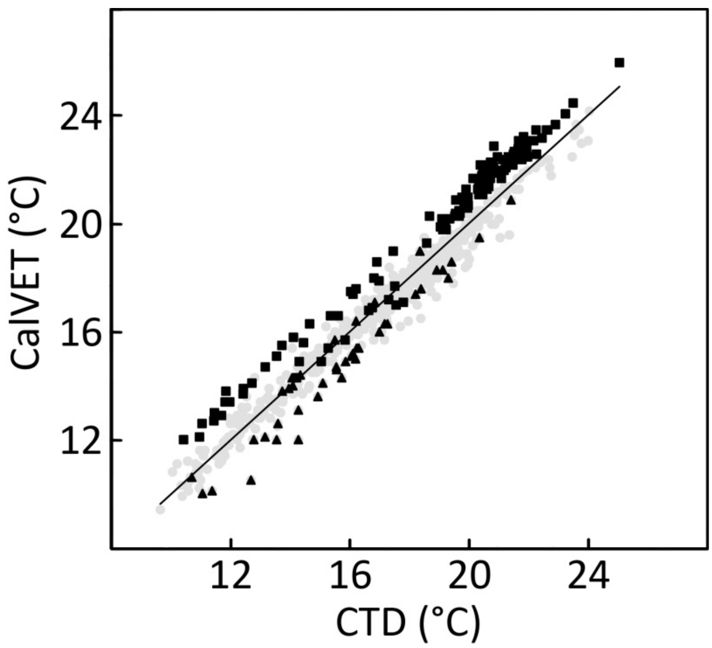
The results of the general linear model (GLM) used to correct the CalVET data to the CTD data showed that the two data sets were very similar (Figure 2.3). The slope of the GLM was 0.99 with 14 of the 20 years requiring a positive adjustment of 0–0.32°C to match the CTD on an annual basis. The largest outliers were the year 2004 (-0.95) and 2000 (+0.77°C). These two years of data are highlighted in Figure 2.3B. CTD data for 1986, 1988, 1989 and 1997 are not available.

Figure 2.3: A) The results of a GLM showing the annual intercept values for the CalVET net temperature data set corrected against the CTD data set. The slope is 0.99 and the results are significant to $p<0.01$. B) Scatterplot of CalVET and CTD temperature data (°C). The year 2000 is highlighted with black triangles and 2004 with black squares

A)

Year	Intercept	n
1986	0.06	0
1987	0.25	25
1988	0.06	0
1989	0.05	0
1990	0	41
1991	0.19	86
1992	0.25	69
1993	0.26	60
1994	0.22	26
1995	0.18	25
1996	-0.13	52
1997	0.06	0
1998	0.11	21
1999	-0.34	20
2000	0.77	42
2001	0.17	61
2002	0.05	122
2003	0.32	161
2004	-0.95	128
2005	-0.38	17

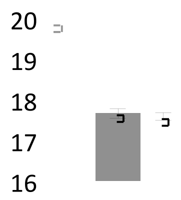
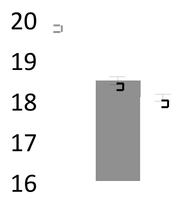
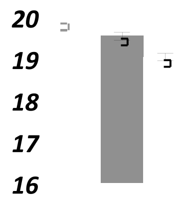
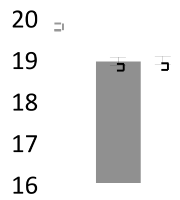
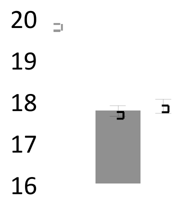
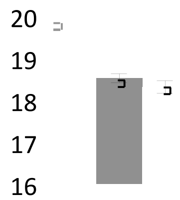
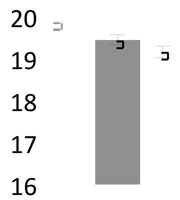
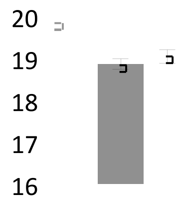
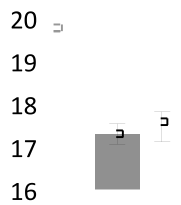
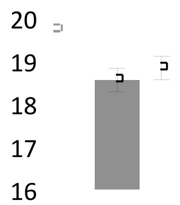
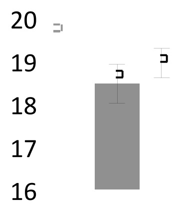
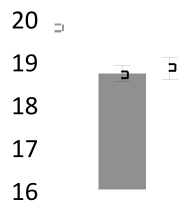
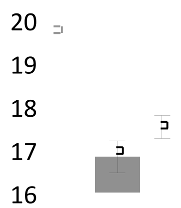
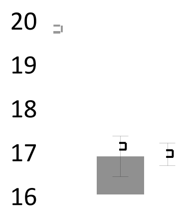
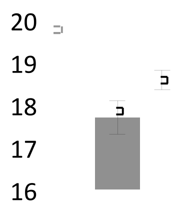
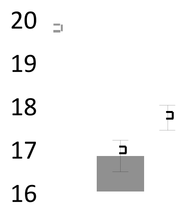
B)



Decadal Trends

It can be seen in Figure 2.4 (Appendix Table A.1) that the mean decadal temperatures for both the Jan-Dec and Oct-Dec means differ among the three different data sets. The Jan-Dec mean OISST.v2 values initially showed significant cooling in the CABC and the EABC of approximately 0.5°C between the first and second decade. However, a sequential Bonferroni procedure, used to determine the significance for multiple tests, showed that only the cooling detected on the EABC was significant. There is less cooling in the WABC while the CABO changes very little between decades. Unlike the Jan–Dec mean values, the Oct–Dec mean values show no significant shifts between the two decadal periods for any of the subdomains, though a similar pattern of cooling occurs. The PISCTD data for all four subdomains show a warming trend between the first and second decades with the EABC showing the strongest warming at 0.4°C, but none of these changes were significant. A power analysis of these results revealed that the CABC had the smallest sample size required for a target power of 0.80 at 276 years. Detailed power analysis results may be found in the appendix (Table A.2) The temperature data from the UTRs show warming between decades, though none of these changes were significant.

Figure 2.4: The Jan-Dec and Oct–Dec decadal temperature values from all three data sets showing standard error bars, with a Y-axis of 16-20°C for all subdomains. 1986-1995 is shown in grey and 1996-2005 in white. Note that the UTR K time series starts in 1990 and UTR T starts in 1991. Significant results are shown in bold italics

Data Set	Subdomain			
	WABC	CABC	*EABC*	CABO
OISST.v2 Jan-Dec				
OISST.v 2 Oct-Dec				
PISCTD Oct-Dec				
	K	T		
UTR Jan-Dec				
UTR Oct-Dec				

The Jan-Dec SST means from the OISST.v2 data set show 1996 was the coldest year with 1992/93 the warmest for all four subdomains (data not shown). The coldest year for the Oct-Dec mean values remains 1996 but the warmest year shifts to 2004 for all four subdomains (Figure 2.5). The average difference between the warmest and coldest years for all subdomains for the Oct-Dec mean values is 1.64°C.

2004 was also the warmest year for three of the subdomains in the PISCTD data set but 1994 was the warmest year for the EABC (Figure 2.5). The coldest years were 1988 for the CABC and EABC, 1989 for the WABC and 1987/96 for the CABO. The average difference between the warmest and coldest years for all PISCTD subdomains was 3.7°C, with the mean EABC temperatures fluctuating 5.1°C within the 20 year period. The PISCTD data show large variability within each subdomain, with the WABC showing the largest amount of variability. During most years the temperatures in the WABC varied by 2°C across the 1°x1° subdomain but in 2000 the temperatures varied by up to 7.5°C. The other subdomains had temperature ranges of 1-2° C difference within each year. The coldest year for the Jan-Dec and Oct-Dec mean values for both the UTR time series was 1995, with 2004 being the warmest (Figure 2.5). The difference between the warmest and coldest Oct–Dec mean values for UTR K was 3.5°C and UTR T 3.3°C.

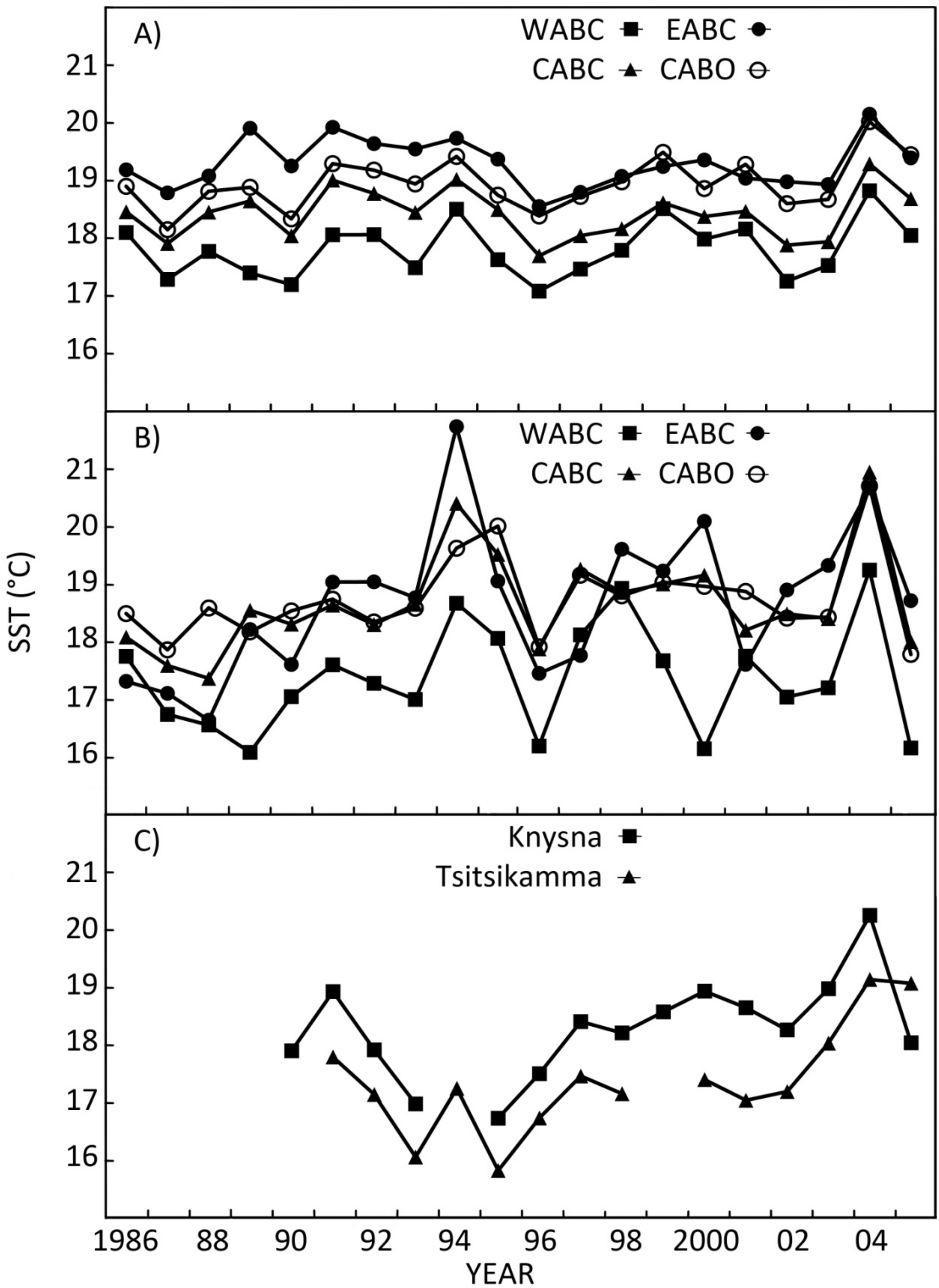


Figure 2.5: Mean temperature time series for the four subdomains of the Agulhas Bank from 1986 to 2005 A) OISST.v2, B) PISCTD, C) UTRs. All means were calculated using Oct-Dec data

Cross-shelf Difference

In both the Jan-Dec and Oct-Dec OISST.v2 data sets, when the temperature values for each of the three inshore subdomains (WABC, CABC, EABC) were subtracted from the offshore subdomain (CABO) for all 20 years, a decadal increase was found (Figure 2.6A), meaning that the difference between the inshore and offshore temperatures increased. The CABO-WABC shows the smallest difference at roughly 0.1°C. The CABO-CABC and CABO-EABC both show an increase of almost 0.5°C. However, the CABO-CABC has the least interannual variability with 1995/96 having the largest fluctuation at 0.44°C, whereas the CABO-EABC has the largest interannual variability of all three cross-shelf differences with the greatest interannual fluctuation reaching 0.75°C between 1988/89.

When compared against the CABO in the PISCTD data set, the CABC and EABC show a decrease in the strength of the cross-shelf difference between decades of 0.2° and 0.4°C respectively, whereas the WABC shows less than a 0.1°C decrease (Figure 2.6B). The PISCTD cross-shelf difference time series show more interannual variability than the OISST.v2 values though the order in which the magnitude of variability occurs is the same, with the CABO-CABC showing the least interannual variability and the CABO-EABC the most. The largest fluctuation in the CABO-CABC time series occurs in 1988/89 at difference of 1.6°C, whereas the greatest interannual fluctuation for the CABO-EABC cross-shelf difference occurs between 1994/95 at 3.1°C. When compared against the PISCTD CABO values, a decrease in the temperature of the offshore region against the temperature for UTR K of 0.93°C was detected while UTR T showed a decrease of 1.16°C (Figure 2.6C).

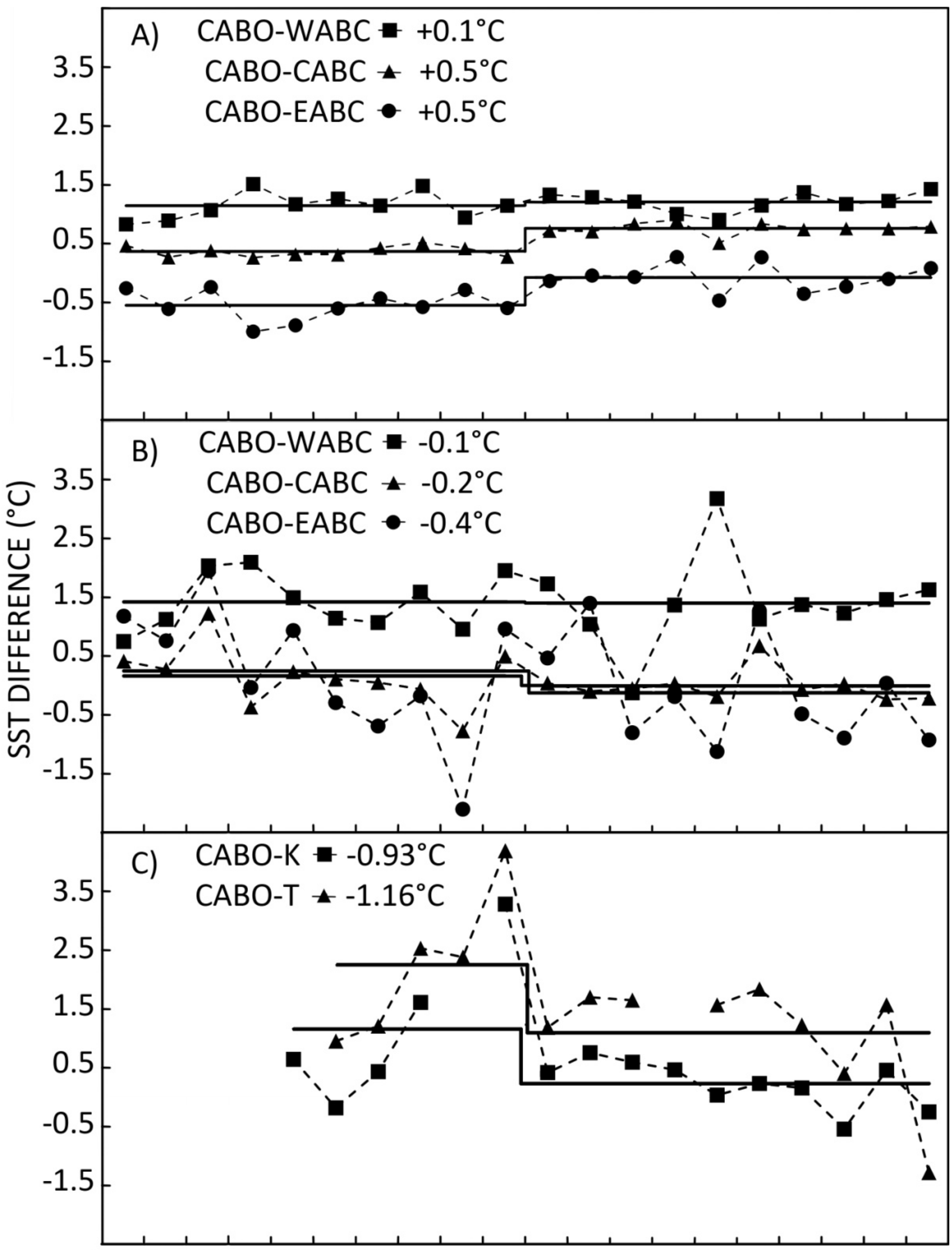
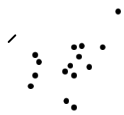
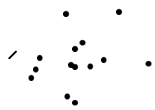


Figure 2.6: Annual temperature (°C) difference (dashed lines) between the offshore surface temperature of the Agulhas Bank (CABO) and the three inshore subdomains (WABC, CABC, and EABC) for the Oct-Dec mean values from 1986 to 2005. Decadal averages are shown as solid lines. A)OISST.v2, B) PISCTD, C) The nearshore difference generated by subtracting the temperatures from UTR K and UTR T from the PISCTD values for the CABO for 1990/91 to 2005

Correlations

The temperature values for each O–D mean OISST.v2 subdomain over the 20 year time series showed significant positive correlations with their PISCTD counterparts until a sequential Bonferroni procedure was applied (Figure 2.7). The UTRs were compared to the EABC temperature values for the OISST.v2 and PISCTD data sets as this was the subdomain closest to these two *eulerian* instruments. Whereas neither of the Oct-Dec mean temperature values for UTR K or UTR T show a significant correlation with the Oct-Dec OISST.v2 or PISCTD values for the EABC, the UTRs show a strong significant positive correlation with each other (Figure 2.7).

Figure 2.7: Correlation matrices for the Oct-Dec values of the three data sets showing the line of best fit, r, p, (n) and the subdomain compared. Y and X axis are 14-22°C. Significant results are shown in bold italics

Data set	PISCTD	UTR K	UTR T
OISST.v2	0.55, 0.01 (20) WABC  0.55, 0.01 (20) CABC  0.57, 0.01 (20) EABC  0.55, 0.01 (20) CABO 	0.34, 0.22 (15) EABC 	0.32, 0.27 (14) EABC 
PISCTD		0.50, 0.06 (15) EABC 	0.27, 0.35 (14) EABC 
UTR K			***0.78, <0.01 (13)*** 

Eastward Shift in Anchovy Spawner Biomass

All three temperature data sets show a different relationship with the biomass data set (Figure 2.8). The Oct-Dec OISST.v2 data set alone shows a significant positive relationship between the CABO-CABC cross-shelf SST difference and the percentage of anchovy spawner biomass east of Cape Agulhas (Figure 2.9). The CABO-CABC values from the PISCTD data show a negative relationship but this is not significant. The percentage of anchovy biomass east of Cape Agulhas has a significant negative relationship with the inshore warming shown by the UTR K and UTR T data sets during the Oct–Dec period.

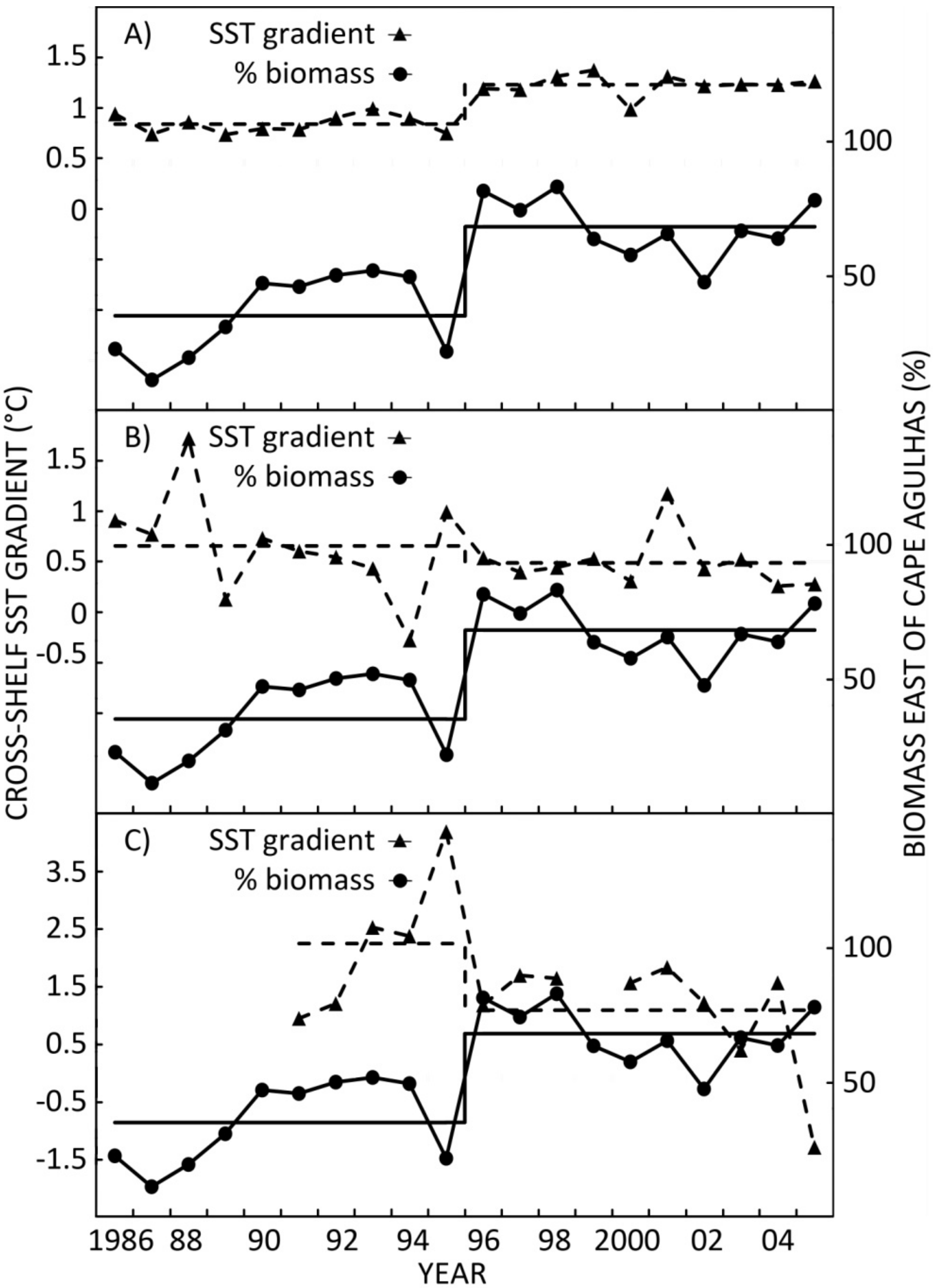


Figure 2.8: Time series showing the cross-shelf temperature difference on the central Agulhas Bank (CABO-CABC) during spring (October-December) from 1986 to 2005 and the percentage of anchovy spawner biomass located east of Cape Agulhas during the annual pelagic spawner biomass surveys. Decadal means are shown as straight lines; A) OISST.v2, B) PISCTD, C) UTR T from 1991 to 2005 with 1999 missing

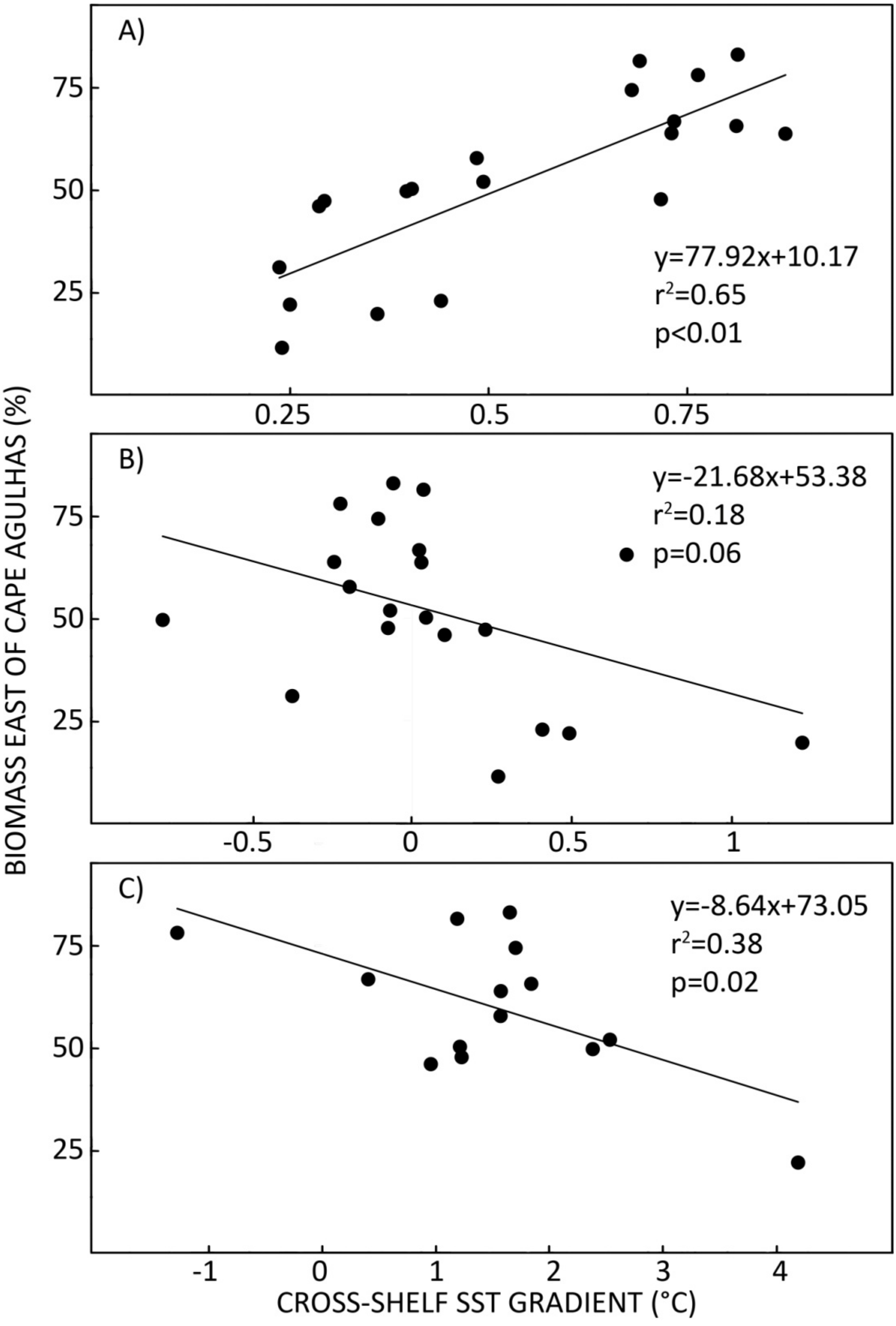


Figure 2.9: Scatterplots showing the percentage of anchovy spawner biomass east of Cape Agulhas against the cross-shelf temperature difference (CABO-CABC) on the central Agulhas Bank during spring (October-December) from 1986 to 2005; A) OISST.v2, B) PISCTD, C) UTR T

Discussion

I investigated whether *in situ* temperature data could be used to validate the hypothesis of Roy et al. (2007), which states that the abrupt eastward shift in anchovy spawner biomass distribution that occurred in 1996 was environmentally mediated. Those authors showed, using OISST.v2 data, a significant positive relationship between the cross-shelf SST difference on the central Agulhas Bank and the proportion of anchovy spawner biomass found to the east of Cape Agulhas.

It was found that the PISCTD data set created for this study did not correlate significantly with the Oct-Dec OISST.v2 data set and did not have a positive relationship with the proportion of anchovy spawner biomass east of Cape Agulhas. The PISCTD data did not show a significant negative relationship with the biomass data, but they did show a negative trend. This was an unexpected result as it was hypothesised that the PISCTD and OISST.v2 data sets would correlate with each other. Upon closer inspection, it becomes clear that the decadal trends of these two data sets do not match up (Figure 2.4, Table A.1). The Oct-Dec OISST.v2 data show a decrease in temperatures for the CABC and EABC with an increase in the strength of the cross-shelf SST difference between decades, whereas the PISCTD data show the opposite. Both Oct-Dec UTR data sets, which only correlated significantly with each other, showed significant negative relationships between the proportion of anchovy spawner biomass east of Cape Agulhas and the cross-shelf temperature difference on the Agulhas Bank. The UTR data sets showed this significant negative relationship because of the warming trend shown between the two decadal periods, which was larger than the warming trend the PISCTD data detected (Figure 2.4, Table A.1). This finding implies that anchovy spawner biomass is greater on the Agulhas Bank when inshore temperatures are warmer and contradicts Roy et al. (2007).

This study has been limited by the temporal availability of the *in situ* data used. Whereas the CTD data and CalVET net data allow accurate temporal comparisons with the anchovy spawner biomass, they cannot be compared to the OISST.v2 or UTR data sets on a 12 month annual basis. Thus the October – December (Oct-Dec) mean values were created for these two annual data sets. The spatial resolution of the CTD data was very poor but this was largely overcome by merging with the CalVET net data set, producing the PISCTD values. These two *in situ* sources were collected from aboard a ship and therefore cannot be used to represent a single value for each subdomain over spring (late October to early December), as accurately as with the Oct-Dec OISST.v2 data. Shipboard data more accurately represent events that occur at the time of sampling than they do long term means, whereas remotely-sensed data, such as the OISST.v2 data set, are more suited to showing a mean value over a large area because these data are synoptically collected (Figure 2.10). The UTRs were used to address this problem as they provide a long, high resolution time series of *in situ* data to be compared against the OISST.v2 data at one set point. Even though this allowed for 12 month and three month annual comparisons, the UTRs do not have the spatial resolution necessary to draw a proper comparison for an entire subdomain. Also, the very close proximity to shore may result in other signals being represented in the temperature values other than upwelling, such as the warmer lagoon water seen for UTR K (Figure 2.5), making UTR T a better indicator of coastal temperature.

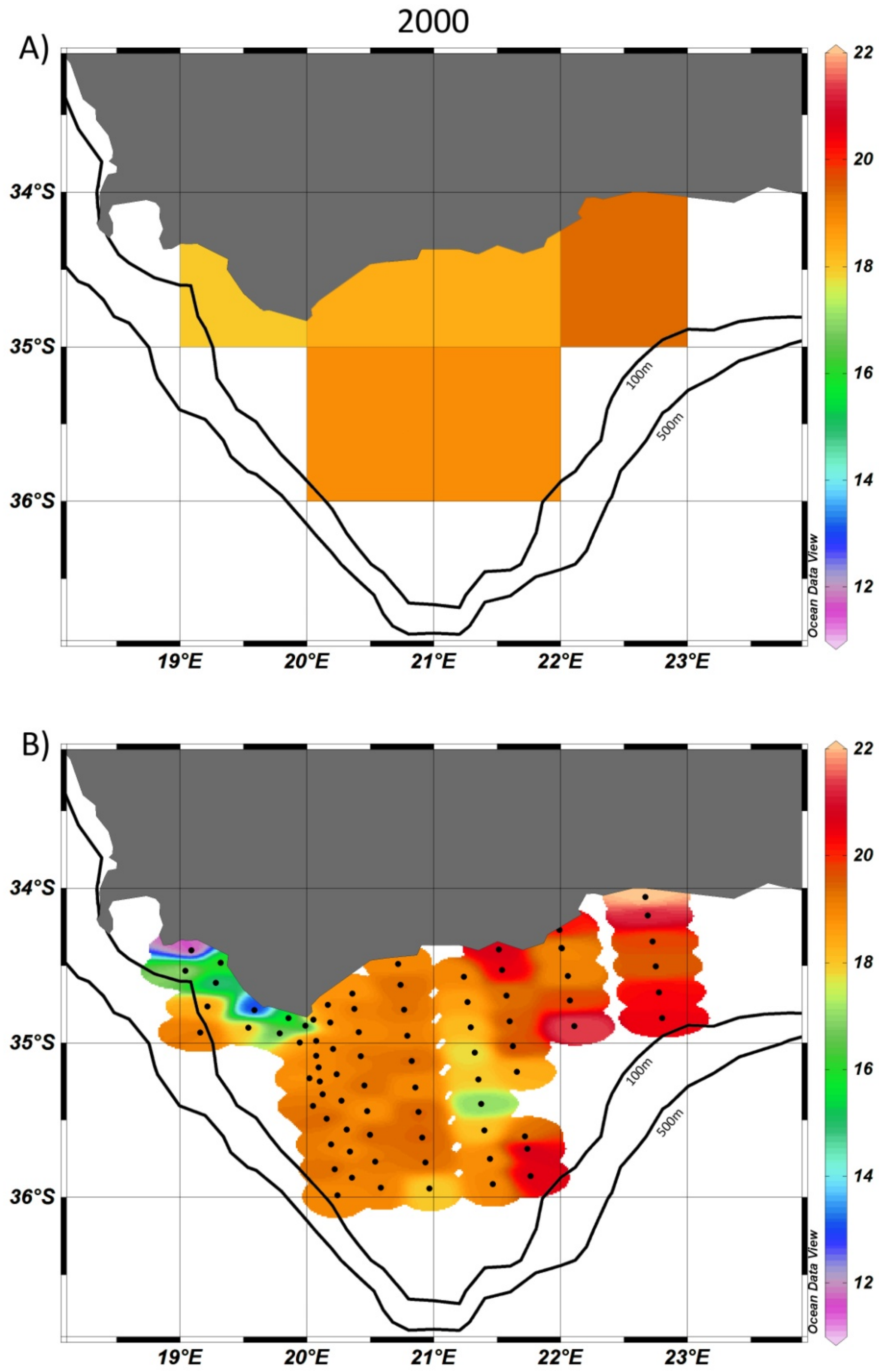


Figure 2.10: Surface plots of the Agulhas Bank showing the difference in temperature detected by A) OISST.v2 and B) PISCTD data. Sample points for PISCTD data shown as black dots. The full time series can be found in the Appendix (Figure A.1)

Due to the sampling differences of the PISCTD and OISST.v2 data, it is likely that the decadal patterns observed in these data sets are being influenced differently by short term events that occurred during the annual pelagic spawner biomass surveys. These would have had a larger impact on the shipboard *in situ* data than both the OISST.v2 and UTR data sets because the annual temperatures for the later two data sets were created from three month means whereas the time frame of the sampling for the PISCTD data set was generally smaller and less consistent. This can be seen in Figure 2.5, wherein 2004 was a hot year for all of the data sets but there are spikes (both negative and positive) in the PISCTD time series that are not shown by any other instrument.

The mean decadal temperature values provided in Figure 2.4 (Table A.1) show the differences between the data sets, but the standard error values are more indicative of the problem faced when comparing these data sets. The OISST.v2 algorithm screens any temperature values whose anomalies are more than 3.5 times the climatological standard deviation (Reynolds and Smith 1994). This can be seen in the much smaller standard error values the Jan-Dec and Oct-Dec OISST.v2 decadal means have than both *in situ* temperature data sets (Figure 2.4, Table A.1). It can also be seen that the standard errors for the Oct-Dec OISST.v2 are almost twice those of the Jan-Dec OISST.v2 means. This implies that the Oct-Dec time period has more variability than the rest of the year. Smit et al. (2013) also found that austral summer was the period of highest temperature variability and that the south coast of South Africa was the most variable part of the entire coast. It is also a known issue with the 1°x1° resolution of the OISST.v2 product that in areas of strong gradients, such as those caused by upwelling on the Agulhas Bank, SST accuracy is reduced (Reynolds 2002; Figure 2.10). These two facts help to explain the finding by Reynolds and Smith (1994) that the Agulhas Bank region had some of the highest guess error values for the OISST.v1 algorithm at up to 0.5°C. As the main difference between the OISST.v1 and v2 algorithms is an improved ice flagging method (Reynolds et al. 2002), these guess error values are likely very similar in the OISST.v2 product. Because the first guess for OISST.v2 values are based on the previous week in order to determine the size of the current anomaly (Reynolds et al. 2002), it is possible that the colder temperatures for this region of the ocean (as compared to PISCTD and UTR values) are overly influenced by previous cold results and the OISST.v2 algorithm prevents itself from recognizing warm anomalies. The warm spike observed in temperatures in the EABC subdomain in the PISCTD and UTR K/T data sets for 2004 are an example of the OISST.v2 algorithm's inability to detect strong short term fluctuations (Figure 2.5).

The standard errors for the temperatures from all four subdomains of the Oct-Dec OISST.v2 data set and two subdomains for the PISCTD data set increased from the first decade to the second, implying an increase in variability from one decade to the next (Figure 2.4, Table A.1). However, the UTR data sets showed a large decrease in standard error from the first decade to the second. This implies that the inshore region of the Agulhas Bank was less variable during the second decade of the study period, whereas the Oct-Dec OISST.v2 and PISCTD data sets imply that the coastal (WABC, CABC and EABC) and offshore (CABO) regions were more variable during the second decade of the study, with the exception of the EABC in the PISCTD data set. The high standard errors of the PISCTD data set show how varied the temperatures were that the CTD and CalVET net temperature probe were able to detect during the research cruises. The largest difference in temperature observed within a single subdomain in any year of the PISCTD data set was 7.5°C in the WABC during 2000, as shown in Figure 2.10. This is important as the OISST.v2 algorithm screens these large outliers (Reynolds and Smith 1994). Therefore, a combination of the inability of the OISST.v2 algorithm to show the strong gradients occurring on the Agulhas Bank, and the strong influence of short term events on shipboard *in situ* data makes an accurate comparison between these data sets tenuous.

Even though the comparison of the OISST.v2 and *in situ* data sets has been shown to be tenuous, the fact that the Oct-Dec OISST.v2 and Oct-Dec UTR data sets found opposite significant relationships with the same biological data set shows that caution must be exercised when choosing a data set to conduct an investigation of coastal temperature variability. The results of this study are supported by a growing body of literature that discusses the risks of using remote sensing to detect coastal temperature changes (e.g. Smale and Wernberg 2009, Smit et al. 2013). I have shown that not only do interannual discrepancies exist between OISST.v2 and *in situ* temperature data within two degrees longitude/ latitude from the coast, but different decadal patterns of warming and cooling were seen as well. It is important to note that the period in which years are binned may have an effect on the outcome of the results and should a similar study be conducted with any of these data sets using a different range of years, a different result could be produced (Xue et al. 2001).

The findings made in this study with *in situ* data do not validate the findings made in Roy et al. (2007), which showed a strong relationship between the cross-shelf SST difference on the central Agulhas Bank and the relative anchovy spawner biomass found east of Cape Agulhas. Roy et al. (2007) also found a relationship between the nearshore cooling on the Agulhas Bank and increases in easterly wind, implying an increase in upwelling that led to a more conducive environment for anchovy. Rouault et al. (2010) also found that the nearshore Agulhas Bank was cooling, likely due to wind forcing, which was also driving the Agulhas to pump harder, leading to an increase in offshore warming. While this study confirms the findings of Roy et al. (2007), both studies were conducted with OISST.v2 data, which have been shown to have issues when detecting coastal temperatures.

The findings of this study are not conclusive as no single *in situ* data set was sufficiently comparable to the OISST.v2 product. More research is necessary to better understand the relationship between the cross-shelf temperature difference on the Agulhas Bank and the relative abundance of anchovy spawner biomass east of Cape Agulhas. Future studies may benefit from using a Jan-Dec coastal *in situ* time series in order to detect the strength of the cold ridge throughout the year (Roberts 2004, Hutchings et al. 2009; Figure 2.1). The cold ridge occurs below the surface, making it difficult for remotely-sensed data to detect. This wind driven coastal upwelling phenomenon is thought to have a positive effect on the retention of anchovy and their prey items on the Agulhas bank and may be a better indicator of optimal conditions than the strength of the cross-shelf SST difference.

The PISCTD data set created for use in this study is also available to a depth of up to 200m. A reinvestigation of temperature change on the distribution of anchovy on the Agulhas bank could be done looking at the depths at which anchovy are more commonly found. While anchovy feed within 35 metres of the surface during the night, they live much deeper than this during the day (van der Lingen et al. 2003). Using the depth profiles provided in the PISCTD data set, an investigation can be made into the correlation between temperatures at specific depths and population densities through time in the areas of the ocean where temperature change is more likely to affect the lifecycle of these small pelagics. The knowledge gained from these correlations would be important as small pelagic fish are a very important part of the wasp waist ecosystem on the Agulhas Bank.

Chapter 3
Conclusions and Self-critique

An abrupt shift in the relative distribution of anchovy spawner biomass to the east of Cape Agulhas during the mid 1990s occurred synchronously with cooling of the inner continental shelf on the central Agulhas Bank as measured using the OISST.v2 dataset, leading Roy et al. (2007) to hypothesize that the shift was environmentally mediated. The main aim of this project was to test that hypothesis using *in situ* temperature data collected during annual pelagic spawner biomass research surveys conducted from 1986 to 2005 that covered the entire Agulhas Bank and from underwater temperature recorders (UTRs) situated to the east of Cape Agulhas. The initial hypothesis of this research project was that *in situ* temperature data collected over the Agulhas Bank during the annual pelagic spawner biomass surveys, as well as temperature from the UTRs, would show similar decadal trends as the remotely-sensed sea surface temperature (SST) data from the same region. The *in situ* data collected during research surveys and aggregated at a 1°x1° spatial resolution (the same as the OISST.v2 data set) were not significantly correlated with the OISST.v2 data and did not show the same change in the cross-shelf temperature difference east of Cape Agulhas that was detected in the OISST.v2 dataset and described by Roy et al. (2007). The UTRs correlated significantly with each other but not with either the OISST.v2 or PISCTD data, nor did the UTR data sets show a significant change in mean decadal temperature. This implies that the *in situ* data analysed in this study do not support the hypothesis that the relative anchovy spawner biomass shifted to the east of Cape Agulhas in response to cooling inshore temperatures. This is an important result as it adds to the growing body of literature that is finding discrepancies between nearshore *in situ* and satellite data (e.g. Hughes et al. 2009, Smale and Wernberg 2009, Dufois et al. 2012, Hutchings et al. 2012, Smit et al. 2013).

Because the goal of the project was to test the Roy et al. (2007) findings the same OISST.v2 data they used was incorporated into this research project. Once the satellite and *in situ* data sets had been acquired and processed it became clear that the largest question at hand was whether these two different types of data were correlated. The OISST.v2 and *in situ* data were already divided into four subdomains over a 20 year period, which made comparisons very convenient and straightforward. The investigation into the eastward shift of anchovy spawner biomass was kept in the project but only used as a final test for the relatedness of the different data sets.

The main issue with the results of this research project is that comparing *in situ* cruise temperature data and UTR data to satellite SST is tenuous. This is because the temperature values generated by the satellite are averaging the synoptically collected SST for an entire 1x1° grid over one week or month (depending on the product used) whereas the *in situ* cruise data are from readings taken several meters below the surface at specific points within the 1°x1° grid over a smaller period of time, usually on the order of days. This prevents the satellite data from accurately recording any temperature fluctuations occurring at an event scale, such as the filaments and cyclonic/ anticyclonic eddies that are common on the highly dynamic Agulhas Bank, whereas the *in situ* data from the research cruises are so sensitive to events occurring on the day of sampling that a few measurements taken from a warm filament or within the cold centre of an anticyclonic eddy can skew the mean temperature value for that year. This is likely the cause of the cold and warm spikes observed in Figure 2.5B.

An issue with the methodology used in Roy et al. (2007), and thus this project, that should be addressed in the future, is the area and location of the four subdomains used to divide up the Agulhas Bank. The first issue is that the coastal subdomains do not all cover the same surface area of the ocean or extend out into the ocean equally (Figure 2.1), meaning that the CABC will potentially have more temperature recordings from further out on the shelf creating the mean value than the WABC or EABC. This creates a difference in the degree to which inshore upwelling or temperature fluctuations can impact these different coastal zones. The second issue is that the offshore subdomain does not have any relationship to the offshore bathymetry in the region. Because the CABC is a set 2°x1° box, only the temperatures moving through this region are used to calculate the cross-shelf difference. To make the cross-shelf difference more applicable to anchovy, the entire Agulhas Bank, out to the 500m isobath, should be used when creating an offshore value. This would more accurately represent the conditions that would influence an anchovy to continue swimming east of Cape Agulhas. If the methodology were to be improved the data should be extracted so that the coastal subdomains begin from the coast and extend to the 100m isobath. The offshore subdomain should start at the 500m isobath and extend north to the 100m isobath. This would better represent any effect the local bathymetry may have.

The largest problem faced during this project was the collection of data. DAFF provided almost all of the biotic and abiotic data. The CTD data were originally collected and compiled by DEA but I received these data from DAFF as well. The UTR data were supplied by DEA quickly upon the outset of the original project.

Due to the disparate nature of the data used in this project many different file types had to be incorporated into the creation of a final product. Many of the data were already processed and in a user-friendly format whereas some were raw and cryptic. No corrupted data were encountered though the older CTD files were zipped in a format that was no longer supported by any modern software. A solution was found and the unpacked data were checked to confirm they were not corrupted.

Any future studies using these data sets should include wind data so as to better understand if the coastal temperature increase detected by the *in situ* data is related to wind-driven downwelling or some other phenomenon. A possible future study using these data would focus on the original aim of this project, that being the investigation of the effect of the cold ridge on the eastward shift in anchovy spawner biomass. A method needs to be devised in which the strength of the cold ridge can be monitored and evaluated through time. This would also require the development of a metric that could be used to grade the strength of the cold ridge through time. Once these two processes are developed the relationship between the strength of the cold ridge and the percentage of anchovy spawner biomass to the east of Cape Agulhas can be observed. Even though the goal of this research project changed somewhat during execution, it is believed that such a project is possible. An analysis of the strength of the cold ridge would be best carried out with the *in situ* data collected during research cruises. As the cold tongue is a sub surface feature it would be unlikely that it could be accurately tracked with satellite observations.

Even though the *in situ* temperature data did not validate the Roy et al. (2007) findings it was found that the CTD data correlated strongly with the CalVET net data and the GLM created to correct the CalVET net data can be used in future research projects. Until now, the *in situ* temperature data collected during the spawner biomass research cruises had never been collated together in a single format. This finished product, the PISCTD data set as well as the OISST.v2 data for the Agulhas Bank and the UTR time series, will be submitted to SADCO for safe keeping and potential use in other research projects.

References

Barange M, Hampton I, Roel BA (1999) Trends in the abundance and distribution of anchovy and sardine on the South African continental shelf in the 1990s, deduced from acoustic surveys. *South African Journal of Marine Science* **21:** 367-391

Barange M, Coetzee J, Takasuka A, Hill K, Gutierrez M, Oozeki Y, van der Lingen CD, Agostini V (2009) Habitat expansion and contraction in anchovy and sardine populations. *Progress in Oceanography* **89:** 251-260

Blamey LK, Howard JAE, Agenbag J, Jarre A (2012) Regime-shifts in the southern Benguela shelf and inshore region. *Progress in Oceanography* **106:** 80-95

Castillo KD, Lima FP (2010) Comparison of in situ and satellite-derived (MODIS Aqua/Terra) methods for assessing temperatures on coral reefs. *Limnology and Oceanography Methods* **8:** 107-117

Coetzee JC, van der Lingen CD, Hutchings L, Fairweather TP (2008) Has the fishery contributed to a major shift in the distribution of South African sardine? *ICES Journal of Marine Science* **65:** 1676-1688

Coetzee JC, Merkle D, Hutchings L, van der Lingen CD, van den Berg M, Durholtz MD (2010) The 2005 KwaZulu-Natal sardine run survey sheds new light on the ecology of small pelagic fish off the east coast of South Africa. *African Journal of Marine Science* **32(2):** 337-360

Cury P (1994) Obstinate nature: an ecology of individuals. Thoughts on reproductive behavior and biodiversity. *Canadian Journal of Fisheries and Aquatic Sciences* **51:** 1664-1673

Cury P, Bakun A, Crawford RJM, Jarre-Teichmann A, Quiñones RA, Shannon LJ, Verheye HM (2000) Small pelagics in upwelling systems: patterns of interaction and structural changes in "wasp-waist" ecosystems. *ICES Journal of Marine Science* **57:** 603-618

DAFF (2012) *Status of the South African Marine Fishery Resources 2012.* Cape Town: DAFF

Dufois F, Penven P, Whittle CP, Veitch J (2012) On the warm nearshore bias in Pathfinder monthly SST products over Eastern Boundary Upwelling Systems. *Ocean Modelling* **47:** 113-118

Donlon CJ, Minnett PJ, Gentemann C, Nightingale TJ, Barton IJ, Ward B, Murray MJ (2002) Toward improved validation of satellite sea surface skin temperature measurements for climate research. *Journal of Climate* **15:** 353-369

Fairweather TP, van der Lingen CD, Booth AJ, Drapeau L, van der Westhuizen JJ (2006) Indicators of sustainable fishing for South African sardine *Sardinops sagax* and anchovy *Engraulis encrasicolus. African Journal of Marine Science* **28:** 661-680

Huggett JA, Richardson AJ (2000) A review of the biology and ecology of *Calanus agulhensis* off South Africa. *ICES Journal of Marine Science* **57:** 1834-1849

Huggett JA, Fréon P, Mullon C, Penven P (2003) Modelling the transport success of anchovy *Engraulis encrasicolus* eggs and larvae in the southern Benguela: the effect of spatio-temporal spawning patterns. *Marine Ecology Progress Series* **250:** 247-262

Hughes SL, Holliday NP, Colbourne E, Ozhigin V, Valdimarsson H, Østerhus S, Wiltshire K (2009) Comparison of in situ time-series of temperature with gridded sea surface temperature datasets in the North Atlantic. *ICES Journal of Marine Science* **66(7):** 1467-1479

Hurrell JW, Hack JJ, Shea D, Caron JM, Rosinski J (2008) A new sea surface temperature and sea ice boundary dataset for the Community Atmosphere Model. *Journal of Climate* **21:** 5145-5153

Hutchings L, van der Lingen CD, Shannon LJ, Crawford RJM, Verheye HMS, Bartholomae CH, van der Plas AK, Louw D, Kreiner A, Ostrowski M, Fidel Q, Barlow RG, Lamont T, Coetzee J, Shillington F, Veitch J, Currie JC, Monteiro PMS (2009) The Benguela Current: an ecosystem of four components. *Progress in Oceanography* **83:** 15-32

Hutchings L, Jarre A, Lamont T, van den Berg M, Kirkman SP (2012) St Helena Bay (southern Benguela) then and now: muted climate signals, large human impact. *African Journal of Marine Science* **34(4):** 559-583

Kilpatrick KA, Podesta GP, Evans R (2001) Overview of the NOAA/NASA advanced very high resolution radiometer Pathfinder algorithm for sea surface temperature and associated matchup database. *Journal of Geophysical Research* **106:** 9179–9197

Lutjeharms JRE (ed.). 2006. *The Agulhas Current.* Heidelberg: Springer–Verlag.

Miller DCM, Moloney CL, van der Lingen CD, Lett C, Mullon C, Field JG (2006) Modelling the effects of physical-biological interactions and spatial variability in spawning and nursery areas on transport and retention of sardine *Sardinops sagax* eggs and larvae in the southern Benguela ecosystem. *Journal of Marine Systems* **61:** 212-229

Reynolds RW, Marsico DC (1993) An improved real-time global sea surface temperature analysis. *Journal of Climate* **6:**114–119

Reynolds RW, Smith TM (1994) Improved global sea surface temperature analyses. *Journal of Climate* **7:** 929-948

Reynolds RW, Rayner NA, Smith TM, Stokes DC, Wang W (2002) An improved in situ and satellite SST analysis for climate. *Journal of Climate* **15:** 1609-1625

Rouault M, Pohl B, Penven P (2010) Coastal oceanic climate change and variability from 1982 to 2009 around South Africa. *African Journal of Marine Science* **32:** 237-246

Roberts M (2004) Chokka squid (*Loligo vulgaris reynaudii*) abundance linked to changes in South Africa's Agulhas Bank ecosystem during spawning and the early life cycle. *ICES Journal of Marine Science* **62:** 33-55

Roy C, van der Lingen CD, Coetzee JC, Lutjeharms JRE (2007) Abrupt environmental shift associated with changes in the distribution of Cape anchovy *Engraulis encrasicolus* spawners in the southern Benguela. *African Journal of Marine Science* **29:** 309-319

Schlitzer R, Ocean Data View, http://odv.awi.de, 2014

Sherley R, Underhill L, Barham B, Barham P, Coetzee J, Crawford R, Dyer B, Leshoro M, Upfold L (2013) Influence of local and regional prey availability on breeding performance of African penguins *Spheniscus demersus*. *Marine Ecology Progress Series* **473:** 291-301

Smale DA, Wernberg T (2009) Satellite-derived SST data as a proxy for water temperature in nearshore benthic ecology. *Marine Ecology Progress Series* **387:** 27–37

Smit AJ, Roberts M, Anderson R, Dufois F, Dudley S, Bornman T, Olbers J, Bolton J (2013) A coastal seawater temperature data set for biogeographical studies: large anomalies between in situ and remotely-sensed data sets around the coast of South Africa. *PLoS ONE* **8(12):** e81944

van der Lingen CD, Coetzee JC, Hutchings L (2002) Temporal shifts in the spatial distribution of anchovy spawners and their eggs in the southern Benguela: implications for recruitment. In: van der Lingen CD, Roy C, Fréon P, Barange M, Castro L, Gutierrez M, Nykjaer L, Shillington F (eds) *Report of a GLOBECSPACC/*

IDYLE/ENVIFISH workshop on spatial approaches to the dynamics of coastal pelagic resources and their environment in upwelling areas. *GLOBEC Report* **16:** 46–48

van der Lingen CD, Huggett JA (2003) The role of ichthyoplankton surveys in recruitment research and management of South African anchovy and sardine. In: Browman HL, Skiftesvik AB (eds) The Big Fish Bang. Proceedings of the 26th Annual Larval Fish Conference, Institute of Marine Research, Bergen, 2003, pp. 303–343

van der Lingen CD, Fréon P, Fairweather TP, van der Westhuizen JJ (2006a) Density-dependent changes in reproductive parameters and condition of southern Benguela sardine *Sardinops sagax*. *African Journal of Marine Science* **28:** 625–636

van der Lingen CD, Hutchings L, Field JG (2006b) Comparative trophodynamics of anchovy *Engraulis encrasicolus* and sardine *Sardinops sagax* in the southern Benguela: are species alternations between small pelagic fish trophodynamically mediated? *African Journal of Marine Science* **28:** 465–478

van der Lingen CD (2011) The biological basis for hypothesizing multiple stocks in South African sardine *Sardinops sagax.* Unpublished Report, Offshore Resources Research, DAFF, South Africa, **MARAM IWS/DEC11/P/OMP/P7**

van der Lingen CD, Coetzee JC, Hutchings LF (2011) Causes and effects of changes in the distribution of anchovy and sardine in shelf waters off South Africa. In: Zietsman L (ed) *Observations on Environmental Change in South Africa.* Stellenbosch: SUN MeDIA. pp 252-257

Xue Y, Smith TM, Reynolds RW (2003) Interdecadal changes of 30-yr SST normals during 1871–2000. *Journal of Climate* **16:** 1601–1612

Appendix

Table A.1: The Jan-Dec and Oct–Dec decadal temperature values from the three data sets and the results of the t tests. Significant results are shown in bold italics

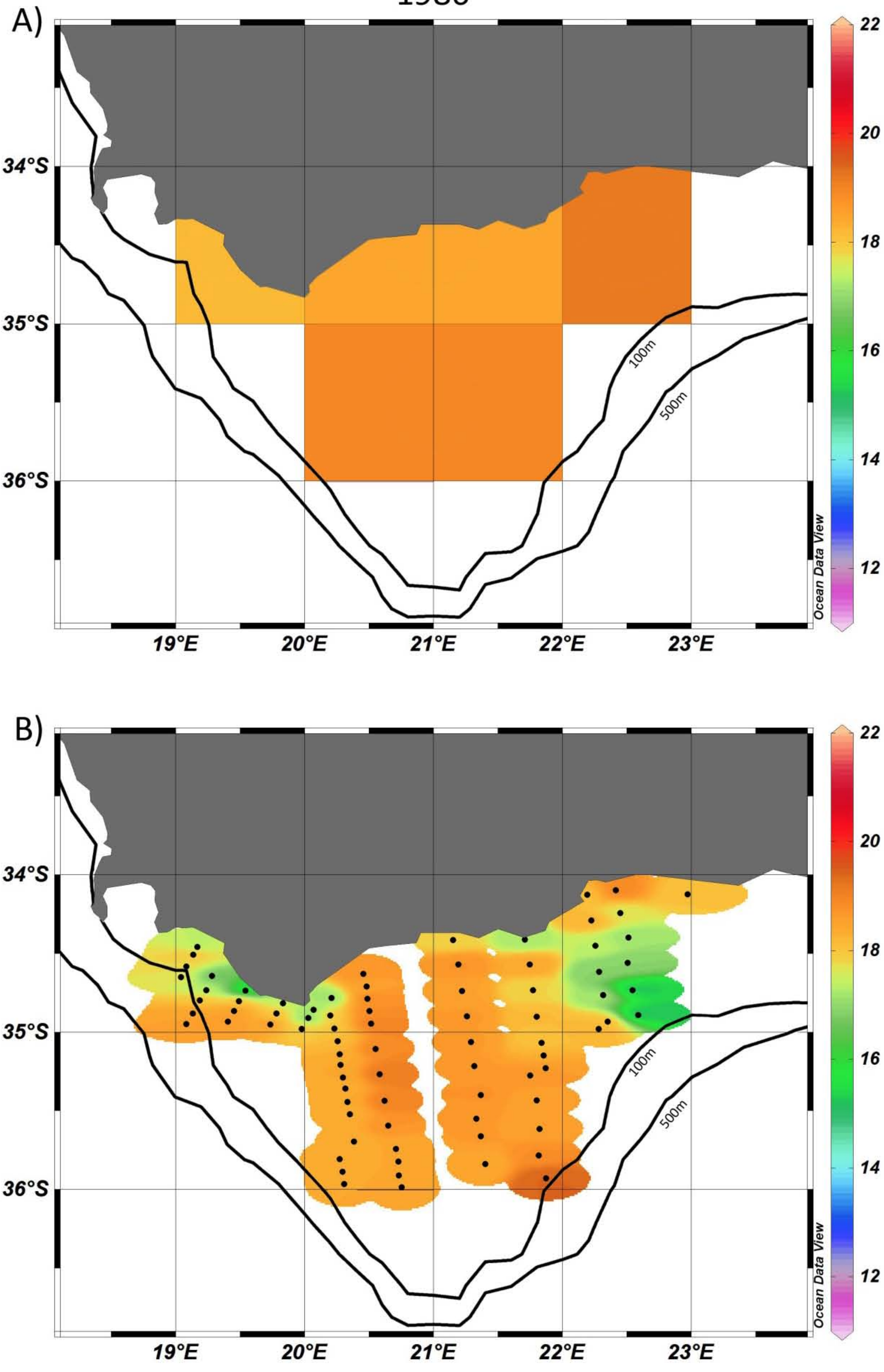
Data set	Subdomain	Mean SST (°C) 1986-1995	SE (°C)	Mean SST (°C) 1996-2005	SE (°C)	t-value	df	p-value
OISST.v2	WABC	17.67	0.12	17.59	0.10	0.49	18	0.63
Jan-Dec	CABC	18.47	0.10	18.06	0.09	2.99	18	0.01
	EABC	***19.54***	***0.10***	***19.03***	***0.09***	***3.68***	***18***	***0.00***
	CABO	18.93	0.10	18.95	0.09	-0.20	18	0.85
OISST.v2	WABC	17.75	0.13	17.87	0.17	-0.53	18	0.60
Oct-Dec	CABC	18.53	0.11	18.32	0.15	1.11	18	0.28
	EABC	19.44	0.12	19.15	0.14	1.61	18	0.12
	CABO	18.87	0.13	19.05	0.16	-0.89	18	0.39
PISCTD	WABC	17.3	0.24	17.5	0.35	-0.40	18	0.69
Oct-Dec	CABC	18.5	0.28	18.8	0.28	-0.71	18	0.49
	EABC	18.5	0.46	18.9	0.34	-0.85	18	0.41
	CABO	18.7	0.20	18.8	0.26	-0.34	18	0.74
UTR	K	16.83[1]	0.37	17.52	0.27	-1.52	14	0.15
Jan-Dec	T	16.87[2]	0.46	16.91	0.25	-0.09	13	0.93
UTR	K	17.69[1]	0.39	18.58	0.23	-2.09	13	0.06
Oct-Dec	T	16.81[2]	0.37	17.69	0.29	-1.83	12	0.09

1. 1990-1995, 2. 1991-1995

Table A.2: Power analysis of the decadal mean values for both Jan-Dec and Oct-Dec mean values for all three data sets. Hypothetical values for power and n required for a power of 0.80 are shown for decadal shifts of 0.25°C, 0.5°C and 1.0°C

Dataset	Subdomain	Mean SST 1986-1995	SD	Mean SST 1996-2005	SD	Power	n at Power = 80
OISST Jan-Dec	WABC	17.67	0.37	17.59	0.31	0.08	574
	CABC	18.47	0.32	18.06	0.29	0.81	20
	EABC	19.54	0.33	19.03	0.29	0.93	14
	CABO	18.93	0.30	18.95	0.29	0.05	6836
OISST Oct-Dec	WABC	17.75	0.42	17.87	0.55	0.08	524
	CABC	18.53	0.36	18.32	0.47	0.19	128
	EABC	19.44	0.37	19.15	0.43	0.33	64
	CABO	18.87	0.40	19.05	0.50	0.13	202
PISCTD Oct-Dec	WABC	17.3	0.76	17.5	1.11	0.07	714
	CABC	18.5	0.88	18.8	0.89	0.11	276
	EABC	18.5	1.45	18.9	1.07	0.10	322
	CABO	18.7	0.65	18.8	0.81	0.06	1696
UTR Jan-Dec	Knysna	16.83	0.90	17.52	0.86	0.26	54
	Tsitsikamma	16.87	1.03	16.91	0.80	0.05	16690
UTR Oct-Dec	Knysna	17.69	0.87	18.58	0.73	0.47	28
	Tsitsikamma	16.81	0.84	17.69	0.87	0.40	32
Dataset	**Subdomain**	**Power if 0.25°C**	**n at 0.25°C**	**Power if 0.5°C**	**n at 0.5°C**	**Power if 1°C**	**n at 1°C**
OISST Jan-Dec	WABC	0.34	62	0.87	18	1.00	8
	CABC	0.41	50	0.93	14	1.00	6
	EABC	0.41	50	0.93	14	1.00	6
	CABO	0.43	46	0.95	14	1.00	6
OISST Oct-Dec	WABC	0.19	124	0.58	34	0.99	10
	CABC	0.24	90	0.71	26	1.00	8
	EABC	0.26	84	0.75	24	1.00	8
	CABO	0.22	106	0.65	28	1.00	10
PISCTD Oct-Dec	WABC	0.09	458	0.20	116	0.60	32
	CABC	0.09	396	0.22	102	0.67	28
	EABC	0.07	818	0.13	206	0.38	54
	CABO	0.11	274	0.30	70	0.82	20
UTR Jan-Dec	Knysna	0.08	392	0.16	100	0.48	28
	Tsitsikamma	0.07	430	0.15	110	0.43	30
UTR Oct-Dec	Knysna	0.08	326	0.18	84	0.56	24
	Tsitsikamma	0.08	370	0.16	94	0.49	26

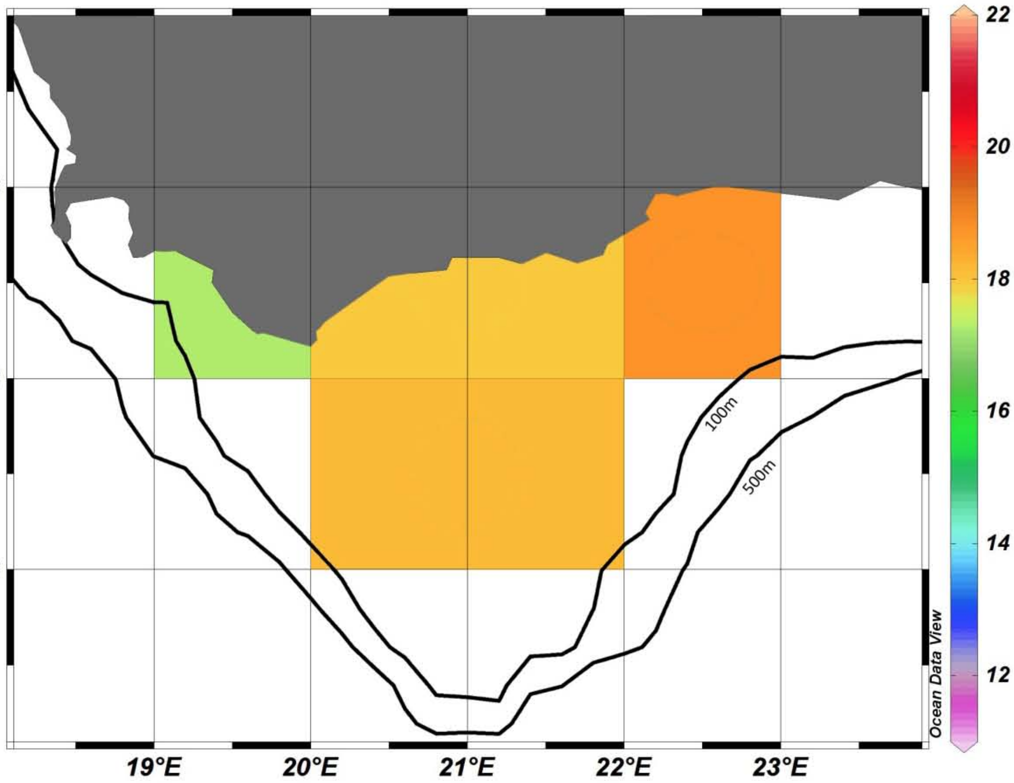
1986



A)
34°S
35°S
36°S
19°E
20°E
21°E
22°E
23°E
100m
500m
22
20
18
16
14
12
Ocean Data View
B)
34°S
35°S
36°S
19°E
20°E
21°E
22°E
23°E
100m
500m
22
20
18
16
14
12
Ocean Data View

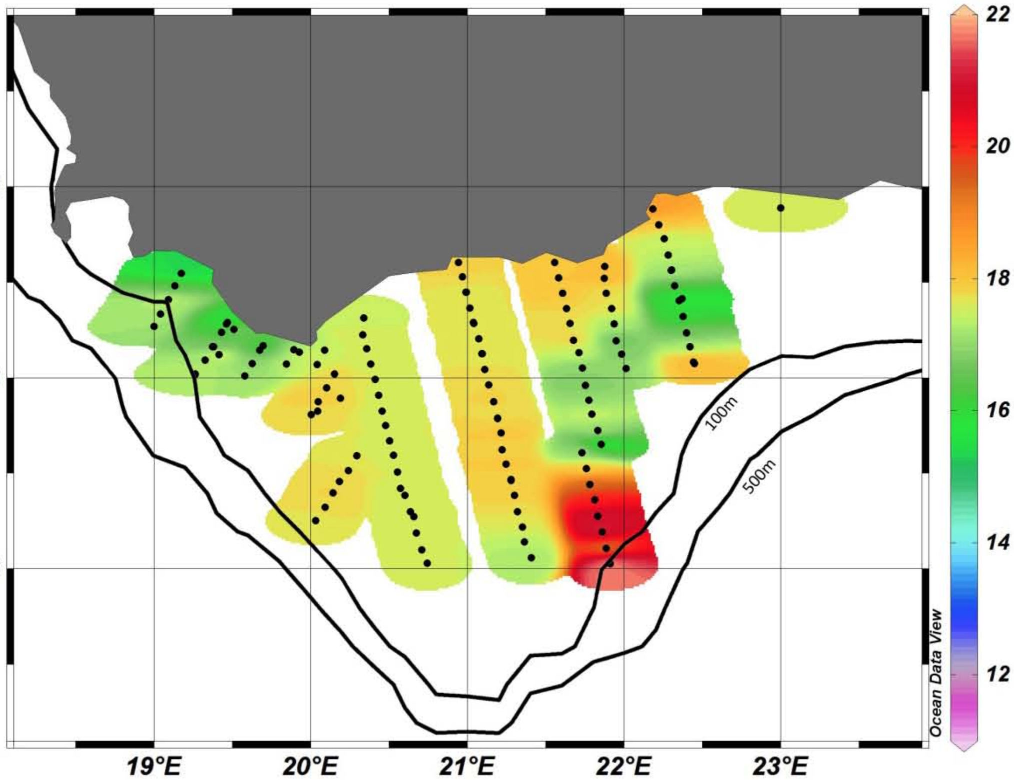
1987

A)

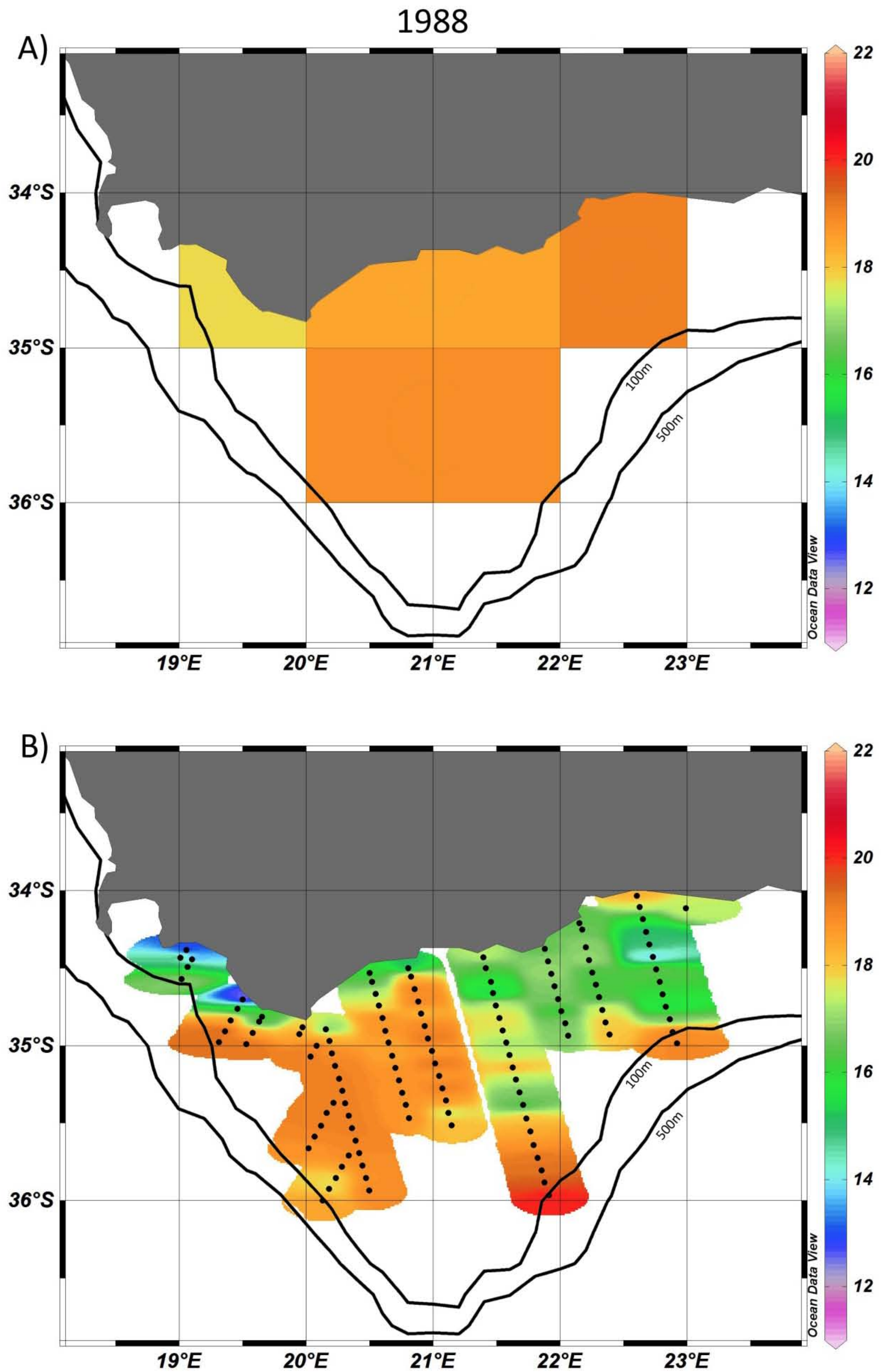


34°S
35°S
36°S
19°E
20°E
21°E
22°E
23°E
100m
500m
Ocean Data View
22
20
18
16
14
12

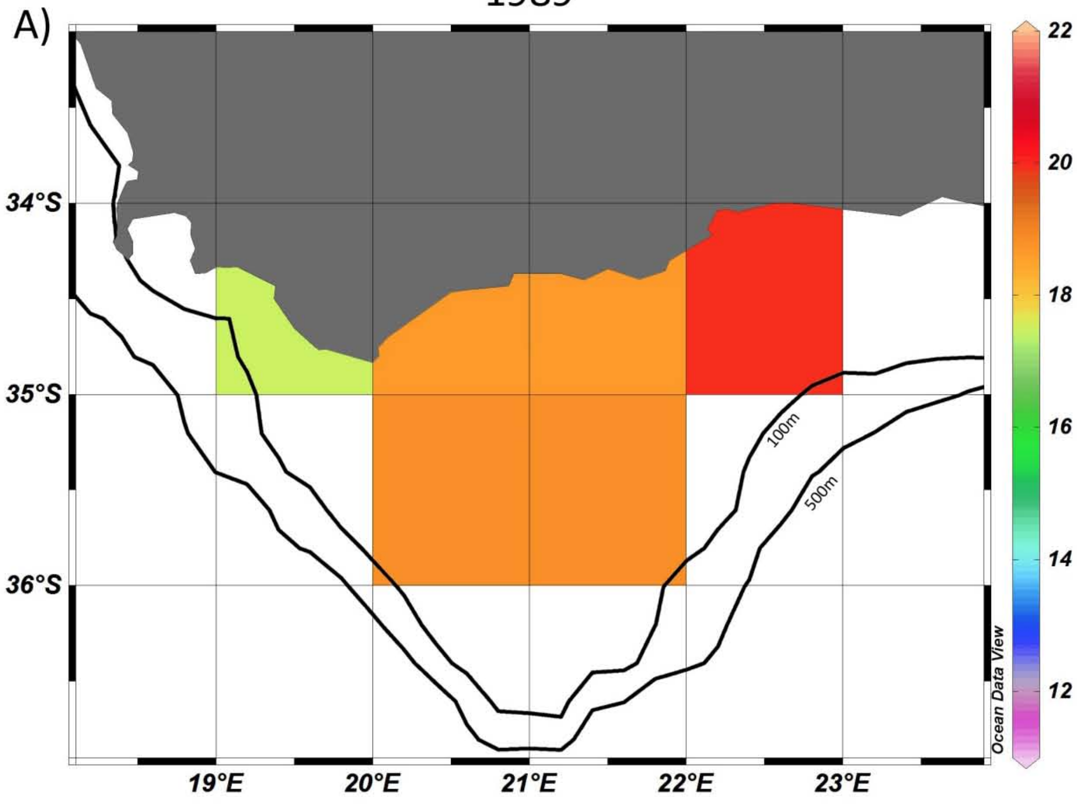
B)

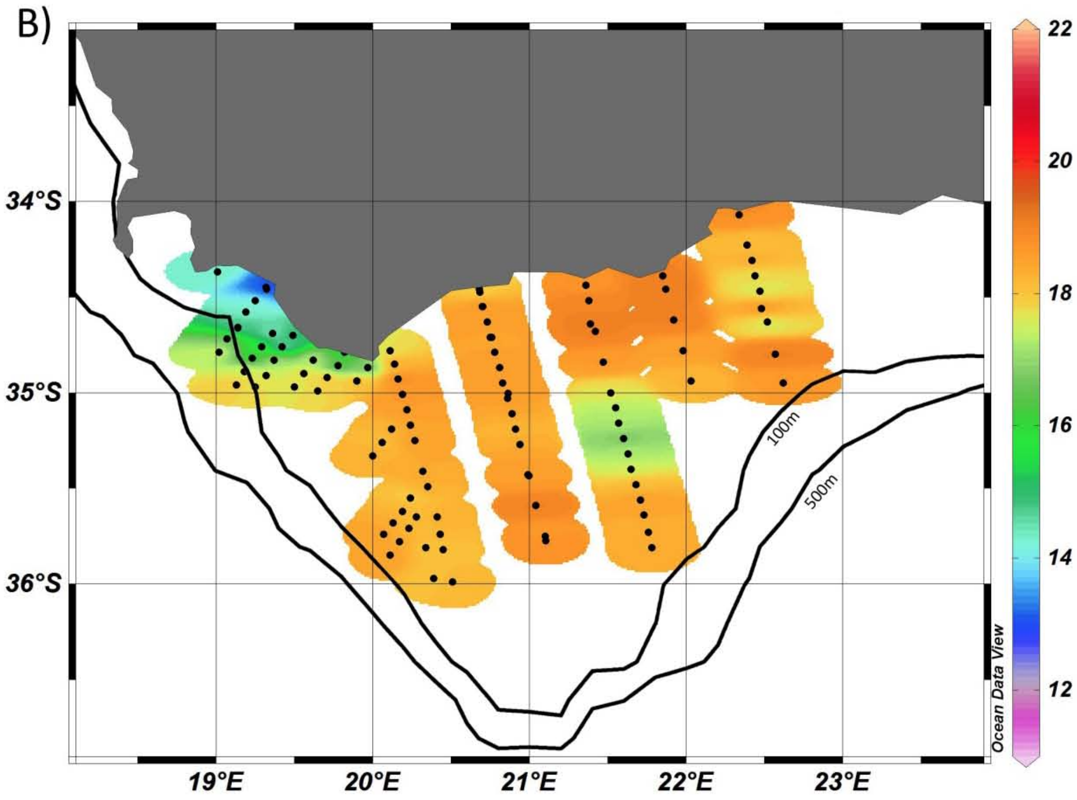


34°S
35°S
36°S
19°E
20°E
21°E
22°E
23°E
100m
500m
Ocean Data View
22
20
18
16
14
12


1988
A)
34°S
35°S
36°S
19°E
20°E
21°E
22°E
23°E
100m
500m
Ocean Data View
22
20
18
16
14
12
B)
34°S
35°S
36°S
19°E
20°E
21°E
22°E
23°E
100m
500m
Ocean Data View
22
20
18
16
14
12

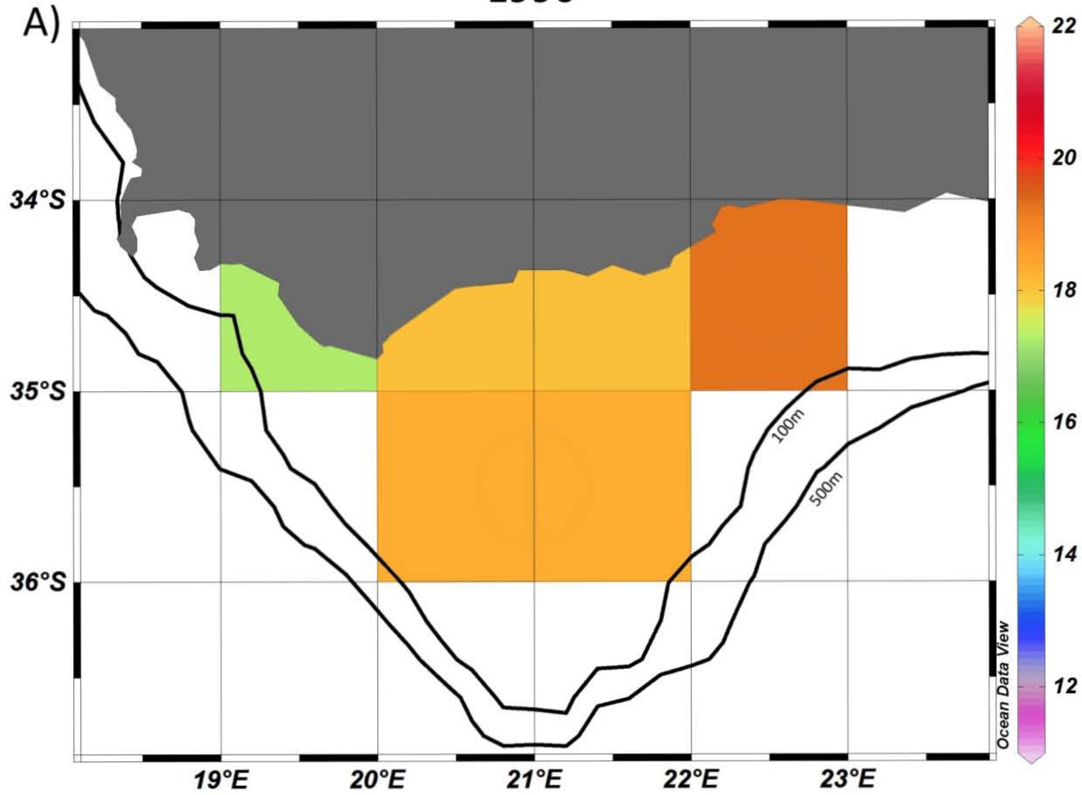
1989


A)
34°S
35°S
36°S
19°E
20°E
21°E
22°E
23°E
100m
500m
22
20
18
16
14
12
Ocean Data View


B)
34°S
35°S
36°S
19°E
20°E
21°E
22°E
23°E
100m
500m
22
20
18
16
14
12
Ocean Data View

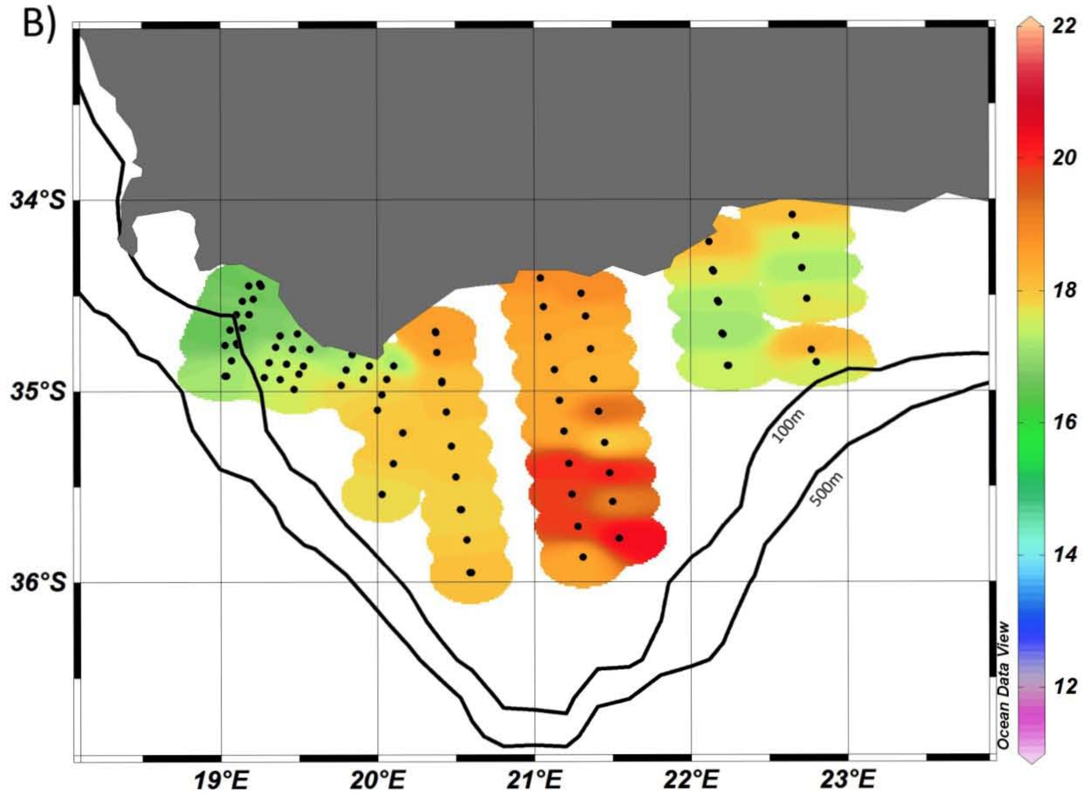
1990

A)



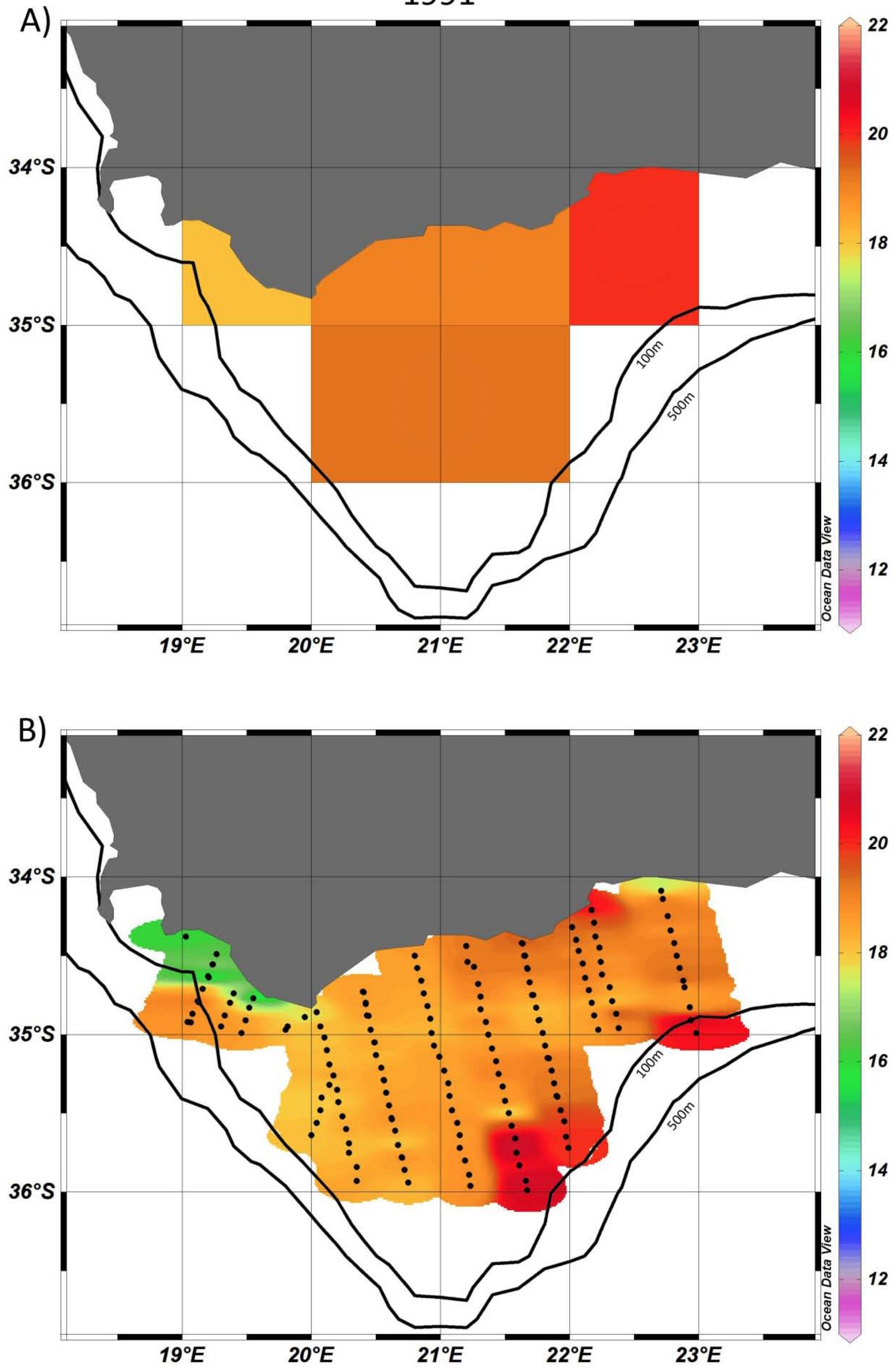
34°S
35°S
36°S
19°E
20°E
21°E
22°E
23°E
100m
500m
22
20
18
16
14
12
Ocean Data View

B)

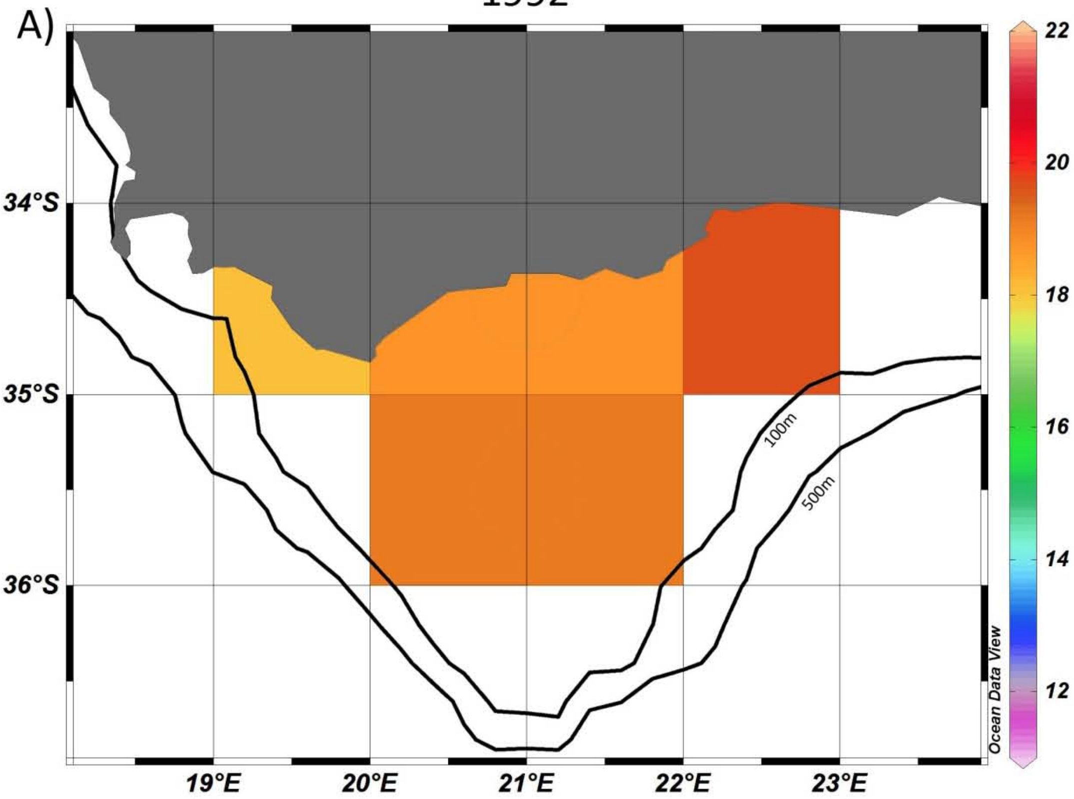


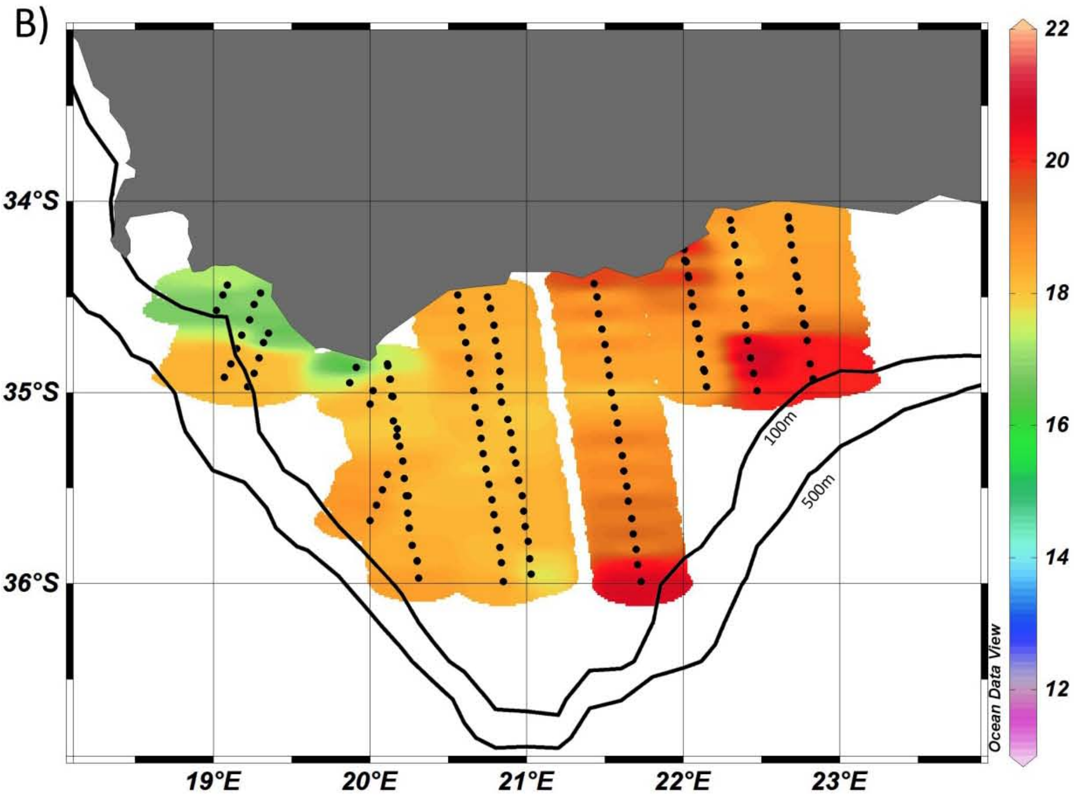
34°S
35°S
36°S
19°E
20°E
21°E
22°E
23°E
100m
500m
22
20
18
16
14
12
Ocean Data View

1991


A)
34°S
35°S
36°S
19°E
20°E
21°E
22°E
23°E
100m
500m
Ocean Data View
22
20
18
16
14
12
B)
34°S
35°S
36°S
19°E
20°E
21°E
22°E
23°E
100m
500m
Ocean Data View
22
20
18
16
14
12

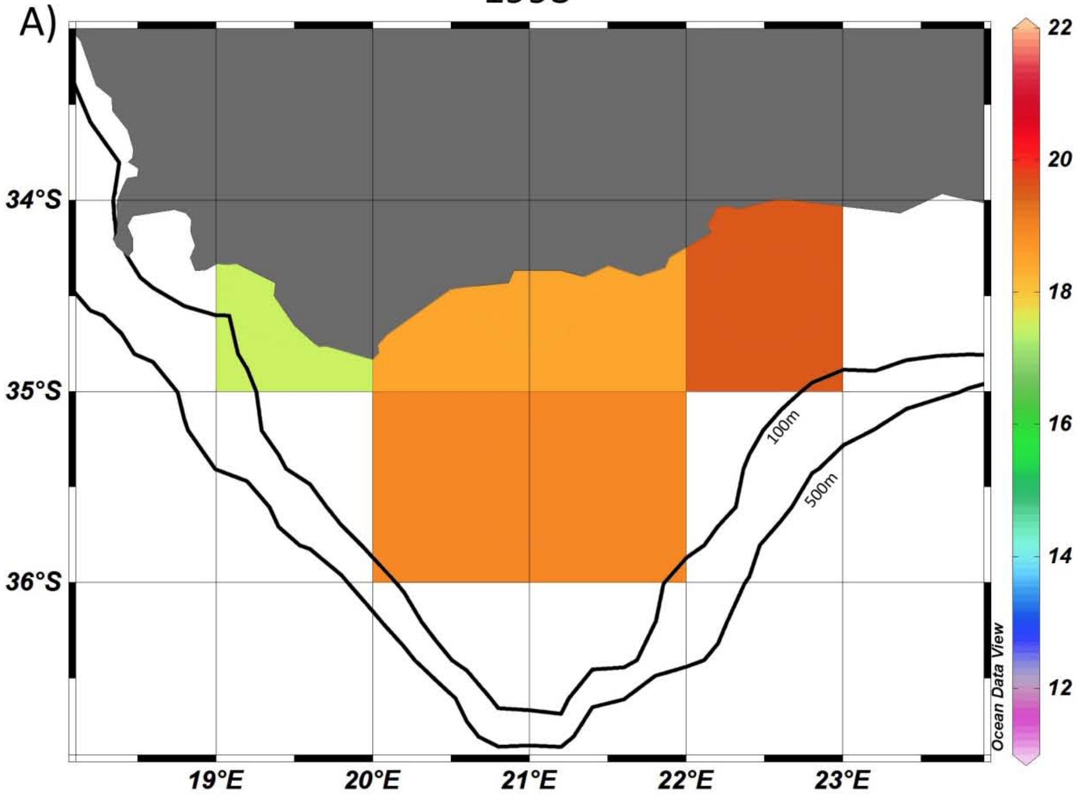
1992


A)
34°S
35°S
36°S
19°E
20°E
21°E
22°E
23°E
100m
500m
Ocean Data View
22
20
18
16
14
12

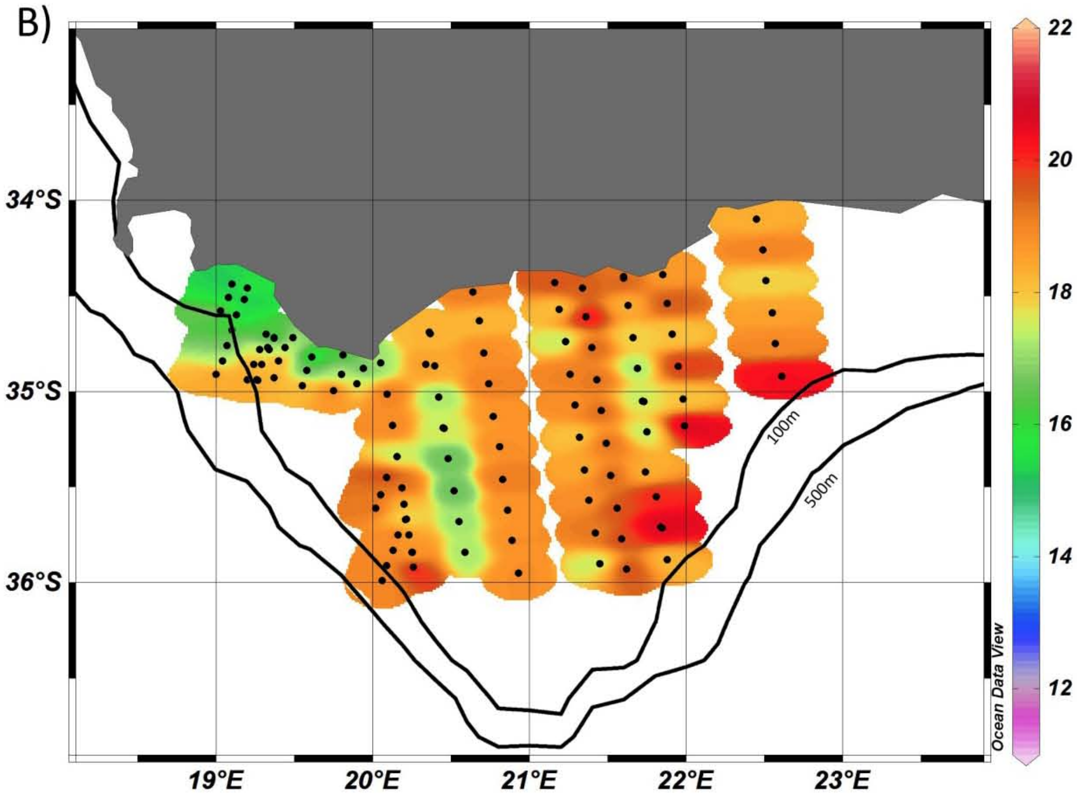

B)
34°S
35°S
36°S
19°E
20°E
21°E
22°E
23°E
100m
500m
Ocean Data View
22
20
18
16
14
12

1993

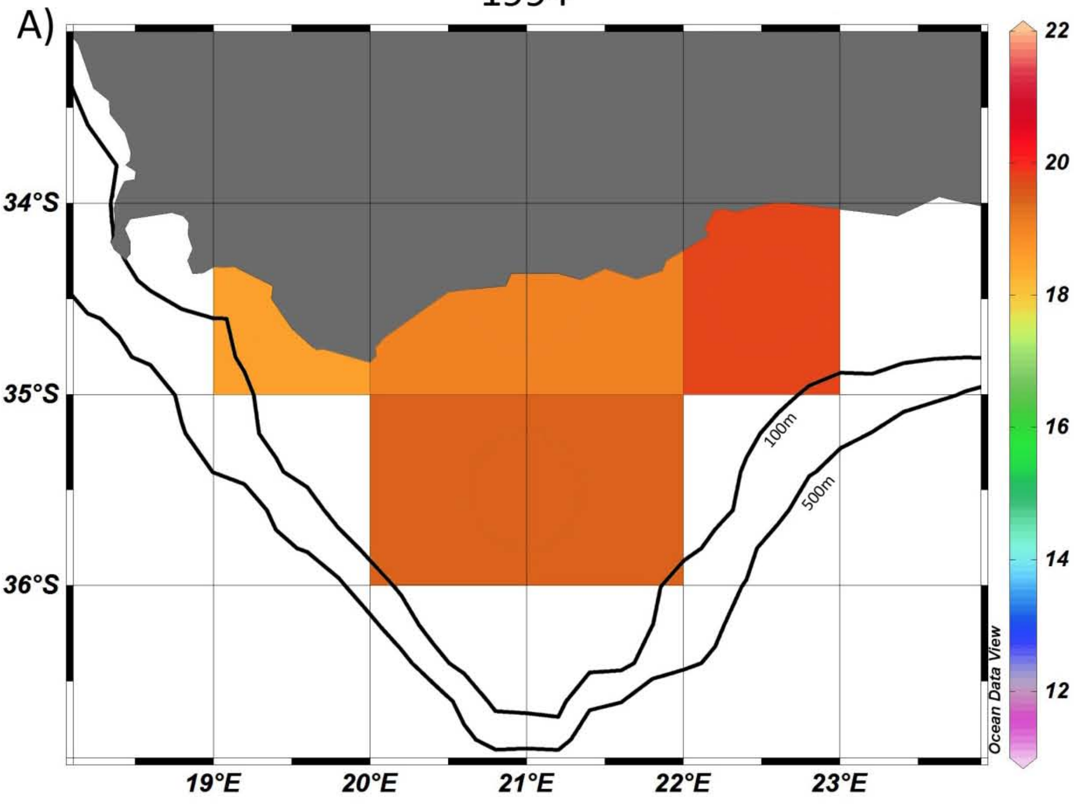
A)

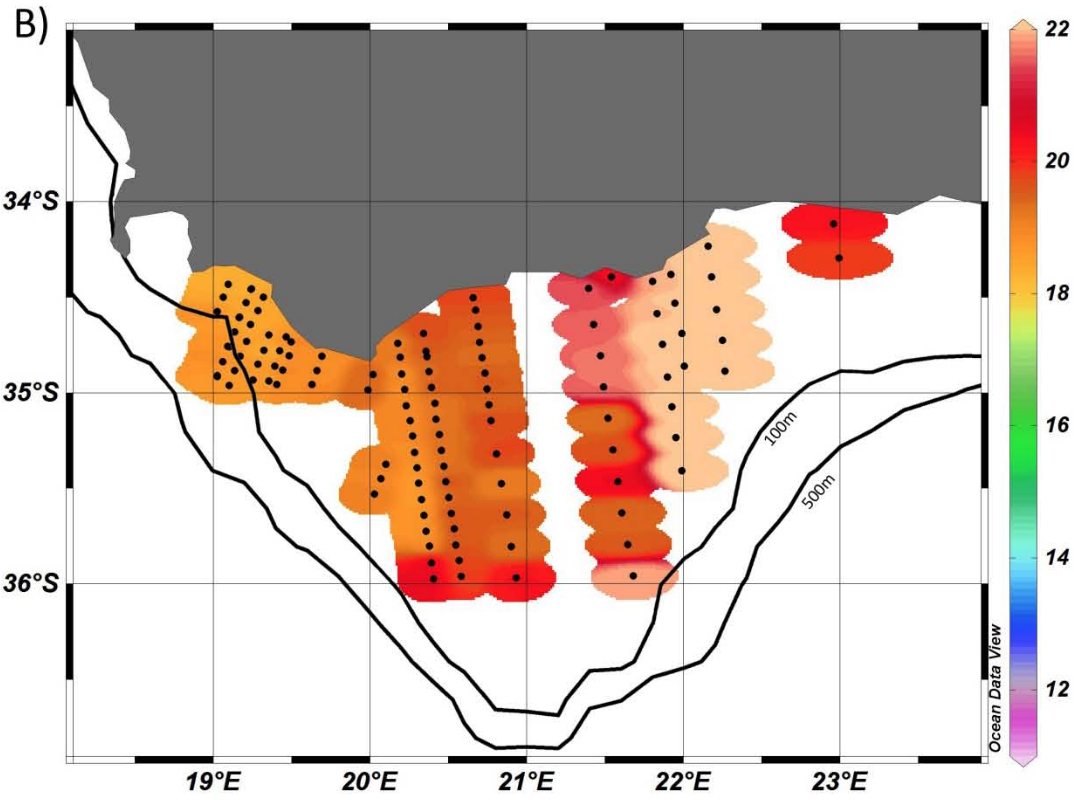

34°S
35°S
36°S
19°E
20°E
21°E
22°E
23°E
100m
500m
22
20
18
16
14
12
Ocean Data View

B)


34°S
35°S
36°S
19°E
20°E
21°E
22°E
23°E
100m
500m
22
20
18
16
14
12
Ocean Data View

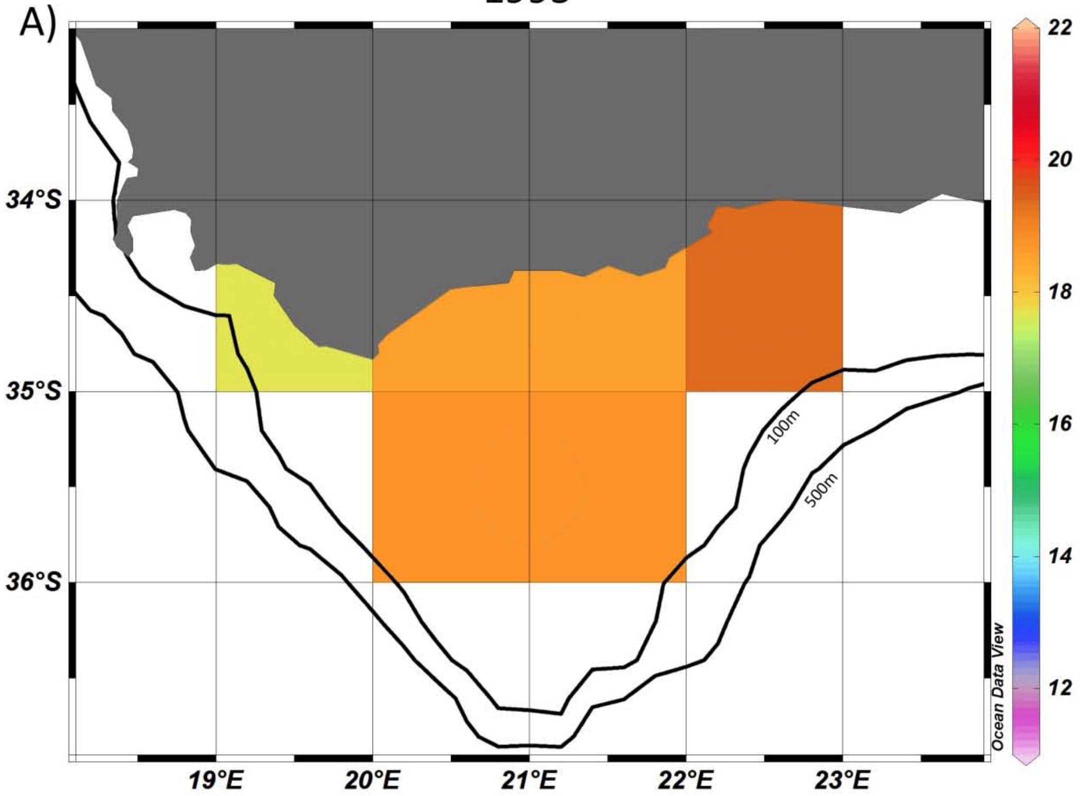
1994


A)
34°S
35°S
36°S
19°E
20°E
21°E
22°E
23°E
100m
500m
22
20
18
16
14
12
Ocean Data View

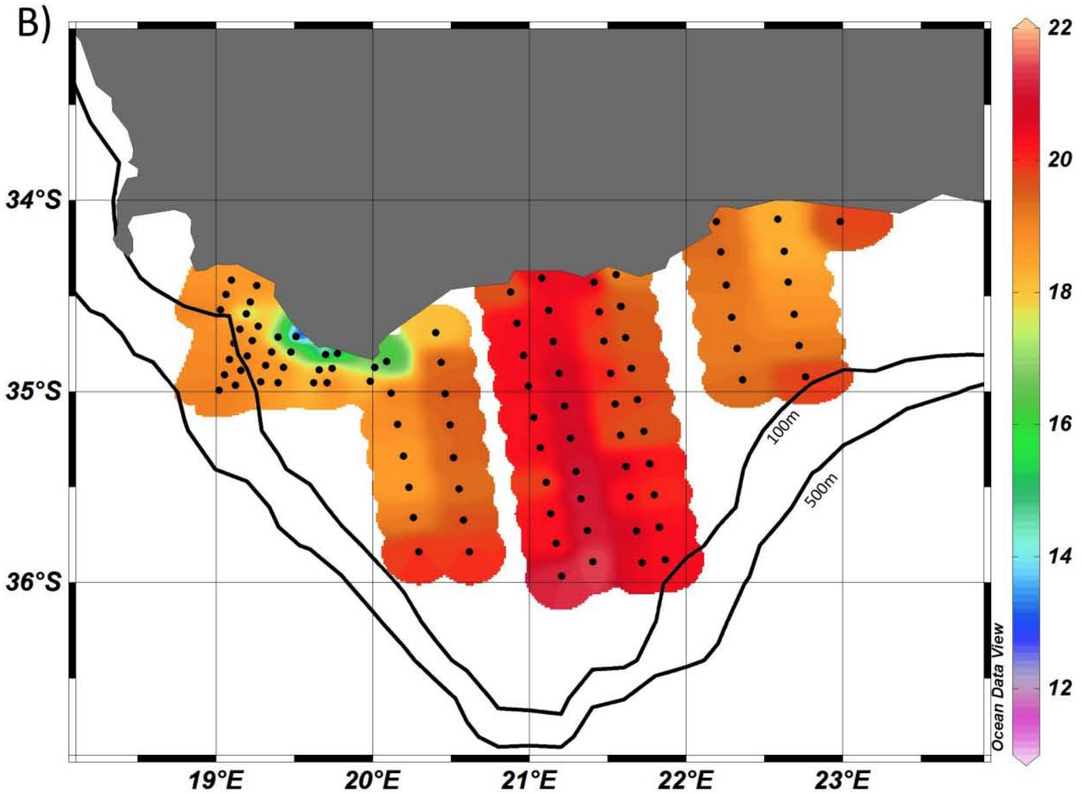

B)
34°S
35°S
36°S
19°E
20°E
21°E
22°E
23°E
100m
500m
22
20
18
16
14
12
Ocean Data View

1995

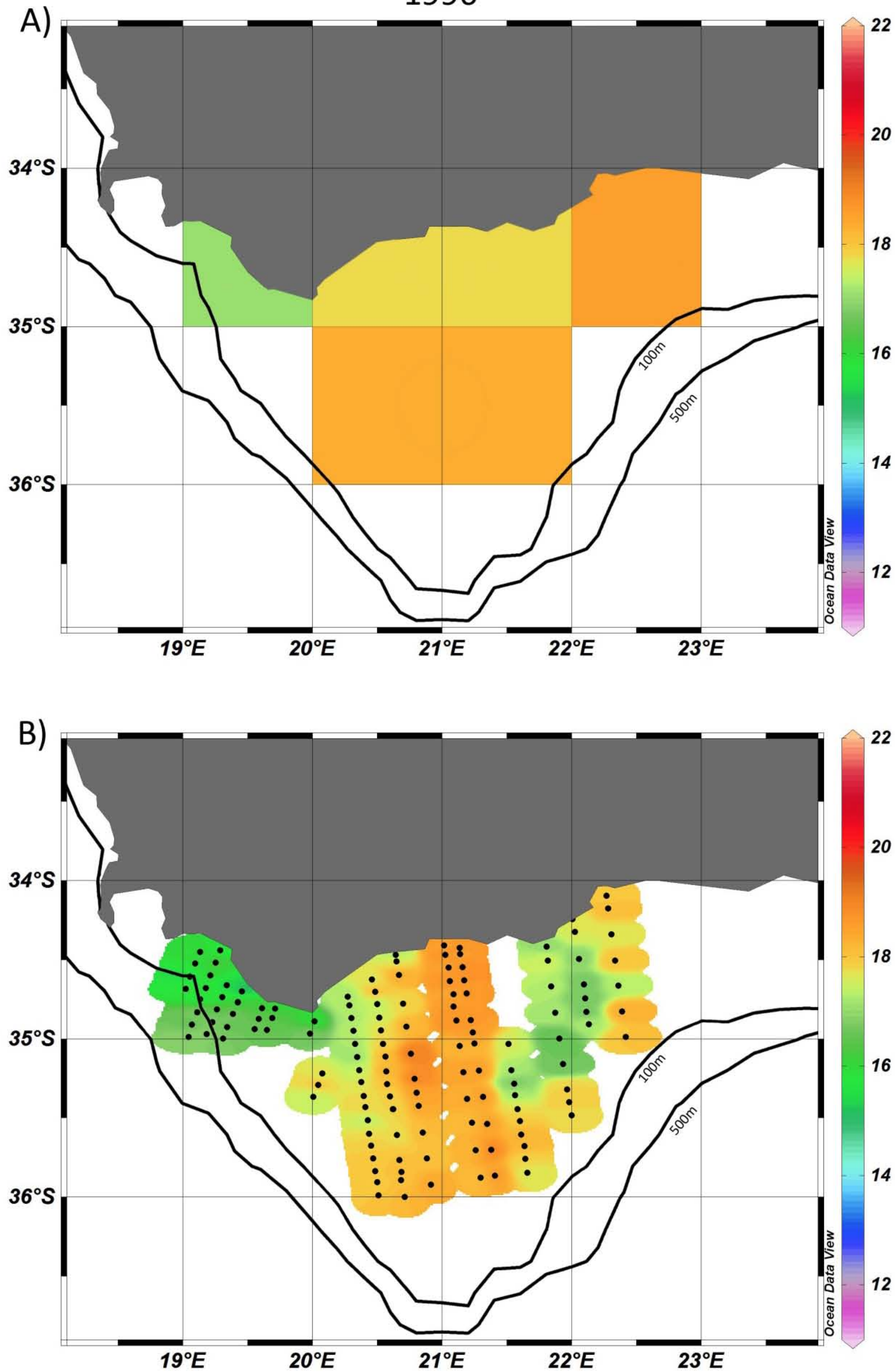
A)


34°S
35°S
36°S
19°E
20°E
21°E
22°E
23°E
100m
500m
Ocean Data View
22
20
18
16
14
12

B)


34°S
35°S
36°S
19°E
20°E
21°E
22°E
23°E
100m
500m
Ocean Data View
22
20
18
16
14
12

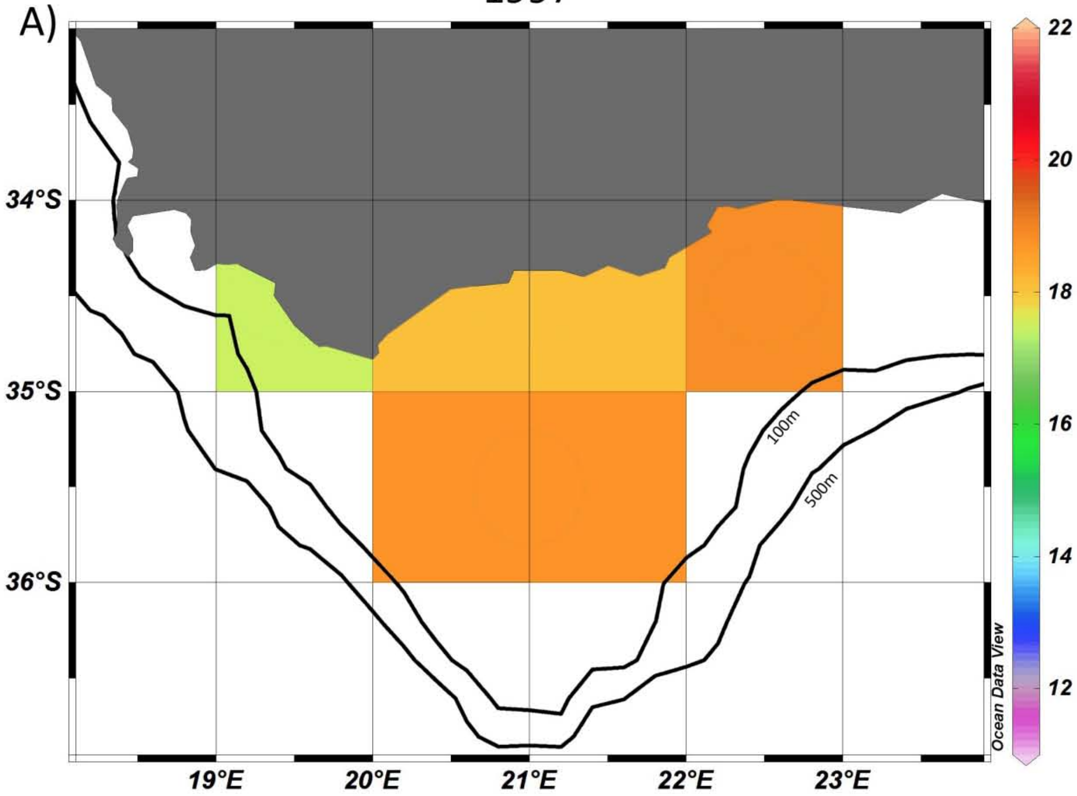
1996



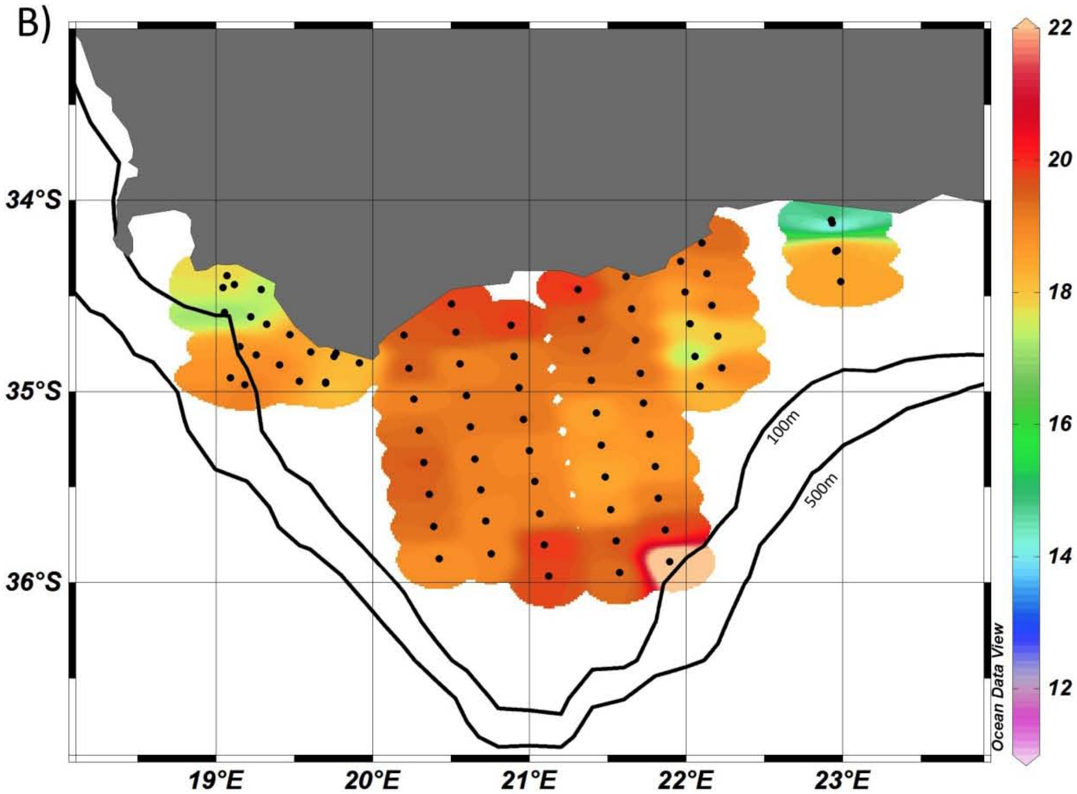
A)
B)
34°S
35°S
36°S
19°E
20°E
21°E
22°E
23°E
100m
500m
22
20
18
16
14
12
Ocean Data View

1997

A)

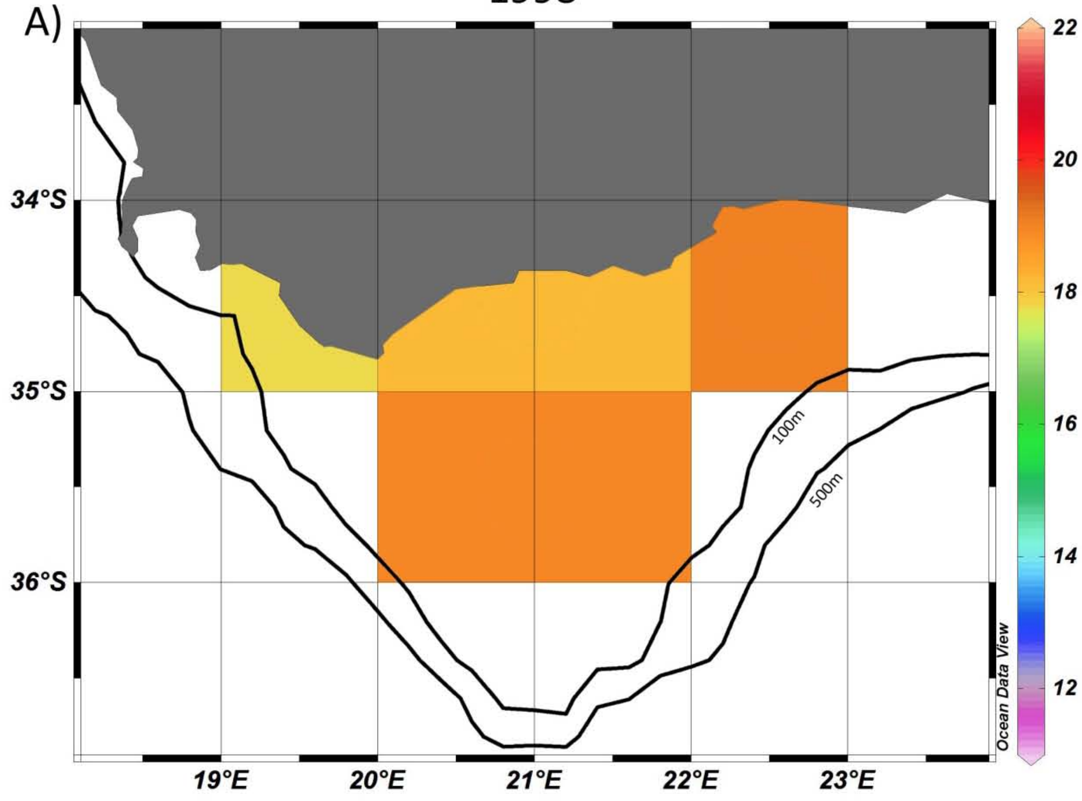

34°S
35°S
36°S
19°E
20°E
21°E
22°E
23°E
100m
500m
Ocean Data View
22
20
18
16
14
12

B)


34°S
35°S
36°S
19°E
20°E
21°E
22°E
23°E
100m
500m
Ocean Data View
22
20
18
16
14
12

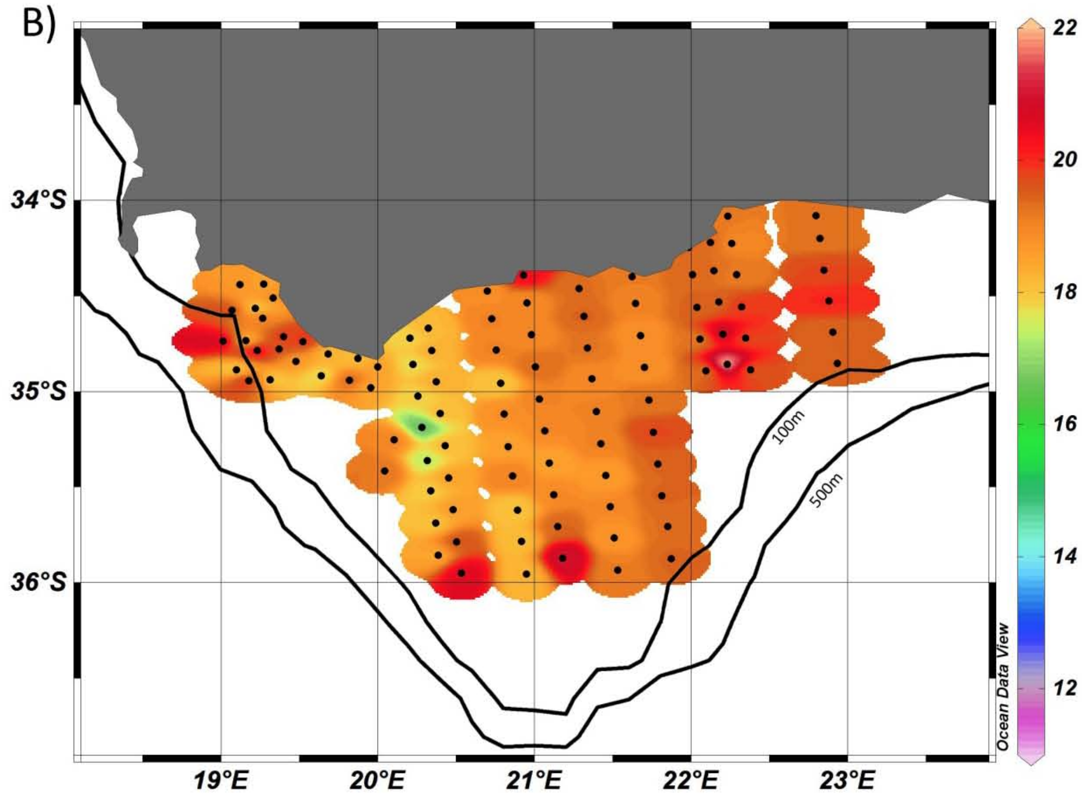
1998

A)

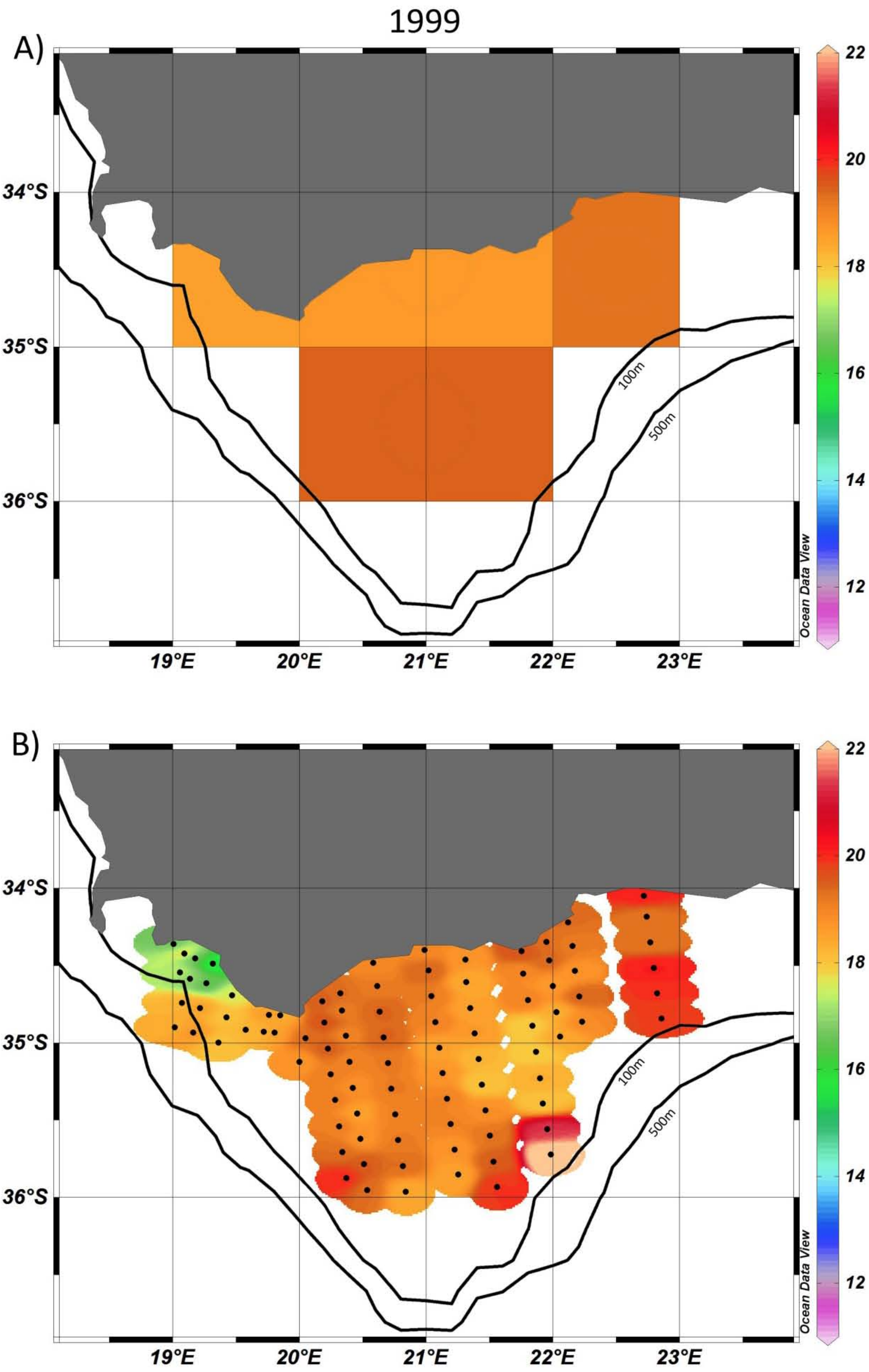


34°S
35°S
36°S
19°E
20°E
21°E
22°E
23°E
100m
500m
22
20
18
16
14
12
Ocean Data View

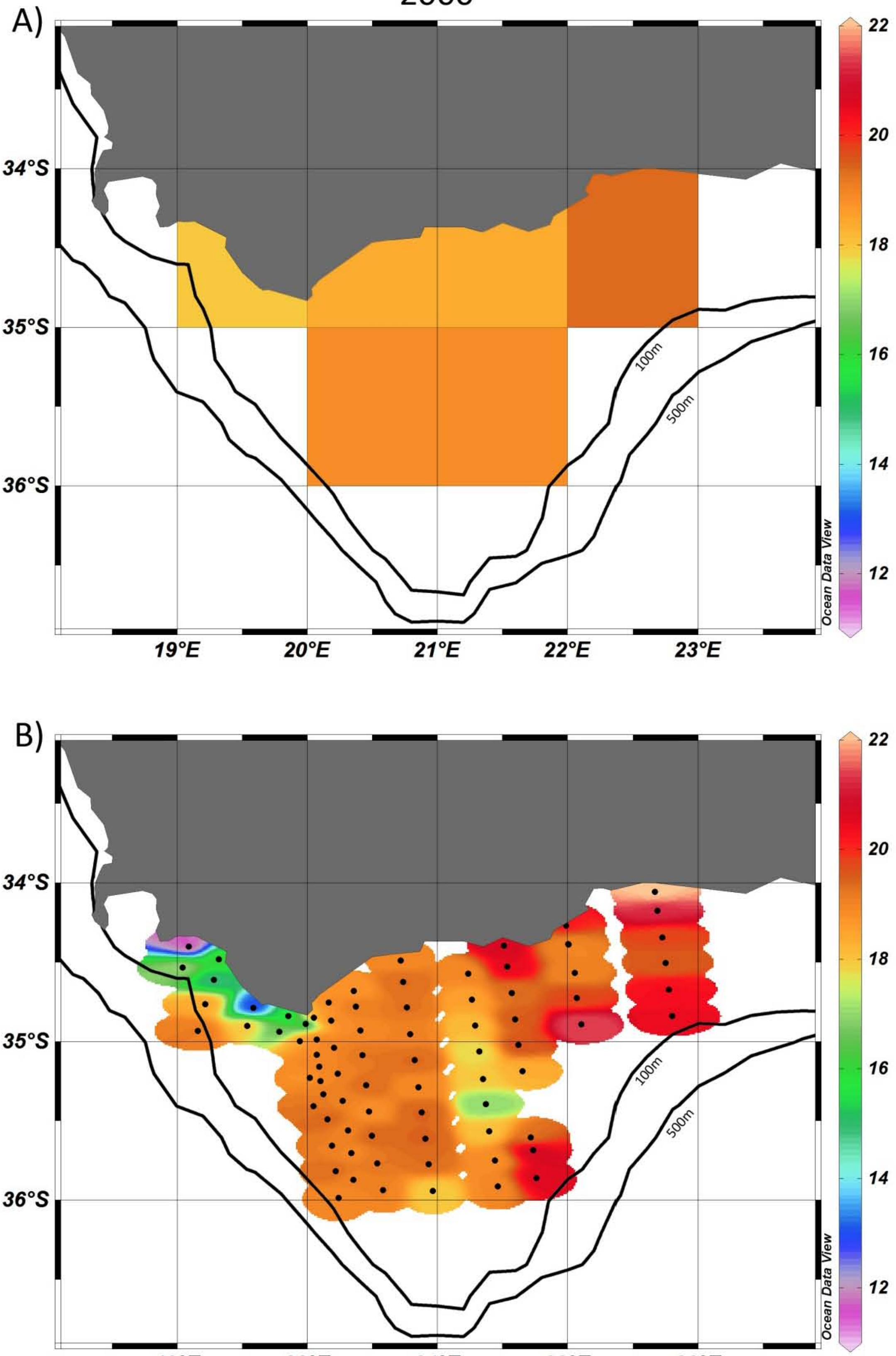
B)



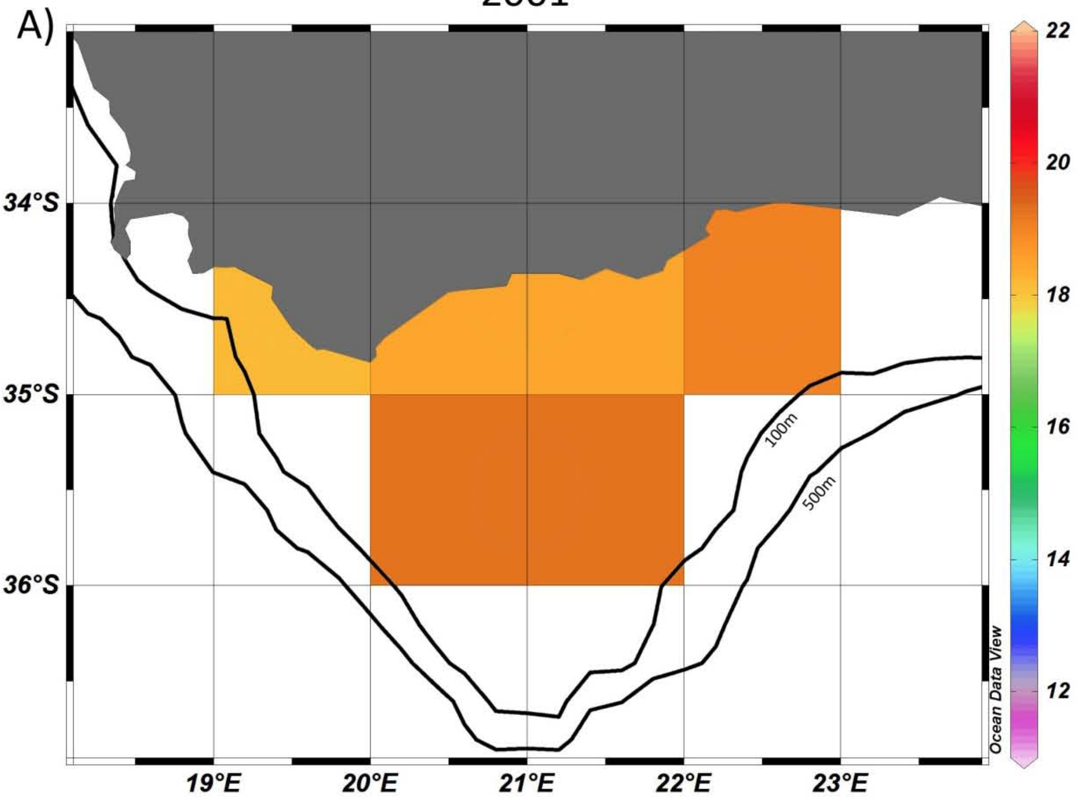
34°S
35°S
36°S
19°E
20°E
21°E
22°E
23°E
100m
500m
22
20
18
16
14
12
Ocean Data View

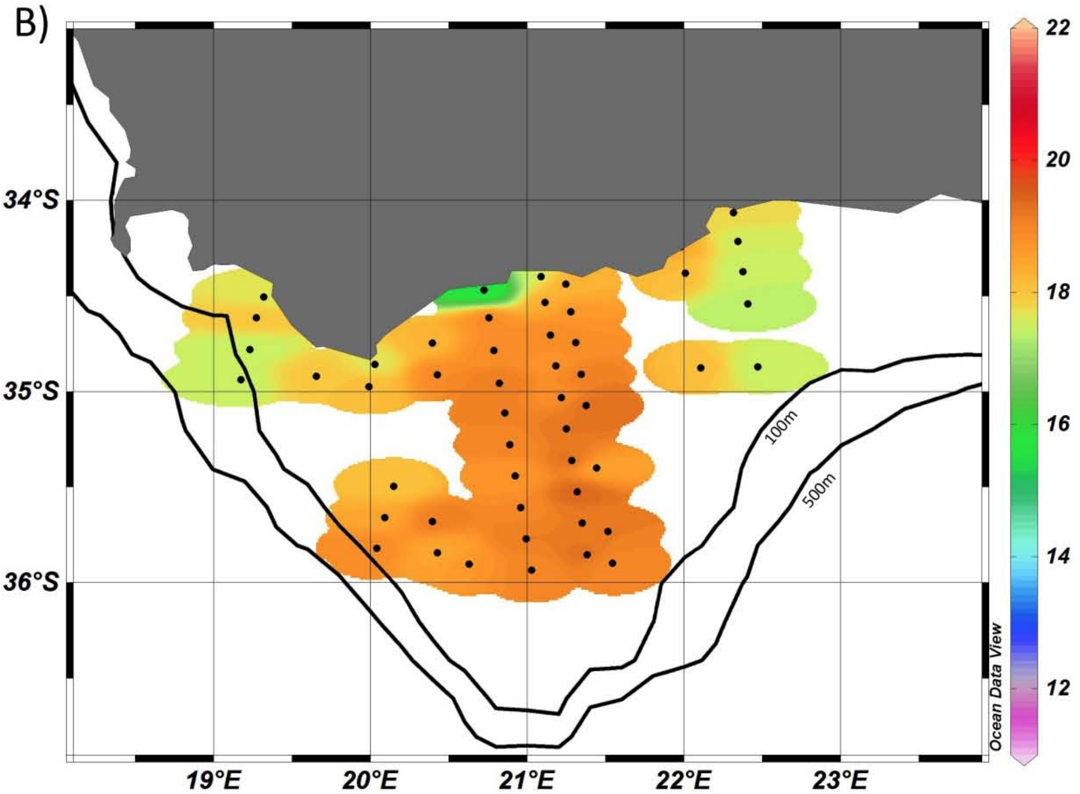

1999
A)
B)
34°S
35°S
36°S
19°E
20°E
21°E
22°E
23°E
100m
500m
22
20
18
16
14
12
Ocean Data View

2000


A)
34°S
35°S
36°S
19°E
20°E
21°E
22°E
23°E
100m
500m
Ocean Data View
22
20
18
16
14
12
B)
34°S
35°S
36°S
19°E
20°E
21°E
22°E
23°E
100m
500m
Ocean Data View
22
20
18
16
14
12

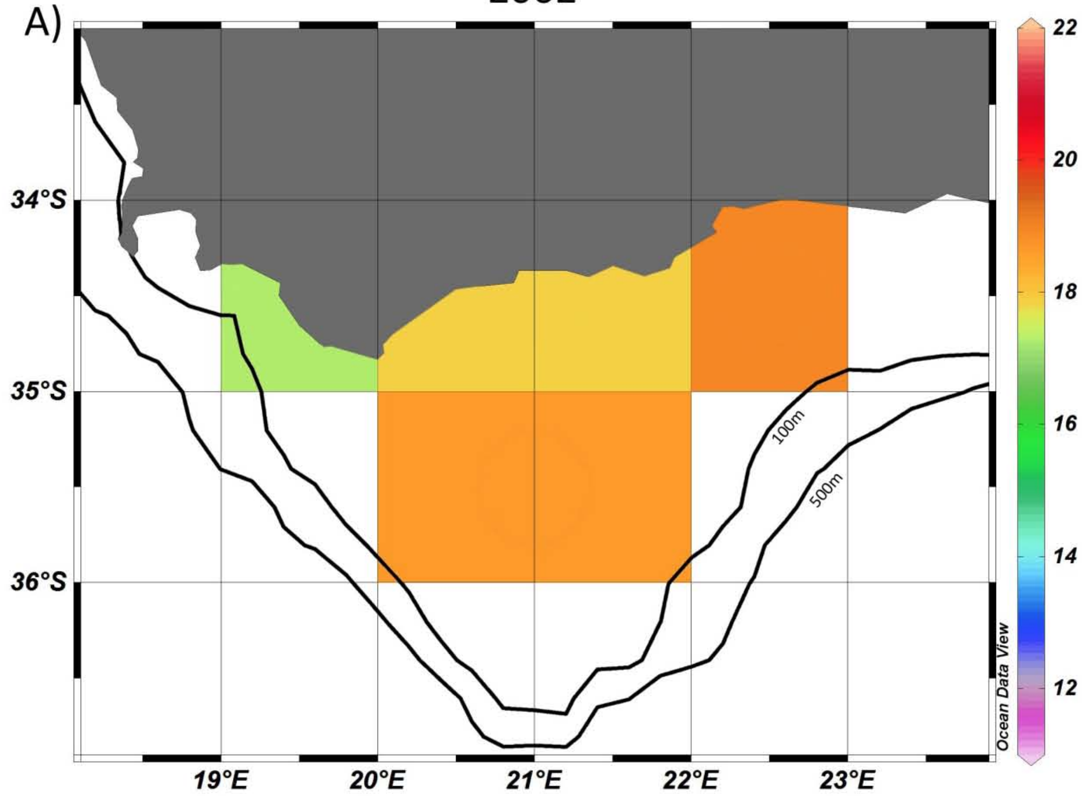
2001


A)
34°S
35°S
36°S
19°E
20°E
21°E
22°E
23°E
100m
500m
22
20
18
16
14
12
Ocean Data View

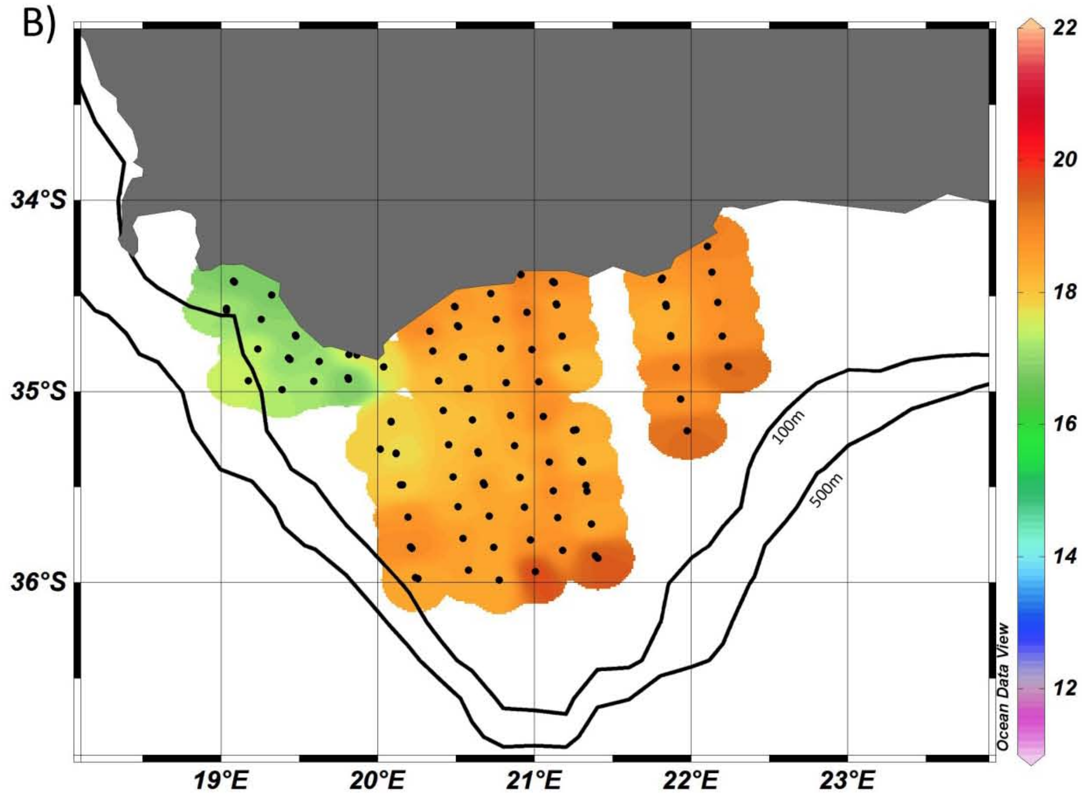

B)
34°S
35°S
36°S
19°E
20°E
21°E
22°E
23°E
100m
500m
22
20
18
16
14
12
Ocean Data View

2002

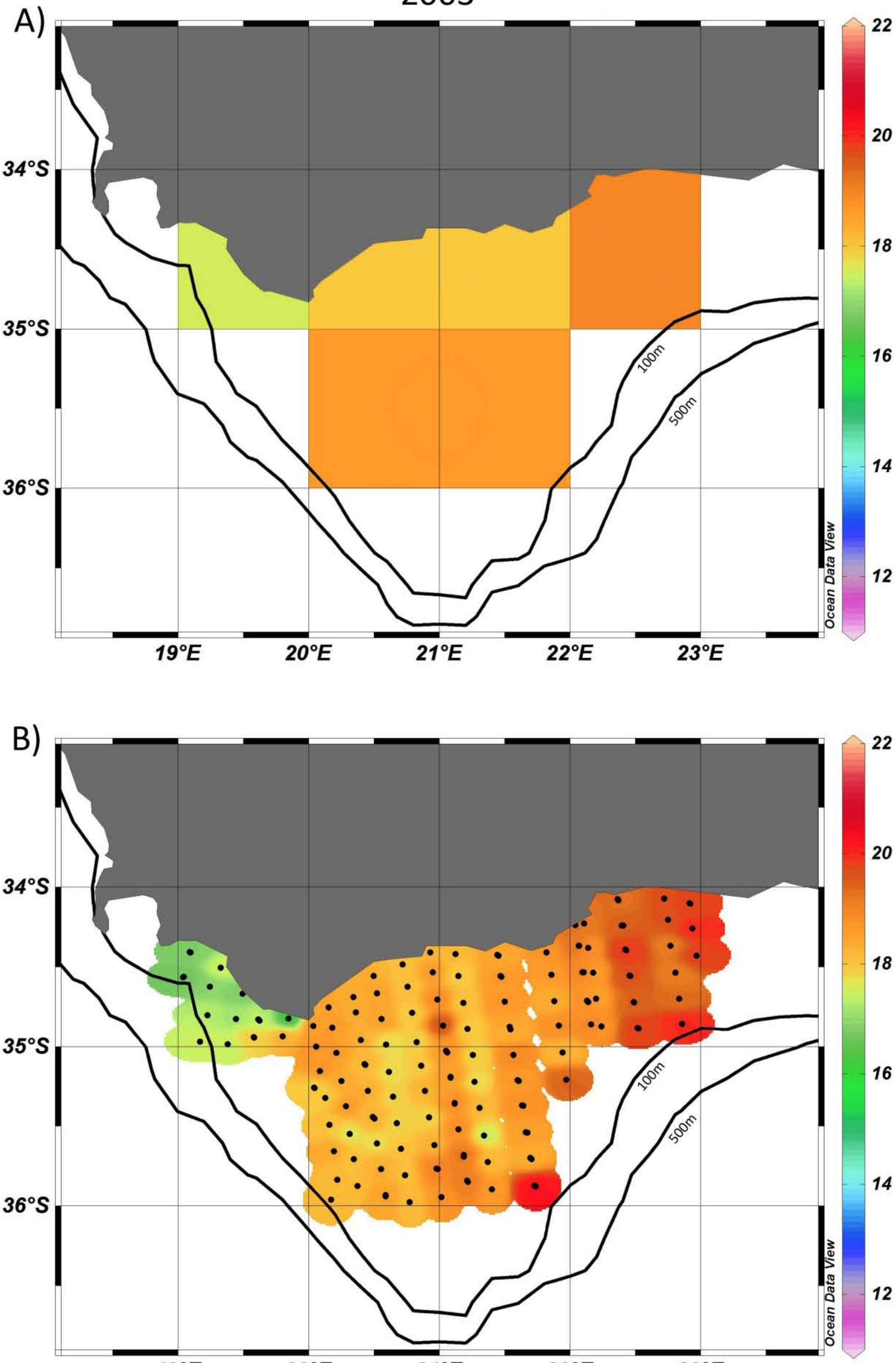
A)

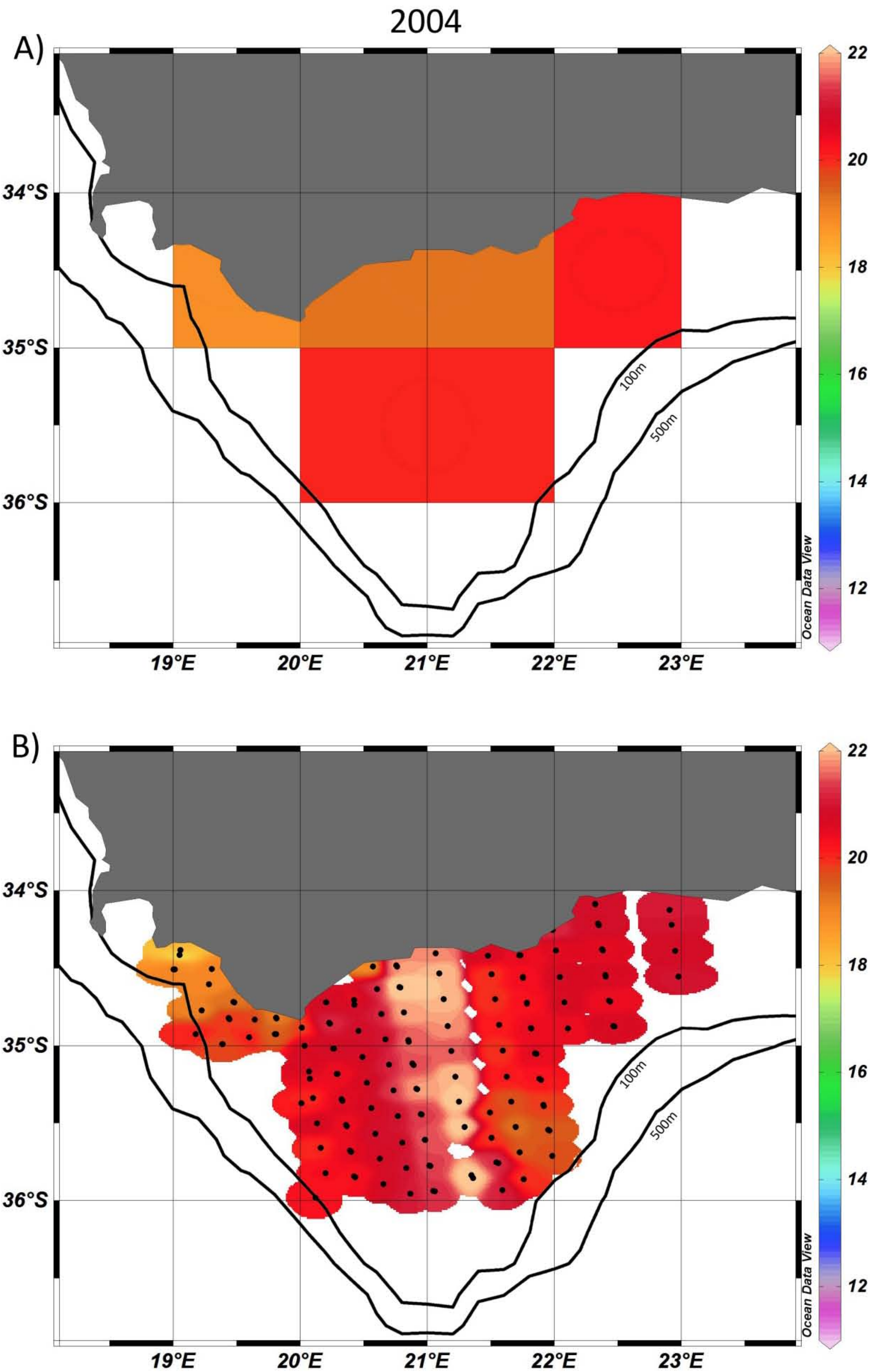

34°S
35°S
36°S
19°E
20°E
21°E
22°E
23°E
100m
500m
Ocean Data View
22
20
18
16
14
12

B)

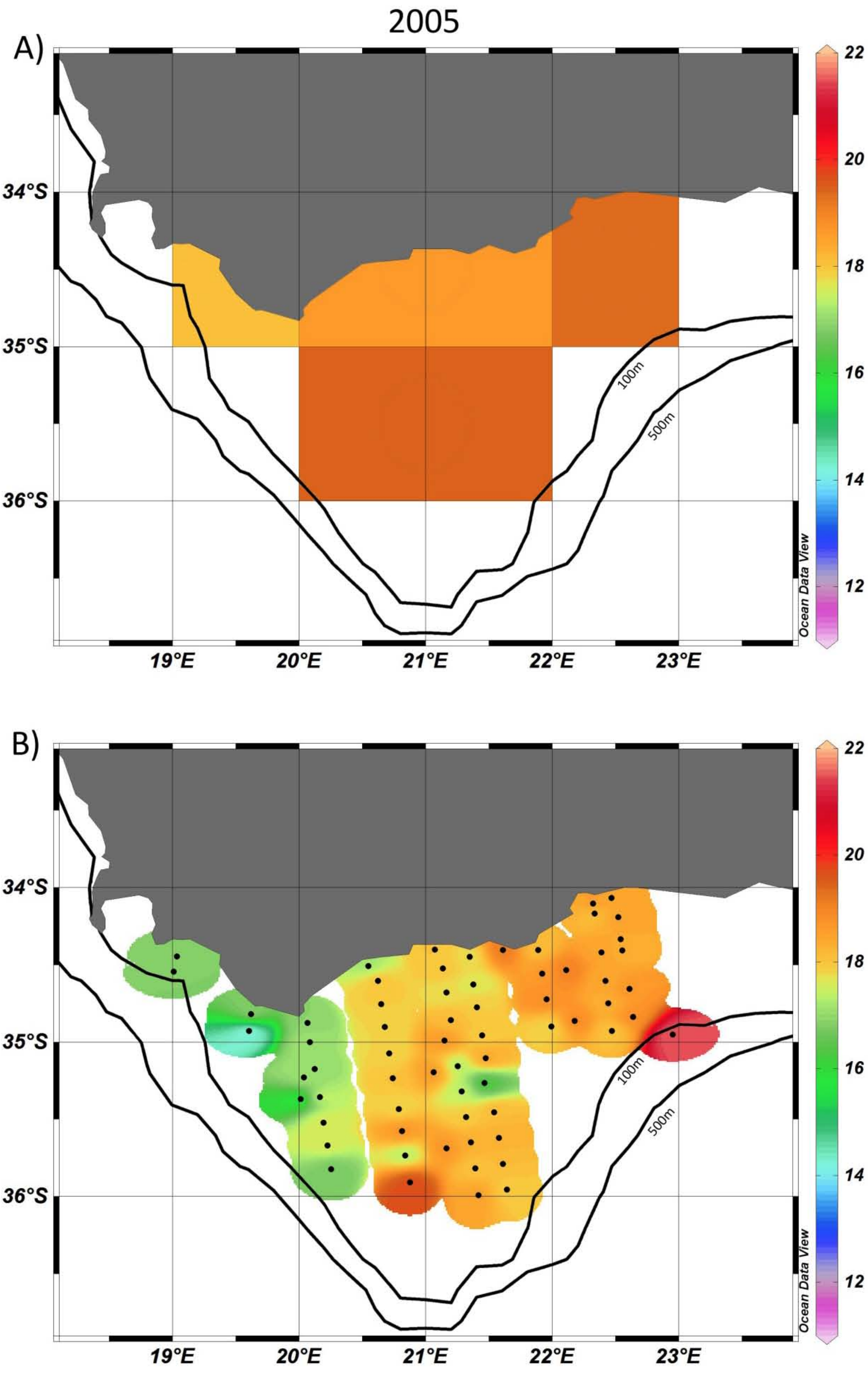

34°S
35°S
36°S
19°E
20°E
21°E
22°E
23°E
100m
500m
Ocean Data View
22
20
18
16
14
12

2003

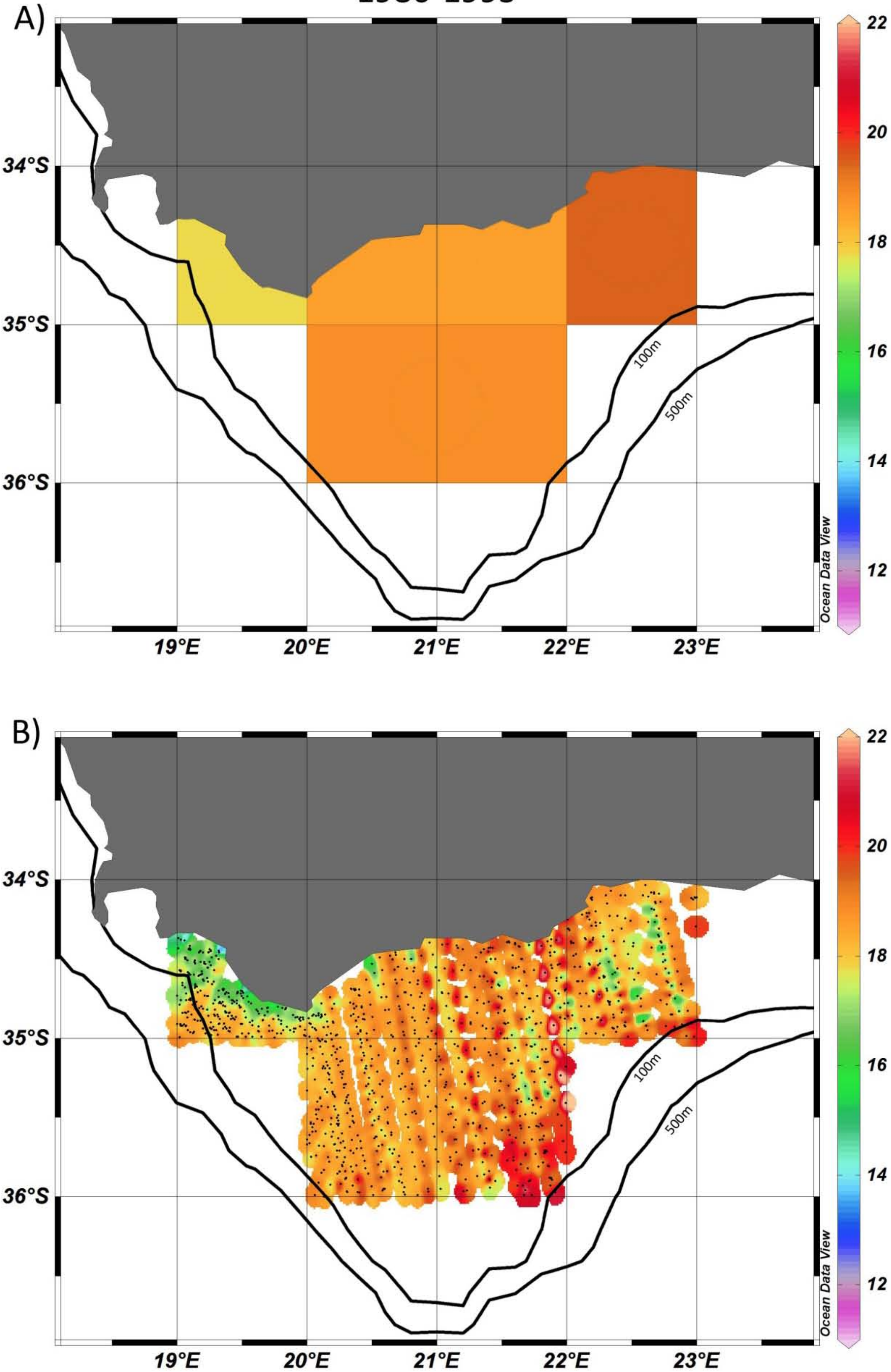

A)
34°S
35°S
36°S
19°E
20°E
21°E
22°E
23°E
100m
500m
22
20
18
16
14
12
Ocean Data View
B)
34°S
35°S
36°S
19°E
20°E
21°E
22°E
23°E
100m
500m
22
20
18
16
14
12
Ocean Data View



2004
A)
B)
34°S
35°S
36°S
19°E
20°E
21°E
22°E
23°E
100m
500m
Ocean Data View
22
20
18
16
14
12


2005
A)
B)
34°S
35°S
36°S
19°E
20°E
21°E
22°E
23°E
100m
500m
22
20
18
16
14
12
Ocean Data View

1986-1995


A)
B)
34°S
35°S
36°S
19°E
20°E
21°E
22°E
23°E
100m
500m
22
20
18
16
14
12
Ocean Data View

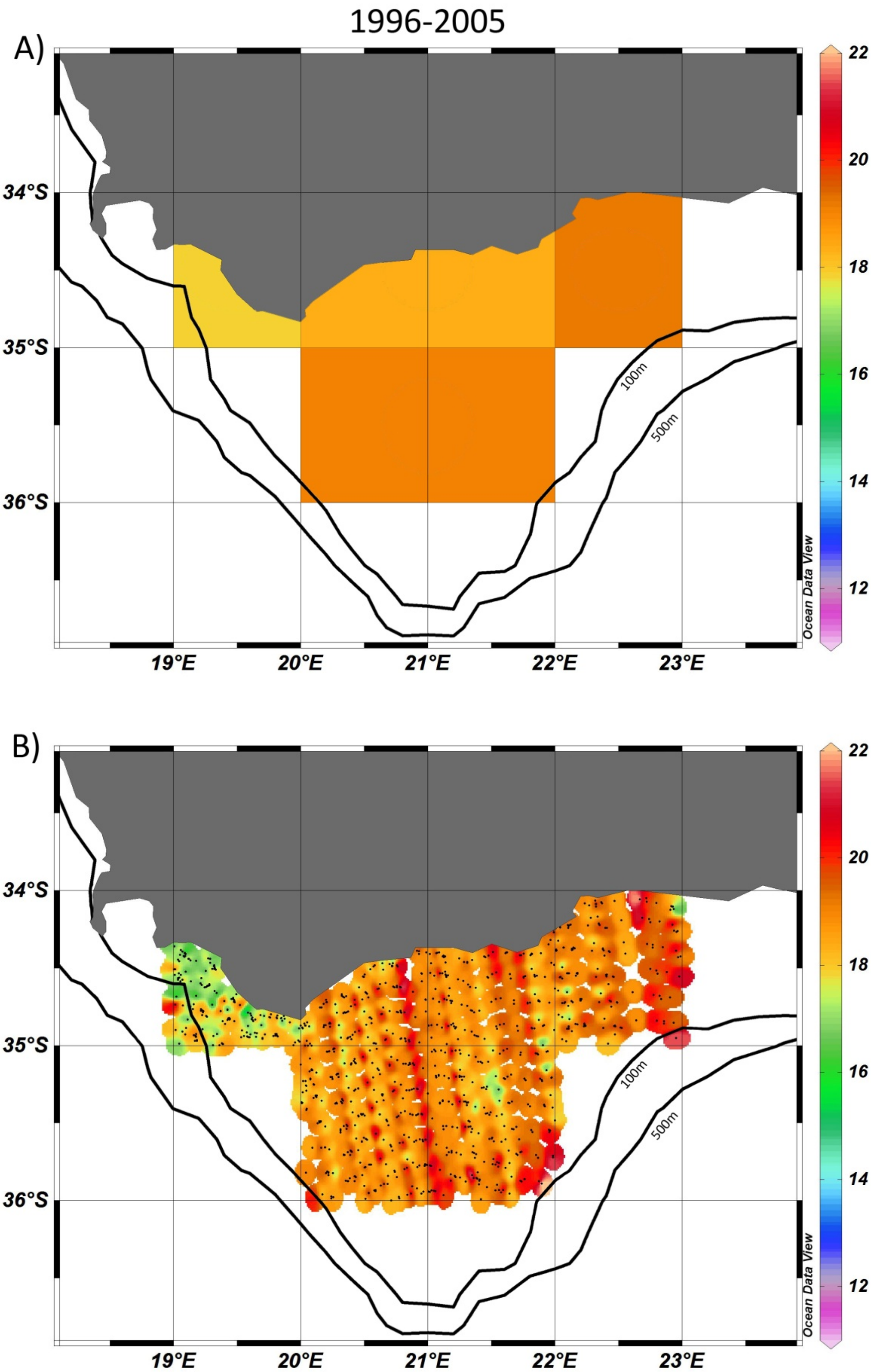


Figure A.1: Surface plots of the Agulhas Bank from 1986-2005 showing the difference in temperature detected by A) OISST.v2 and B) PISCTD data. Sample points for PISCTD data shown as black dots