Scales of variability of phytoplankton composition and biomass in Algoa Bay, South Africa

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ABBREVIATIONS AND ACRONYMS

Chl-*a*	Chlorophyll-*a*
CTD	Conductivity, Temperature, Depth
DOC	Dissolved Organic Carbon
FAO	Fisheries and Agriculture Organisation
ICES	International Council for the Exploration of the Sea
MDS	Multi-dimensional Scaling
PUFAS	Polyunsaturated Fatty Acids
POM	Particulate Organic Material
PIM	Particulate Inorganic Material
PRIMER	Plymouth Routine In Multivariate Ecological Research
SAEON	South African Environmental Observation Network
SIMPER	Similarity Percentages
TN	Total inorganic Nitrogen

Abstract

This study investigated the variability of environmental drivers of phytoplankton communities and biomass at different time scales in Algoa Bay. This research was motivated by Pacific oyster culturing at an Algoa Bay oyster farm. Time series of winds, sea surface temperatures (SSTs) and fluorescence were presented for the period from September/October 2010 to May/June 2012. The time series showed strong seasonal and interannual variability in the winds and SSTs. SSTs ranged from 12.5–25.5°C with a mean (±S.D.) of 18.4 ± 2.3°C. The dominance of south-easterly and south-westerly winds in summer of 2010/11 resulted in cooler temperatures and higher chlorophyll-*a* concentrations than were found in 2011/12. The summer of 2011/12 had non-persistent south-westerly winds that lead to warm temperatures and low chlorophyll-*a* concentrations. Two short field trips in early summer 2011 and early autumn 2012 sampled physical, chemical and biological variables. There was minor variability in the winds during these sampling periods and little spatial variability in SST. However, there were spatial differences in nutrient concentrations and chlorophyll-*a* distributions. The sampling trip in early summer 2011 found a strong thermocline at a depth of approximately 15 m, and SST ranged between 13.5 and 21°C. In early autumn 2012, deep water mixing was evident when the thermocline dropped to about 30 m, with a range of SSTs from 16.5–21°C. Temperature and nutrient values were significantly correlated (at $p < 0.001$) for NO_3, PO_4, and SiO_4 in both field trips. Phytoplankton community structure in early summer 2011 showed a 30% level of similarity in grouping of species for stations closest to the shore, which had depleted NO_3 concentrations. There was a dominance of dinoflagellates of *Gonyaulax polygramma* and other species, which are known for creating hypoxic conditions in the water column, leading to shellfish mortalities. In early autumn 2012 there was a strong grouping of samples at a 50% level of similarity alongshore, at stations with high NO_3 concentrations. In this period pennate diatoms of *Pseudo-nitzschia* sp. were abundant; this genus has been reported to produce the neurotoxin, domoic acid. Variable environmental conditions with low chlorophyll-*a* concentrations at Algoa Bay's marine culture site indicate unsuitable conditions for Pacific oyster production.

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CHAPTER 1

Introduction and Background Literature

Phytoplankton play a critical role in the primary productivity of the world's oceans (and other aquatic systems) and support marine food webs (Dawes, 1998). Phytoplankton are free-floating, microscopic, unicellular organisms that produce chemical energy from light through photosynthesis. The main groups include diatoms, dinoflagellates, flagellates and cyanobacteria. Primary productivity is normally measured in grams of carbon fixed per unit area per unit time ($g.C.m^{-2}.year^{-1}$) and defined as the rate at which light is converted into chemical energy by chemosynthetic and photosynthetic organisms (Dillion and Rodgers, 1980). This makes light an important environmental variable in phytoplankton productivity.

Other environmental variables that are essential for phytoplankton productivity include seawater temperature, nutrients and water column structure, which include mixing and upwelling events that are driven by wind. The interplay of these variables influences primary productivity. Chlorophyll-*a* concentrations ($mg.m^{-3}$) are an indicator of phytoplankton biomass in the oceans. Long-term variability in climatic conditions has an impact on phytoplankton biomass and composition at different spatial and temporal scales (Hays *et al*., 2005; Zingone *et al*., 2010), which affect phytoplankton dynamics in coastal regions. These climatic conditions primarily include wind, which drives mixing and circulation (Zingone *et al*., 2010). Rainfall also can be a significant factor as it influences freshwater inputs, nutrient loading and turbidity from terrestrial water seepage and atmospheric deposition (Zingone *et al*., 2010).

In some open bays and estuaries, variability in phytoplankton biomass relates to changes in rainfall on inter-annual scales (Gallegos *et al*., 2010), as leaching of nutrients from land supports phytoplankton biomass. However, high rainfall can suppress phytoplankton

biomass through accelerated flushing, resulting in reduced times of residence (Zingone *et al*., 2010). These are expected processes in Algoa Bay, though minor as only the Swartkops and Sundays Rivers, have estuaries opening into the bay.

Goschen and Schumann (2011) noted that changes in wind direction and speed are critical drivers in terms of intra-annual phytoplankton dynamics. Such changes can be related to the trends in phytoplankton biomass. These can either be temporary or persistent, which can also drive shifts in phytoplankton community structure. Trends in sea surface temperature (SST) over a long period and how these affect phytoplankton biomass and structure need further investigation (e.g. Kromkamp and Van Engeland, 2010; Zingone *et al*., 2010; Wiltshire *et al*., 2010).

Globally, the Pacific oyster (*Crassostrea gigas*) has been regarded as a successful bivalve culture species because of their easy adaptation to different salinities and temperatures, easy handling, fast growth and availability of culture techniques (FAO, 2006; Cassis *et al*., 2011). This species has been cultured in South African coastal waters for almost 30 years (FAO, 2006). This study will examine the marine culture site in Algoa Bay, on the South African east coast, to understand phytoplankton community structure and biophysical dynamics.

Coastal and estuarine environments are well suited for oyster culture because of enhanced primary productivity through coastal upwelling and sheltered waters, allowing more intensive rearing (Haupt *et al*., 2010). Enhanced primary productivity in coastal waters is mainly governed by coastal upwelling, where there is vertical transport of nutrient rich waters from greater depths to the surface, caused by winds at different spatial and temporal scales (Whitney *et a*l., 2005). Schumann *et al*. (2005) noted that there is persistence of easterly wind components in Algoa Bay, and this allows upwelled waters from Cape Padrone to reach Algoa Bay from the eastern sector (Figure 1.2). In this regard the physical

environment becomes a critical component that drives the phytoplankton composition in the water column.

The broad rationale for this research was to examine phytoplankton biomass and community structure in relation to the physical and chemical environment in Algoa Bay, to better understand the bivalve culture site, and assess its compatibility for Pacific oyster (*Crassostrea gigas*), which will enable better interpretation of the growth of cultured oysters.

Physics and hydrography of Algoa Bay

Algoa Bay is an open, relatively shallow (depth <70 m), eastward-facing bay located on the south-east coast of South Africa (Figure 1.1). The city of Port Elizabeth is located in the south-west of the bay within the shelter of Cape Recife. There are freshwater inputs into the bay from the Swartkops and Sundays Rivers but these are, on average, considered to be minor (Schumann *et al*., 2005). Offshore, the Agulhas Current flows south-westwards at the edge of the continental shelf. The Agulhas Current brings warm subtropical waters into the region, and sometimes these waters penetrate into the bay (Schumann, 1987).

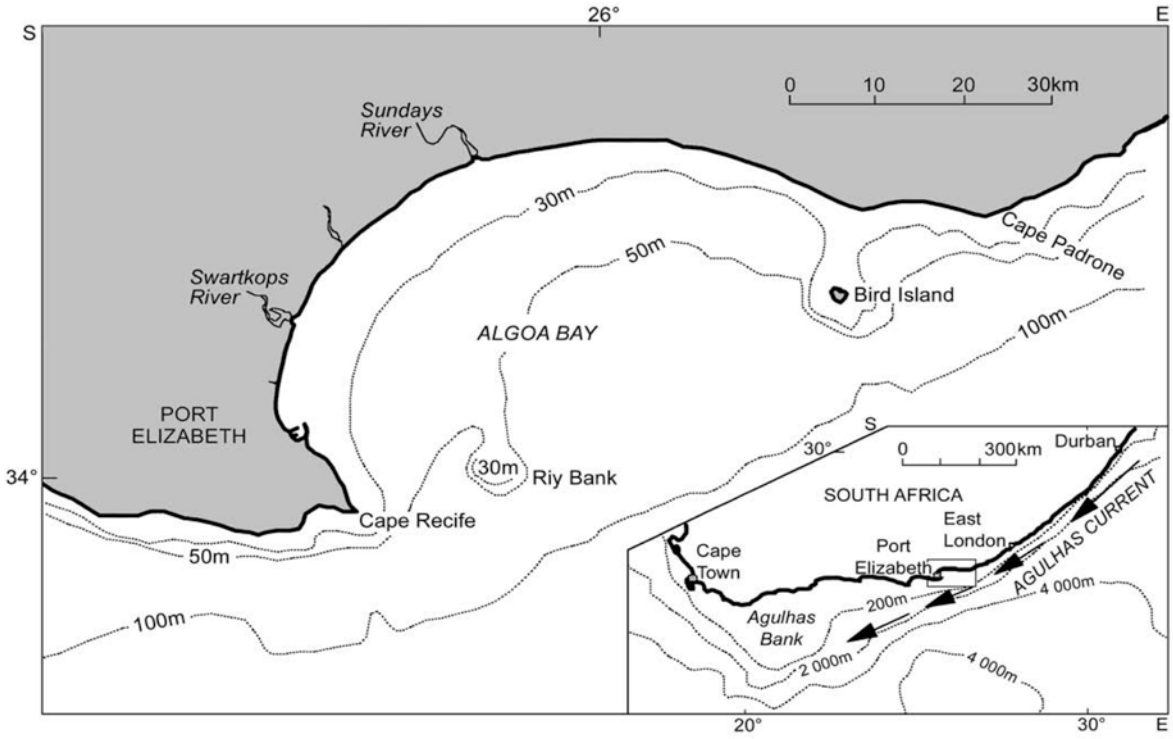

Figure 1.1: Map of Algoa Bay. The map insert indicates the flow of the Agulhas Current. Source: Schumann e*t al*. (2005).

The continental shelf widens south of the bay, which causes the core of the Agulhas Current to move offshore (Figure 1.1). Waters on the shelf are significantly colder than the Agulhas Current; consequently the inner boundary of the current displays a marked thermal gradient (Pearce, 1977). Ekman veering occurs at the bottom boundary layer, when the

direction of the current moves in a clockwise direction (southern hemisphere), from the direction of interior geostrophic velocity (Gill and Schumann, 1979; Schumann, 1986; Goschen *et al*., 2012). The evidence for Ekman veering off East London was presented by Schumann (1987). This progresses farther downstream and reaches the bottom boundary layer of the Agulhas Current. Extant colder water on the north of Algoa Bay's narrow shelf was described by Lutjeharms *et al.* (2000). However, evidence for an upwelling cell at Port Alfred was rather unresolved. There is rapid response of near shore waters to wind forcing along the coastline between Woody Cape and Port Alfred. This wind moves cold, deep water to the surface and onshore as per Schumann (1986; 1987). This coastal upwelling is driven by north-easterly winds with a northward interval and usually penetrates to the surface layers (Goschen *et al*., 2012). This influences circulation, which is controlled by the outer widened shelf of the bay (Goschen *et al*., 2012). The dominant winds throughout the year are from the south-west, although during summer the frequency of winds with an easterly component increases (Schumann and Martin, 1991). Winds are strongest in October and November and weakest in May and June (Schumann *et al*., 2005). There is marked spatial variability in winds across the bay, with land and sea breezes important in the central region of the bay, but with marked seasonal variability in the winds (Schumann *et al*., 1991). Easterly winds favour upwelling of waters off Cape Recife (Figure 1.2) (e.g. Schumann *et al*., 1988; Goschen and Schumann, 2011), but subsequent westerly winds may drive this colder water into the bay (Goschen and Schumann, 1995), favouring diatom growth on the continental shelf as nutrient rich waters dominate the shelf (e.g. Goschen and Schumann, 1995). These dynamics in the circulation cause high variability in terms of chlorophyll-*a* concentration in the bay (Goschen and Schumann, 1995).

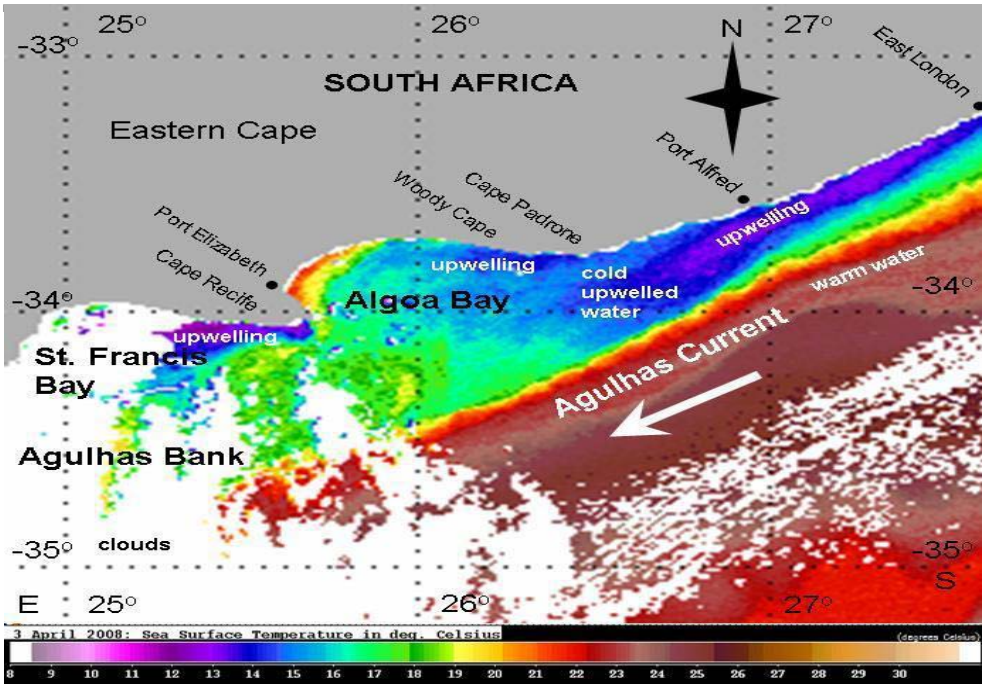

Figure 1.2: Satellite thermal image showing surface ocean dynamics off the Eastern Cape. Colder upwelling waters are indicated in blue, along the southern shoreline of Cape Recife and northern Algoa Bay in Port Alfred. The Agulhas Current is indicated by a red-brown colour with the inshore boundary at the continental shelf break. Land cover is denoted by grey area and white patches are cloud cover (Courtesy of UCT Marine Remote Sensing Unit). From Goschen and Schumann, (2011).

Chemistry

There is an increased flow of water from the bottom to the surface on the continental shelf during upwelling, which coincides with strong south-easterly winds (e.g. Boyd *et al*., 1985; Largier and Swart, 1987). This enhances nutrient supply at the surface in Algoa Bay. Carter *et al*. (1987) reported similar events on the eastern Agulhas Bank, where nitrate supply at the surface was enhanced by upwelling of water, which optimized diatom growth when the thermocline was between 10-20 m. These are anticipated conditions in Algoa Bay to support phytoplankton production, as Schumann *et al*. (2005) noted that easterly wind components are responsible for upwelling in summer.

Sustained phytoplankton growth requires a consistent and sufficient nutrient supply across the water column (Boyd *et al*., 1985). Studies on nutrient-limited marine environments in terms of phytoplankton production have indicated imprecise understanding of nutrient limitation and the scales at which these take place (Hecky and Kilhan 1988; Howarth 1988; Malone *et al*., 1993; 1996).

Research has indicated that most regions on the western boundary of ocean basins are associated with nutrient limitation on the coastal sites, especially nitrogen elements. This could be a similar case for Algoa Bay, which can have an impact on phytoplankton productivity and biomass. Nitrogen is essential for primary productivity, and mainly consists of two differently formed nitrogenous elements of ammonium and nitrate (Yool *et al*., 2007). Nitrate formation is based on oxidation of ammonium through nitrification, whereas ammonium is generated when nitrogen is used up in food webs through the metabolic processes of marine organisms and recycled as dissolved ammonium (Yool *et al*., 2007). Shallow, open bays normally limit nitrification rates, which are normally assumed to be maximised by greater depths. However, it remains a challenge to quantify nitrification based on depth because light penetration is limited by depth (Yool *et al*., 2007).

Phytoplankton composition and biomass

Several studies of phytoplankton and seasonal chlorophyll-*a* productivity have been conducted on the southern coastal region of the Agulhas Bank (e.g. Probyn *et al*., 1994). However, there has not been much focus on phytoplankton productivity in Algoa Bay. Time series for the periods of June to August 1989 and November 1989 to January 1992 on the eastern Agulhas Bank have indicated that there were marked seasonal cycles for mean chlorophyll-*a* concentrations over the Agulhas Bank. In winter the chlorophyll-*a* concentrations were low and increased steadily from spring to late summer (Probyn *et al*., 1994). *In situ* measurements indicated that the western sector of the Agulhas Bank is a coastal upwelling dominated area with enhanced chlorophyll-*a* concentrations. However, the eastern sector had limited chlorophyll-*a*, which reached Algoa Bay through the impact of western coastal upwelling and an inner upwelling ridge at Cape St. Francis (Probyn *et al*., 1994). These chlorophyll-*a* concentrations also indicated high spatial variability between eastern and western sectors of the Agulhas Bank.

Studies on seasonal phytoplankton composition have been conducted in Chesapeake Bay, Virginia, in the United States of America. This area has been studied extensively for phytoplankton composition and seasonal dynamics (e.g. Wolfe, *et al*., 1926; Cowles 1930; Nocross, 1971; Mulford, 1972; Patten *et al*., 1973; Marshall 1976). Chesapeake Bay shares some features with Algoa Bay, such as freshwater inputs from surrounding rivers, coastal water inputs and the fact that both are shallow bays, although at different latitudes. In both of these bays water circulation is strongly influenced by winds that are controlled by seasonal variability. Chesapeake Bay is a more complex system than Algoa Bay as it is composed of a number of estuarine ecosystems surrounding the bay, which strongly influence internal flow in the system. In contrast, the western sector of Algoa Bay has only two estuarine inputs,

from the Swartkops and Sundays Rivers. However, the diversity and composition of phytoplankton in Chesapeake Bay and Algoa Bay might be comparable.

Persistence in physical variables and their impacts on seasonal cycles differ between ecosystems. Wind and rain contribute prominently to seasonal variability in many near shore ecosystems (Briceño and Boyer, 2010), due to stochasticity in hydrology, light intensity and nutrients. Light and temperature are great determinants of inter-annual resilience of the seasonal chlorophyll cycle in open bays and estuaries, which drive phytoplankton communities and the overall pattern of species succession (Zingone *et al*., 2010). Short-term and seasonal variability can be challenging to study in terms of accurate quantification because the spatial and temporal scales of observations are limited. In this regard, the impact of environmental variables on phytoplankton structure and abundance vary from one coastal region to another (Zingone *et al*., 2010).

Time series are needed to understand trends in phytoplankton dynamics in relation to perturbations from environmental factors such as eutrophication and nutrient leaching in coastal regions (Duarte *et al*., 2009). Studies have shown that phytoplankton biomass and community structure have strong correlations with variability in nutrient concentrations, altering species composition. Zingone *et al*. (2010) noted that shifts in phytoplankton community structure in most estuaries and shallow bays can coincide with changes in nutrient loads, such as a shift in the dominance from *Skeletonema* to *Chaetoceros* species. Such shifts in Algoa Bay might be associated with the interactions between the hydrography and environmental variables. These include winds and sea surface temperatures, which vary at short term to seasonal scales (Goschen *et al*., 2012), influencing nutrient concentrations and the phytoplankton community.

According to Dali (2010), variability in spatial and temporal distributions of nutrients and sea surface temperatures in Algoa Bay results in variability of phytoplankton biomass.

On a seasonal scale, there is lowest phytoplankton biomass in winter and highest in summer (e.g. Schumann and Campbell, 1999). In Algoa Bay phytoplankton biomass ranges from 1 to 6 $\mu g.L^{-1}$, with higher values near the surface (Schumann and Campbell, 1999; Campbell, 2000). A coastal upwelling cell off Cape Recife was noted by Beckley (1988). This causes temporal differences in temperature in the bay. These wind-driven upwelling events cause the intrusion of nutrient-rich waters to surface, and enhance phytoplankton production on the western sector of Algoa Bay. This dissertation tests the hypothesis that phytoplankton production is generally low within Algoa Bay due to dissolved nitrogen and phosphorous nutrient limitation, as is the case in most coastal areas (Fisher *et al.*, 1992; Berman *et al.*, 2005), but can be enhanced through intermittent upwelling or mixing events, which influence phytoplankton community composition.

There has been limited research on phytoplankton beyond the surf zone in Algoa Bay, resulting in a need for better understanding of the phytoplankton community structure of the region. This project is aimed at understanding the role of variability in the physics (seawater temperature and winds) and chemistry (nutrients) of Algoa Bay in driving phytoplankton communities and assemblages. These biophysical dynamics will be examined at three different scales: event (upwelling/algal bloom), seasonal and inter-annual, to test the hypothesis that the scales of variability influence the suitability of the marine environment for the culture of Pacific oysters (*Crassostrea gigas*) in Algoa Bay.

CHAPTER 2

Environmental drivers of phytoplankton composition in Algoa Bay.

Introduction

Algoa Bay is one of the few commercial shellfish culture sites in South Africa. In general, an expanding consumer base has propelled growth in the shellfish industry and has therefore motivated extensive research in an effort to boost shellfish production by understanding the food quality requirements and growth rates (Loret *et al*., 2000). Cloern and Jassby (2010) stated that understanding the scales of variability of phytoplankton composition can depict persisting environmental conditions that drive phytoplankton production and biomass, and their relationship at different time scales. Furthermore, this has ecological implications for the dynamics in the marine culture site in terms of the potential for shellfish growth, water quality and food availability (Cloern and Jassby, 2010).

This study investigated phytoplankton composition and biomass to understand the relationships between environmental variables and phytoplankton community structure. This was motivated by culturing of the Pacific oyster, a non-invasive alien species (*Crassostrea gigas*) in Algoa Bay. Since Algoa Bay is located in a western boundary warm current (Figure 1.1), the water has been characterised as nutrient deficient (e.g. Goschen and Schumann, 1995). This limits growth of phytoplankton that serves as food for the oysters, measured in terms of chl-*a* concentration at the depth where oysters are cultured (Gangnery *et al*., 2003). Oysters are filter-feeders, and are unable to make their own required nutrients to nurture their growth and development. Polyunsaturated fatty acids (PUFAS) and sterols are main food requirements in oysters' diets (Loret *et al*., 2000). The understanding of the phytoplankton species composition in Algoa Bay will give an idea of the potential for oyster growth. This information can be used by the oyster farm to improve oyster food requirements and also to

optimize oyster culture in a cost-effective manner, because not all phytoplankton contain required nutrients for oyster culturing (Loret *et al*., 2000).

Light and nutrient concentrations in the water column are the main drivers for phytoplankton growth and influence chlorophyll-*a* concentrations. Temperature, algal biomass and concentrations of particulate organic material (POM) and particulate inorganic material (PIM) are the environmental variables that are predominantly responsible for oyster growth (Brown, 1988; Brown and Hartwick, 1988; Bougrier *et al*., 1995; Barille *et al*., 1997; Toro *et al*., 1999; Gangnery *et al*., 2003; Flores-Vergara *et al*., 2004).

Nutrient supply in Algoa Bay is limited (e.g. Goschen and Schumann, 1995), which creates unsuitable environmental conditions for phytoplankton growth as food for oyster. A study by Pieterse *et al*. (2012) compared the growth rate and condition of the Pacific oyster cohorts in three different oyster farms in South Africa, and related these to sea temperature and phytoplankton biomass. The results in Algoa Bay showed higher phytoplankton consumption compared to other oyster culture sites on the west coast, such as Saldanha Bay (Pieterse *et al*., 2012), when fed on smaller-sized phytoplankton. These enhanced oyster growth rates, despite low phytoplankton growth (Pieterse *et al*., 2012), makes Algoa Bay not suitable as a commercial oyster farm but rather a nursery. Growth rates of oysters in Algoa Bay and Saldanha Bay respectively were 0.25-0.58 and 0.17-0.35 g.oyster^{-1}.day^{-1}(Pieterse *et al*., 2012). Oysters in oligotrophic ponds at Kleinzee yielded 0.04-0.23 g.oyster^{-1}.day^{-1} (Pieterse *et al*., 2012). There was reasonable growth in oysters at juvenile stages in Algoa Bay.

In Algoa Bay the mean chlorophyll-*a* concentration was 2-6 times lower than at Saldanha Bay. Oysters in Algoa Bay showed better shell growth than body size, which uplifted mass gain in all weighed cohorts (Pieterse *et al*., 2012). In Saldanha Bay the growth of oysters was enhanced by cool water temperatures enriched with nutrients at the bottom

cage layers, which yielded chlorophyll maxima of 41.9 $mg.m^{-3}$ (Pieterse *et al*., 2012). In Kleinzee there was a slow growth rate of oysters because of low phytoplankton biomass, regardless of high oyster shell masses (Pieterse *et al*., 2012). These measurements were done to understand oyster feeding efficiency with response to food supply (phytoplankton) in all three sites.

Previous phytoplankton research conducted in Algoa Bay mainly investigated naturally occurring diatoms in the surf zone, especially species of *Anaulus*, *Asterionella* and *Aulacodiscus* diatoms (Perissinoto *et al*., 1987). Other studies on surf zone diatoms were conducted by Talbot and Bate (1986), where they looked at the phytoplankton biomass to understand factors responsible for the formation and decline in cell patches in the surf zone. They specifically investigated diel changes in cell division of *Anaulus australis* (Grunow), to characterise asexual reproduction in the north-east sector of Algoa Bay. Since Algoa Bay is oriented on the western boundary of the warm Agulhas Current, it is hypothesized that Algoa Bay is generally nutrient limited and phytoplankton production is low.

This study aimed at identifying microalgal species in the phytoplankton that are found within the western sector of Algoa Bay and relating them to environmental variables to understand their scales of variability in terms of chlorophyll-*a* concentration and community structure.

Materials and methods

The study was located in the western sector of Algoa Bay on the south-eastern coast of South Africa. Sampling was centred at a station located on an oyster farm (33°56'48.65S; 25°36'40.70E) about 1 km from the Port Elizabeth harbour (Figure 2.1). Sampling was undertaken through a deployment of a mooring on the oyster farm and two field studies providing further spatial details.

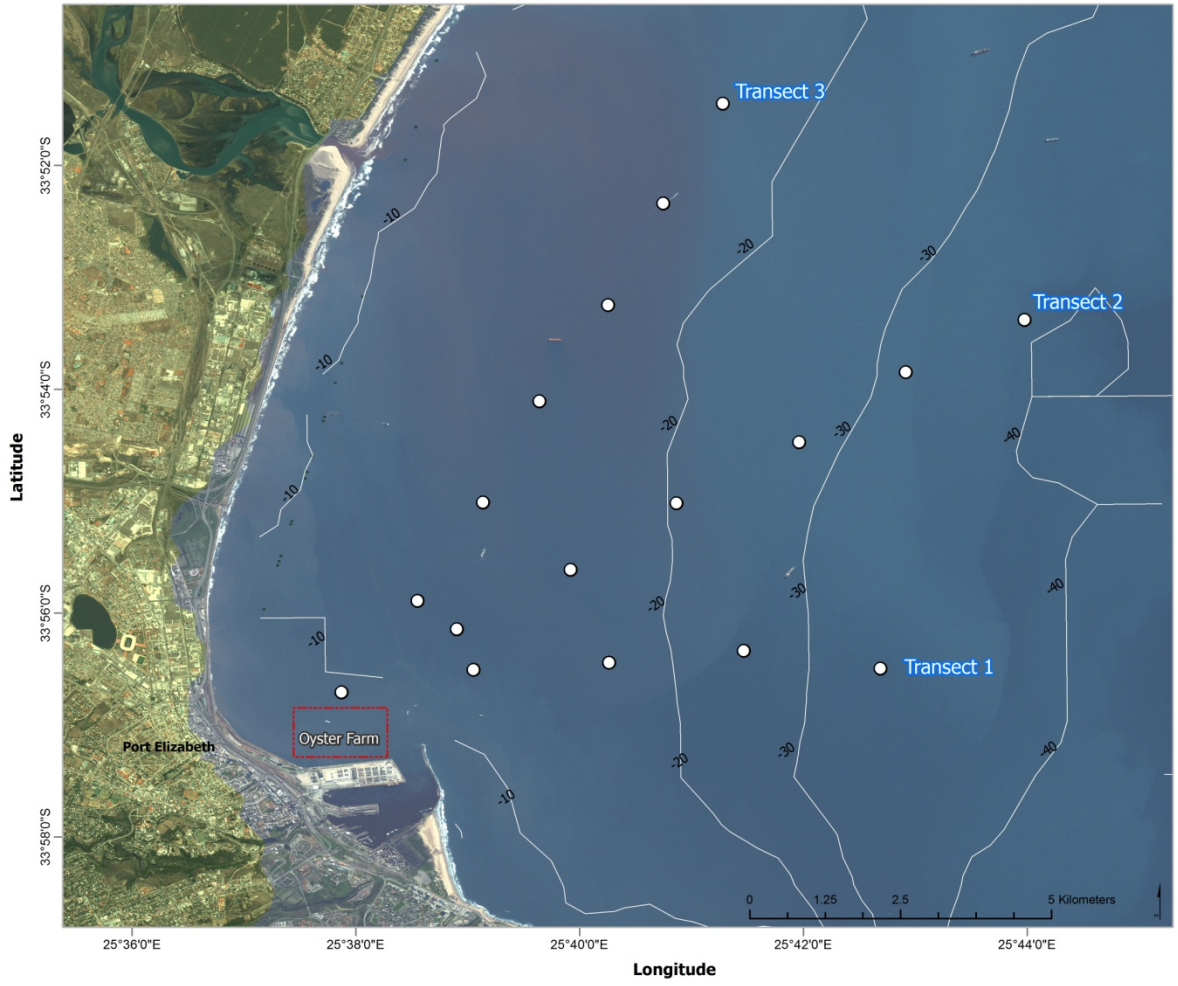

Figure 2.1: Aerial photograph of Algoa Bay illustrating the geographical setting of the oyster farm demarcated by the red box on the left and location of the sampling stations denoted by white dots within the three transects. Aerial photograph: courtesy of SANBI, Biodiversity Planning Unit (Kirstenbosch).

In situ wind data were obtained from the Weather Bureau at Port Elizabeth Airport through the South African Environmental Observation Network (SAEON). The wind data run from 1 October 2010 to 1 May 2012 and progressive wind plots were provided using

MATLAB for two eight-month periods, which covered the two field trips. Wind vectors were also produced using *MATLAB* for the periods from 19 November to 2 December 2011 (early summer) and from 27-30 March 2012 (early autumn), providing wind conditions before and during the two field trips.

A submersible WET Labs ECO Fluorometer was moored on the oyster farm from 15 September 2010 to 4 June 2012. This instrument provided mean hourly estimates of temperature and chlorophyll-*a* concentrations. *In situ* fluorescence readings were calibrated through comparison with extracted chlorophyll concentrations. Data obtained were used to plot the time-series.

Water samples were taken in early summer and early autumn. Three ski-boat transects of approximately 13 km length were sampled. The transects consisted of 5-7 stations that were 1 nautical mile apart (Figure 2.1). A portable Sea-Bird (SeaCat SBE-19) conductivity [=salinity], temperature, and pressure [=depth] (CTD) was used to profile the water column at each station, providing records of temperature, salinity and depth, which were stored on an internal logger. Profiles were made at discrete depths ranging from 0 m to 5 m inshore and from 0 m to 35 m offshore. Also attached to the CTD was a WET Labs Fluorometer (WETStar), providing fluorescence data. The calibrated fluorescence data were used to provide estimation of chlorophyll-*a* concentration. Data were stored as Excel files.

For nutrients, water samples were collected in 50 mL plastic bottles and stored in a cooler box before being analysed at the laboratory. Five nutrients were measured: NO_3, NH_4, NO_2, PO_4 and SiO_4. These nutrients were analysed according to the standard methods of Grasshoff *et al*. (1976). Total nitrogen (TN) was estimated by adding the concentrations of inorganic nitrogen-containing compounds i.e. NO_3, NH_4 and NO_2. Total nitrogen concentration was plotted against PO_4 and SiO_4 concentrations. This was done to determine if nitrogen was a limiting element or not in coastal waters.

For chlorophyll-*a* concentration, water samples of 200 mL were collected in plastic bottles and kept in a coolbox prior to analysis. These were collected from depths at 0 m, 5 m, 10 m, 15 m, 20 m, 30 m, and 35 m by means of Niskin bottles. Samples were filtered through Whatman GF/F filters and extracted in 90% acetone overnight. Chlorophyll-*a* analyses were done according to Parsons *et al*. (1984).

Sample preservation and identification

In total, 34 water samples of 200 mL were collected over 3 days for each field trip and fixed in buffered formalin solution for the enumeration of phytoplankton by the Utermohl method, as modified by Hasle (1978). Prior to counting, samples were gently shaken 50 times to allow all the cells to be fully suspended, before pouring into cleaned sedimentation chambers of 25 mL, and allowed to settled overnight at room temperature with no direct sunlight. The chamber bottoms with settled cells were viewed with either a *ZEISS 476100* or *OLYMPUS IX50* inverted microscope. The chamber bottoms were viewed initially at *16x* magnification to assess cell density and distribution, and then counted at the higher magnification of *40x*. In each sample four diagonal transects were counted to quantify the numbers of cells in each slide (Utermohl, 1931; 1958). Phytoplankton cells were mainly identified to genus level and others to species level. A book by Tomas *et al*. (1997), with species names and pictures, was used to verify identification.

The following formula was used to calculate cell concentrations for each sample.

$$Cell\ concentration\ (cells.ml^{-1}) = \frac{cell\ count\ x\ area\ of\ chamber\ (mm^2)}{area\ counted\ (mm^2)\ \text{X}\ {}^{1}/_{volume\ settled\ (ml)}}$$

Where:
Area of the chamber = 490.87 mm^2
Area counted (AC) = width of strip (e.g. 0.76µm^2 at x16 and 0.31µm^2 at x40 magnification) x length of strip (e.g. 15 mm) x number of strips (e.g. 4)
Volume settled (e.g. 25ml)

Data handling and processing

Microsoft Excel was used to store the CTD data and to produce scatter plots. *STATISTICA* (StaSoft Enterprise, 2013) version 10 was used to calculate correlation coefficients between nutrients and temperature, and to calculate linear regressions and plot time-series data for temperature and chlorophyll-*a* concentrations. *MATLAB* version 7.10.0 (The Mathworks Inc., 2010a) was used to produce progressive vectors and feather plots for the wind data. An aerial photograph, obtained from the SANBI data base, was imported using *ARC-GIS* version 9.1 (ESRI, 2006) to produce a geographical display of the location of the oyster farm and sampling stations. Sections of temperature, nutrient profiles and chlorophyll-*a* plots were created using the contouring package, *SURFER* 8.06 (Golden Software Inc., 2002).

Multivariate analysis for biological and environmental data in early summer and early autumn was done using *PRIMER* version 6.1.5 (Clarke and Gorley, 2006). The data for early summer were square root transformed, and the early autumn data were fourth root transformed to down-scale the dominance of abundant species. A Bray-Curtis similarity matrix was used. Dendrograms and multidimensional scaling (MDS) were used to examine sample groups and compare community structure between the two sampling periods. Similarity percentage (SIMPER) analysis with a cutoff of 90% was performed for transformed data to determine species responsible for dissimilarity between the sampling periods. Biological data (samples) were denoted by groups *a* to *e* and nitrate concentrations were arranged in three different ranges of 0.01-0.04 $\mu M.L^{-1}$, 0.06-0.08 $\mu M.L^{-1}$ and 0.09-0.47 $\mu M.L^{-1}$ for early summer and 0.02-0.09 $\mu M.L^{-1}$, 0.12-0.46 $\mu M.L^{-1}$ and 0.51-1.43 $\mu M.L^{-1}$ for early autumn. These analyses were presented through the MDSs in both sampling periods.

Results

Time series and progressive winds

A time-series plot of temperature and chlorophyll-*a* concentrations was presented from 15 September 2010 to 4 June 2012 (Figure 2.2). Seasonal variability was indicated by cool sea surface temperatures in winters (of 2011 and 2012) and warm sea surface temperatures in summers (of 2010/11 and 2011/12). Throughout the full time series, sea surface temperatures ranged from 12.5 to 25.5°C with a mean ± S.D. of 18.4 ± 2.3°C. The field trips showed a similar trend in SSTs. The early summer field trip was at the beginning of the warming period with mean SST of 20.9°C, whereas the early autumn field trip had a mean of 19.8°C.

Seasonality was less evident in the chlorophyll-*a* concentrations. In summer and winter of 2011 there were periods of very high and low values. In summer 2012 the chlorophyll-*a* concentration was relatively lower than the previous summer. Chlorophyll-*a* median concentration for the time-series was 3.1 $mg.m^{-3}$ with a range of 0.5 to 138.7 $mg.m^{-3}$ and a mean ± S.D. of 4.1 ± 2.8 $mg.m^{-3}$. The field trips showed differences in chlorophyll-*a* concentrations with relatively lower concentrations for early summer than the early autumn field trip. The early summer field trip had a mean chlorophyll-*a* concentration of 3.6 $mg.m^{-3}$ and the early autumn trip had a mean chlorophyll-*a* concentration of 3.0 $mg.m^{-3}$. There was also interannual variability in SST between the two years. The summer of 2012 was notably warmer than that of 2011, with low chlorophyll-*a* concentrations.

Winds were different between the two years (Figure 2.3a and b). In 2010/11 south-easterly and south-westerly winds dominated, whereas in 2011/12 south-easterly winds were far less prominent. In 2010, the winds blew from a south-westerly direction during spring (October to December) (Figure 2.3a) but in summer (December to March) the wind direction changed to south-easterly, and persisted for approximately three months. In the following year, the winds were predominantly south-westerly, with less variability compared to the

previous year (Figure 2.3b). The dominance of south-easterly winds in summer of 2010/11 was responsible for notable cooling, which elevated phytoplankton biomass (Figure 2.2). The absence of south-easterly winds in summer of 2011/12 was associated with warming and low phytoplankton biomass. Wind vectors for early summer alternated between south-westerly and easterly winds, with a few reversals in wind direction. Early autumn showed strong south-westerly winds, with periodic easterly-winds.

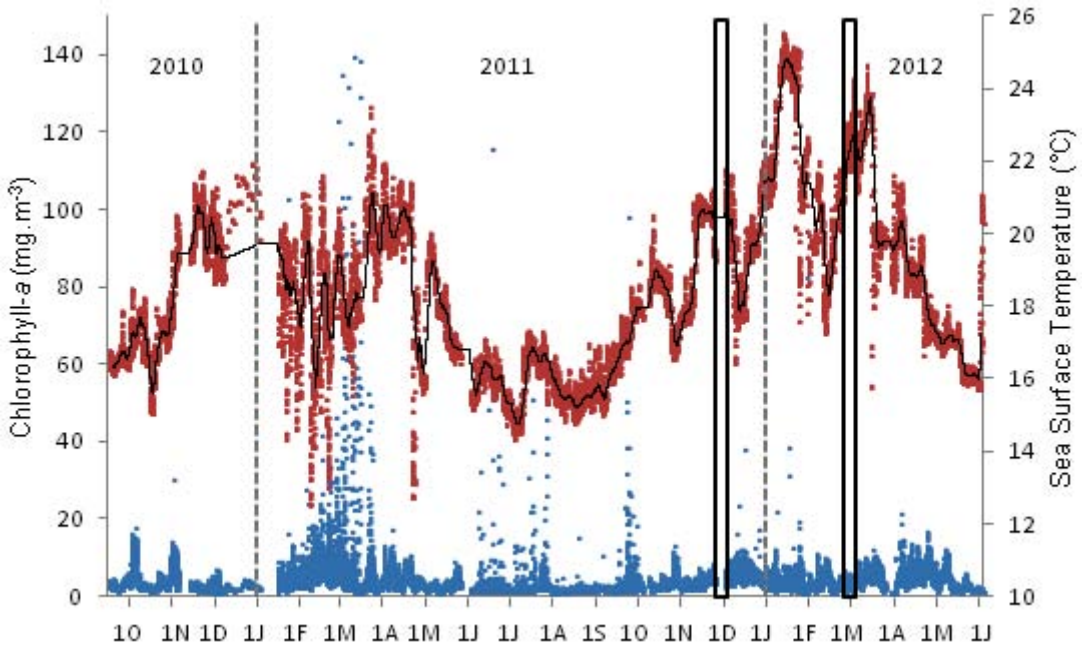

Figure 2.2: Time-series plot of calibrated fluorescence data expressed as chlorophyll-*a* concentrations (blue dots) and Sea Surface Temperature (SST) (red dots) from 15 September 2010 to 4 June 2012. Data was recorded at hourly intervals, but plotted at 10 hourly intervals. The grey dotted lines separate years and hollow black lines indicate the field sampling periods. A 50-hourly running mean is shown for SST values.

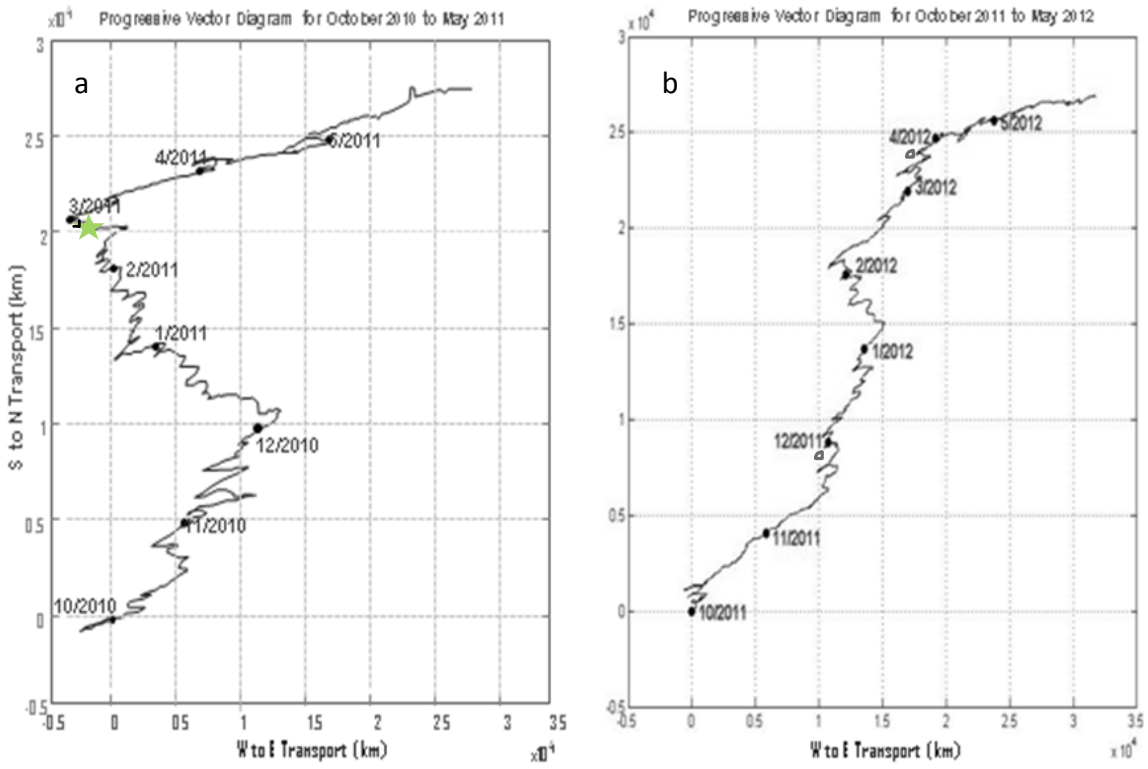

Figure 2.3: Port Elizabeth Weather Bureau *in situ* wind data. **(a)** Progressive wind vectors from the 1 October 2010 to 01 May 2011. **(b)** Progressive wind vectors from 1 October 2011 to 1 May 2012. These hourly wind periods cover both field trips, grey circles denote the field sampling periods and the green star indicates the period with the highest chlorophyll-*a* concentration in the time-series. Data plots start at the origin of (0, 0) in both years.

Field trips

Wind Vectors

Hourly wind vectors for early summer showed that winds started as south-westerlies and changed to north-easterly. Strong south-easterly winds were evident with minor wind reversals to westerlies (Figure 2.4a). In early autumn there was high variability in terms of wind vectors. There were strong south-easterly winds, with periodical south-westerly winds interspersed. There was little persistence in either south-easterly or south-westerly winds (Figure 2.4b).

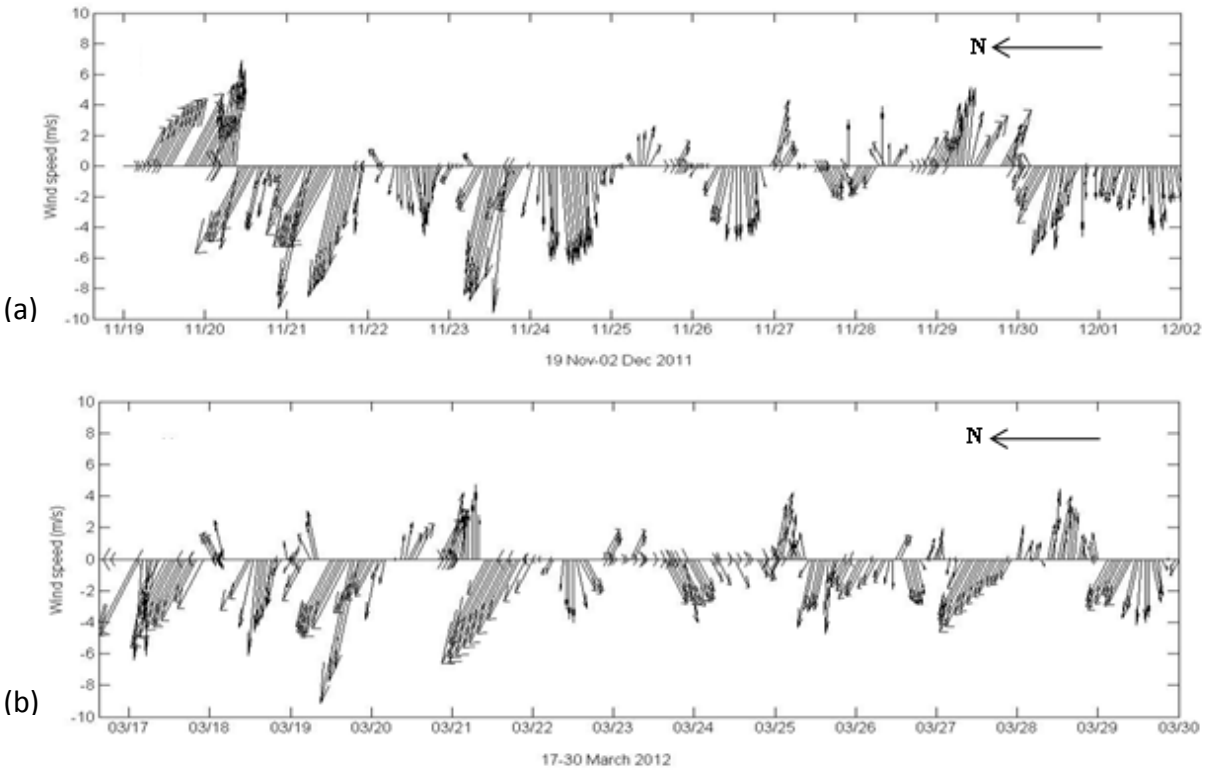

Figure 2.4: Port Elizabeth Weather Bureau *in situ* wind data from Port Elizabeth airport, shown in an oceanographic sense where they point in the direction from which the wind was blowing **(a)** Hourly wind vectors from 19th November to 2nd December 2011. **(b)**Hourly wind vectors from17th to 30th March 2011.

Seawater temperature

Surface seawater temperatures in early summer and early autumn (Figure 2.5a) were quite similar, both with a range of 17–21°C, with cool temperatures offshore. Vertical temperature profiles for early summer showed a varying temperature range of 13.5–20.5°C for all transects, with a strong thermocline at 15 m depth. In early autumn the vertical temperature range was different from the previous field trip, with a temperature range of ~16–20°C for bottom depths (Figure 2.5b).

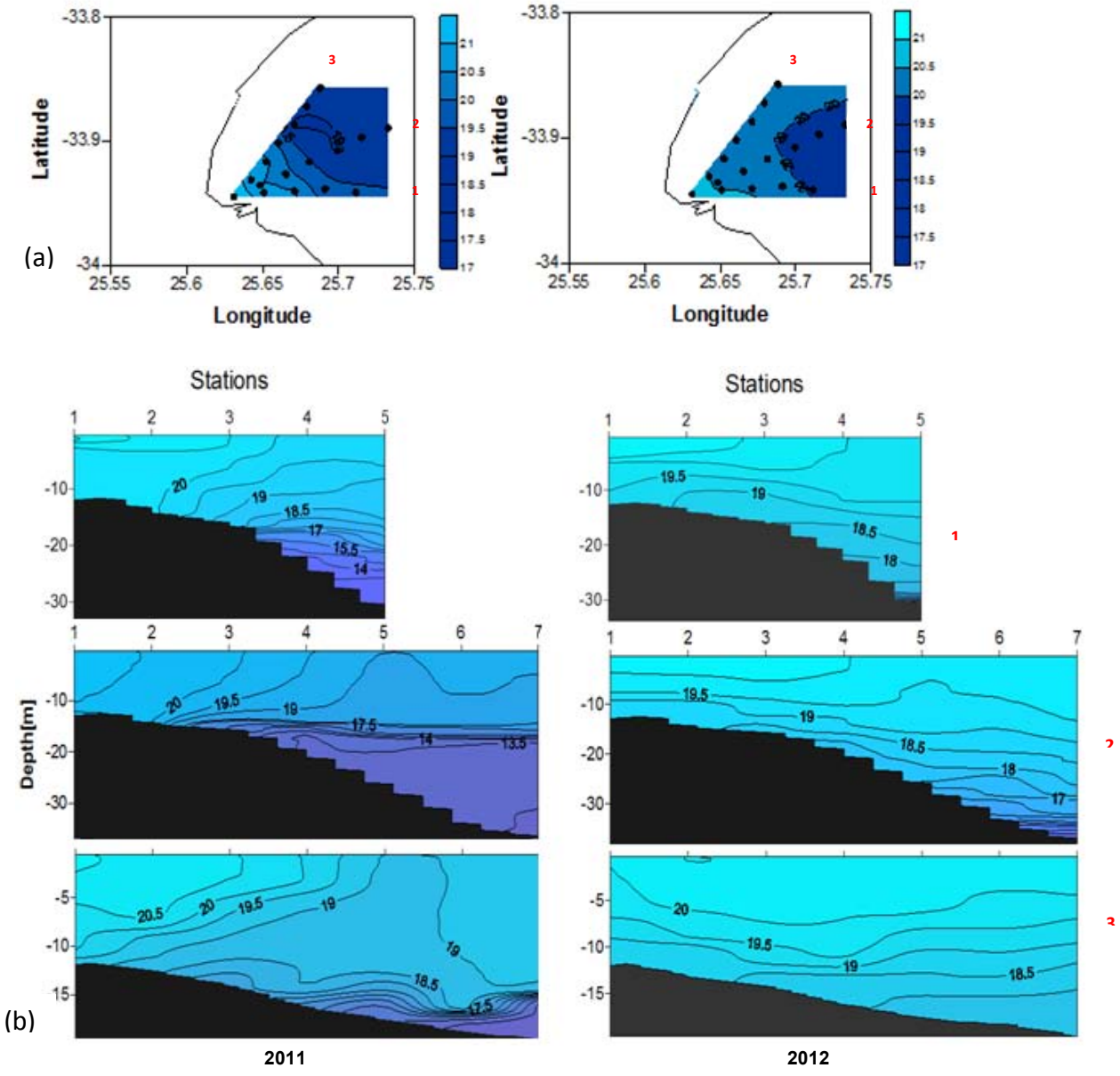

Figure 2.5: (a) Sea surface temperature (°C) distribution for all stations sampled in Algoa Bay in early summer (left panel) and early autumn (right panel). **(b)** Vertical temperature (°C) profiles for each of the three transects measured in early summer and early autumn. Note three transects are represented by red numbers (1, 2 and 3), in figure (a) & (b).

Nitrates (NO_3)

The distributions of surface nitrate concentrations were different between seasons; in early summer they ranged from 0–0.5 µM.L^{-1} and in early autumn from 0–1.4 µM.L^{-1}, with highest concentrations on transect 1 (Figure 2.6a). Vertical profiles showed lower concentrations near the surface, ranging from 0–0.6 µM.L^{-1}, and for the bottom depths reaching a maximum of 12.9 µM.L^{-1} in 2011 (Figure 2.6b). These concentration values indicated differences between the two sampling periods.

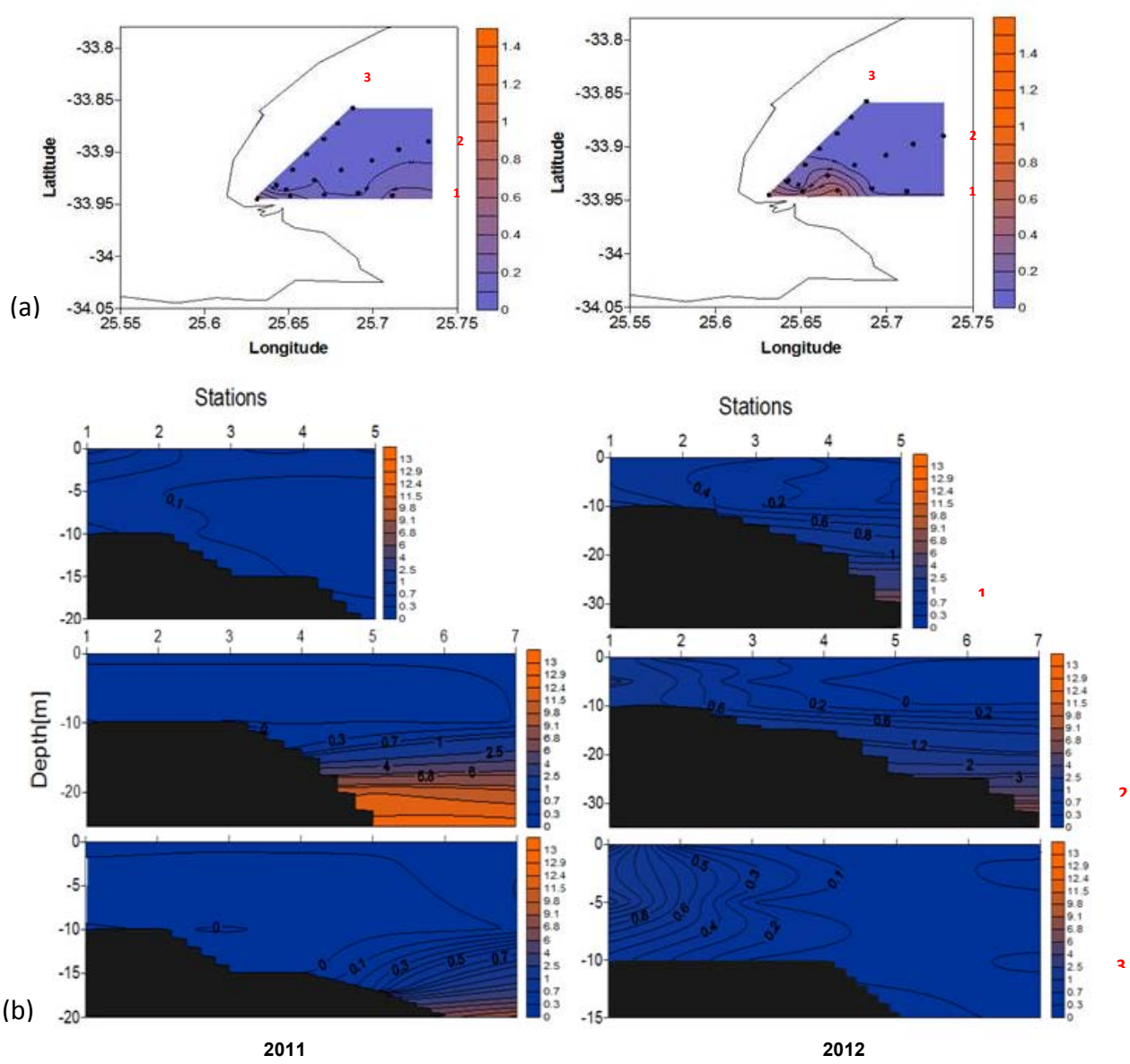

Figure 2.6: (a) Surface nitrate µM.L^{-1} (NO_3) distribution for all stations sampled in Algoa Bay in early summer (left panel) and early autumn (right panel). **(b)** Vertical profiles of nitrate µM.L^{-1} (NO_3) concentrations for each of the three transects sampled in early summer and early autumn. Note three transects are represented by red numbers (1, 2 and 3) in figure (a) & (b).

Phosphates (PO_4)

Surface phosphate concentrations for early summer ranged from 0–2 $\mu M.L^{-1}$ and for early autumn from 0-1.8 $\mu M.L^{-1}$ (Figure 2.7a). This was similar in both trips with inshore stations tending to have higher concentrations than offshore stations. Vertical profiles indicated lower concentrations near the surface, from 0–0.3 $\mu M.L^{-1}$ with higher concentrations at greater depths, with a maximum of 1.1 $\mu M.L^{-1}$ (Figure 2.7b).

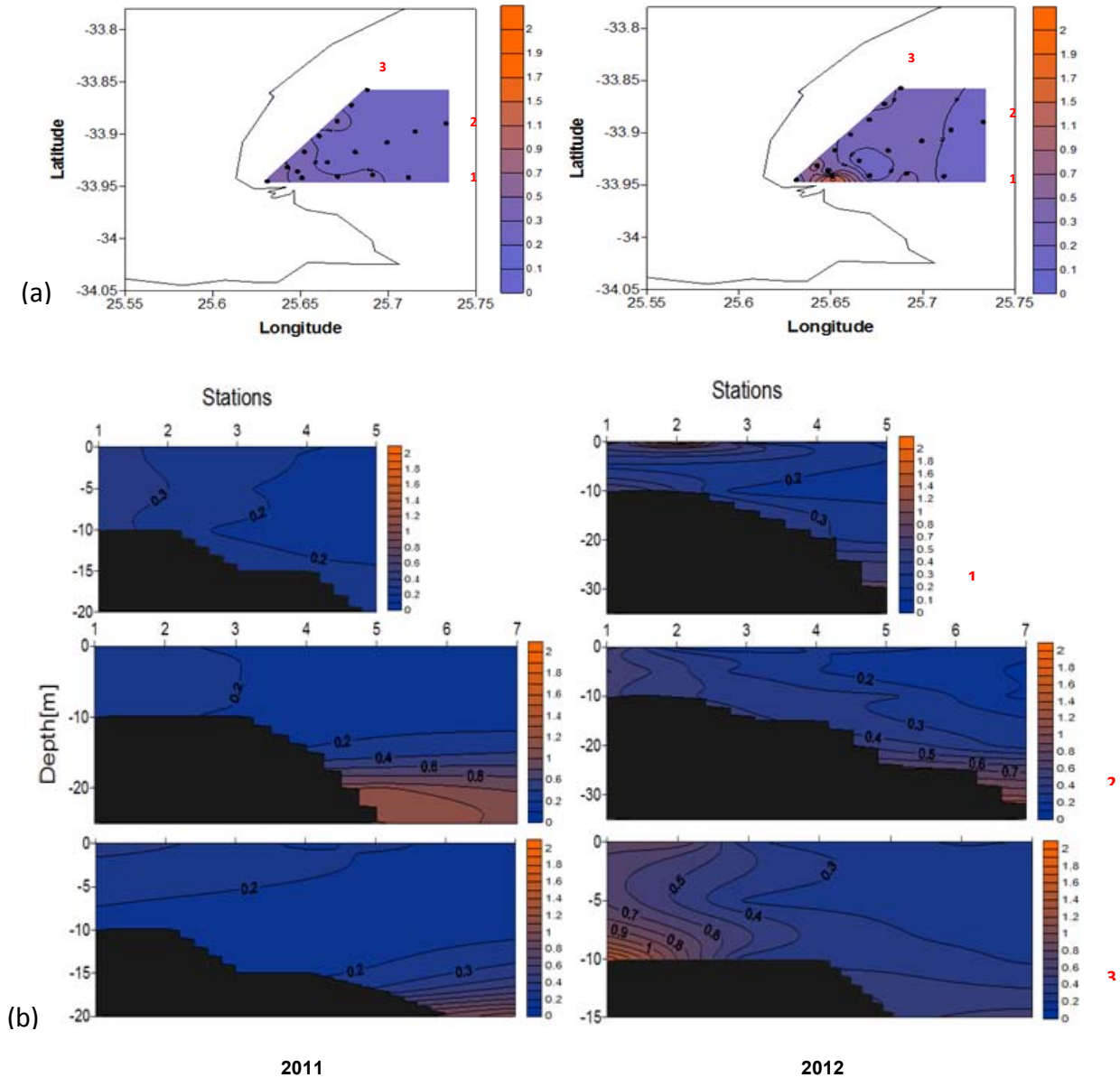

Figure 2.7: (a) Surface phosphate $\mu M.L^{-1}$ (PO_4) distribution for all stations sampled in early summer (left panel) and early autumn (right panel). **(b)** Vertical phosphate $\mu M.L^{-1}$ (PO_4) profiles measured in each of the three transects in early summer and early autumn. Note three transects are represented by red numbers (1, 2 and 3) in figure (a) & (b).

Silicates (SiO_4)

Surface silicate concentrations for early summer ranged between 0–9.5 $\mu M.L^{-1}$ and 0–16 $\mu M.L^{-1}$ for early autumn (Figure 2.8a). This distribution was different between the two field trips, with transect 2 showing higher concentrations and reaching a maximum of 18 $\mu M.L^{-1}$ in 2012. Silicate profiles indicated lower concentrations near the surface and higher concentrations at greater depths for both trips, except transect 1 in early summer with higher concentrations near the surface (Figure 2.8b).

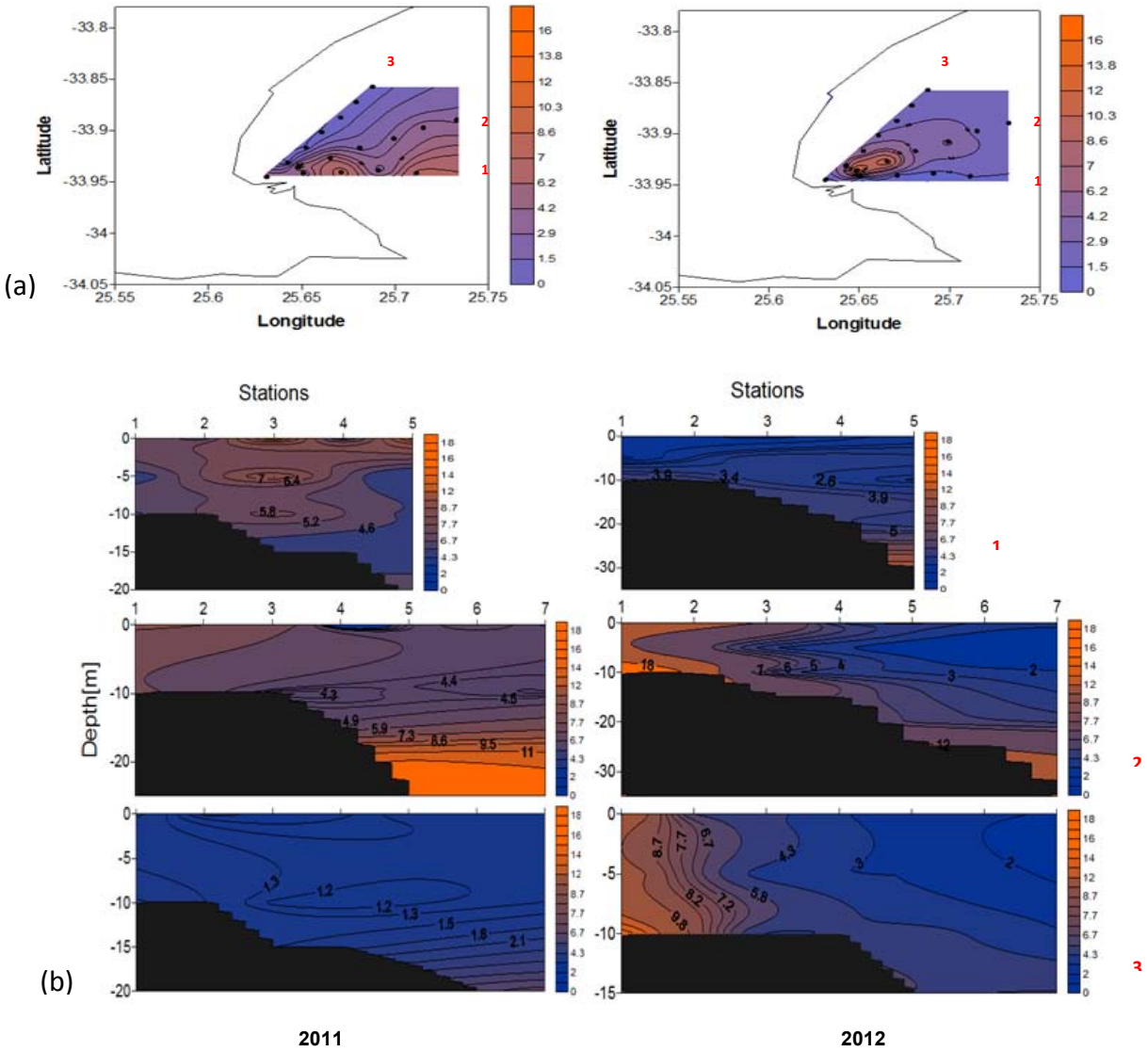

Figure 2.8: (a) Surface silicate $\mu M.L^{-1}$ (SiO_4) distribution for all stations in Algoa Bay in early summer (left panel) and early autumn (right panel). **(b)** Vertical profiles of silicate $\mu M.L^{-1}$ (SiO_4) distribution in each of the three transects sampled in early summer and early autumn. Note three transects are represented by red numbers (1, 2 and 3) in figure (a) & (b).

Nutrient and temperature relationships

There was a strong negative relationship between NO_3 and seawater temperature in both early summer and early autumn; in cold waters there were high NO_3 concentrations and in warm waters they were low (Figure 2.9a). Seawater temperature and PO_4 showed a moderately strong negative relationship. Variability in the PO_4 concentration was indicated by the different PO_4 concentrations in water in the two field trips. In early summer there was more PO_4 at 15°C and less at warmer temperatures, and for early autumn the same trend occurred, with higher concentrations around 20°C (Figure 2.9b). SiO_4 against temperature also showed a moderately strong negative relationship between the two variables. There was a pattern in early autumn, whereby in cold deep waters there were higher SiO_4 concentrations than in early summer (Figure 2.9c).

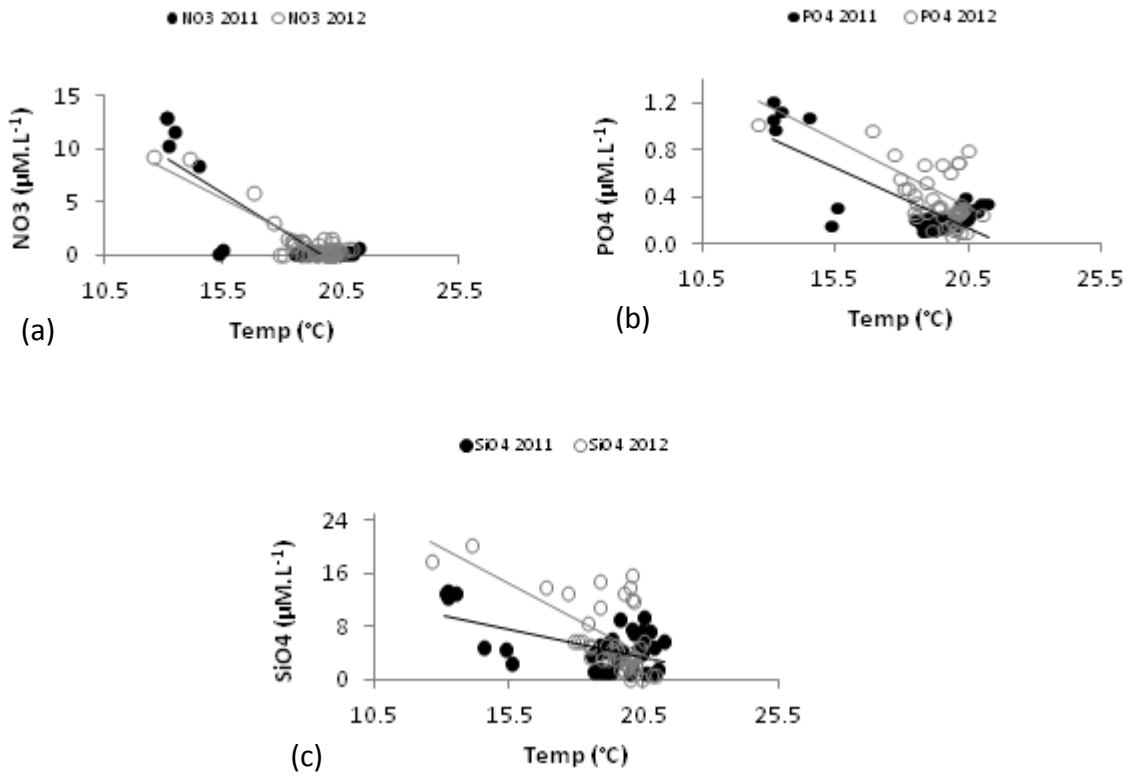

Figure 2.9: Scatter plots showing the relationships between seawater temperature and (a) nitrates, (b) phosphates, and (c) silicate concentrations in Algoa Bay on the 29 November to 1 December 2011 (early summer) and 27 to 29 March 2012 (early autumn) (n = 92, df=91). The following summaries of statistics include both early summer and early autumn.

For **(a)** 2011: NO3 = -1.3733*temp + 27.13; 2012: NO3 = -1.1511*temp + 23.104 (r= -0.85, p=0.0001),

(b) 2011: PO4= -0.1018*temp + 2.22; 2012: PO4= -0.1139*temp + 2.6392(r= -0.55, p= 0.001),

(c) 2011: SiO4= -0.850*temp + 20.86; 2012: SiO4= -2.1784*temp + 48.28 (r= -0.47, p=0.001).

Total nitrogen vs. PO_4 and SiO_4

Concentrations of PO_4 (Figure 2.10a) and SiO_4 (Figure 2.10b) were plotted against total nitrogen (TN) to illustrate whether nitrogen, SiO_4 and PO_4 are limiting or not in non-upwelling regions of the shelf. The results indicated that nitrogen is usually the limiting element in coastal waters with low concentrations. The ratios of PO_4 to total nitrogen illustrated that nitrogen is limiting primary productivity. Assuming there is a balance of different chemical elements in seawater, there will be carbon fixation per assimilated nutrient. This balance is known as the 'Redfield stochiometry' or 'Redfield ratio', and is expressed as C106: N16: P1 for phosphates and as C106: N1: S1 for silicates. In Figure 2.10 Redfield ratios of TN: PO_4 of 16 and TN: SiO_4 ratio of 1 are indicated by red dotted-lines. These ratios are used as standards or thresholds to estimate TN against PO_4 and SiO_4 concentrations. If most data points are below the Redfield ratio that will mean the waters are nitrogen limited, with an excess of PO_4 and SiO_4 (Redfield, 1958; Capone *et al*., 2008).

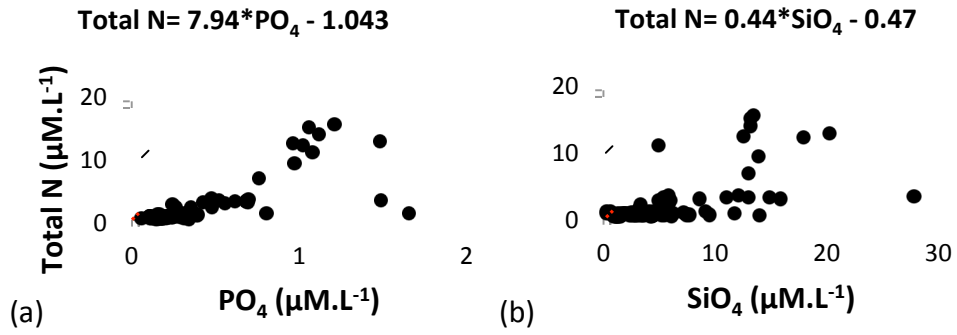

Figure 2.10: Scatter plots illustrating total nitrogen versus PO_4 and SiO_4 in all the samples for early summer and early autumn. Redfield ratios are indicated by red-dotted lines **(a)** Total nitrogen versus phosphate (N: PO_4 = 7.94). **(b)** Total nitrogen versus silicate (SiO_4 Redfield ratio N: SiO_4 = 0.44).

Chlorophyll-a distribution

Surface chlorophyll-*a* concentrations were different between the two field trips, with higher concentrations during the second trip. Early summer had higher concentrations inshore in transect 3 and low concentrations at the rest of the stations (Figure 2.11a). Early autumn had higher concentrations in transect 2 and at inshore stations in transect 1. Chl-*a* concentrations ranged from 0.21–2 mg.m^{-3} in both field trips (Figure 2.11a). In early summer vertical profiles of chlorophyll-*a* concentrations were greatest at approximately 10–15m depth with lower concentrations near the surface, ranging from 0.08–4.8 mg.m^{-3}. For early autumn, greatest chlorophyll-*a* concentrations were at the surface, approximately between 0–5 mg.m^{-3}, which was different from early summer. Highest concentrations were inshore, reaching a maximum of 6 mg.m^{-3} (Figure 2.11b).

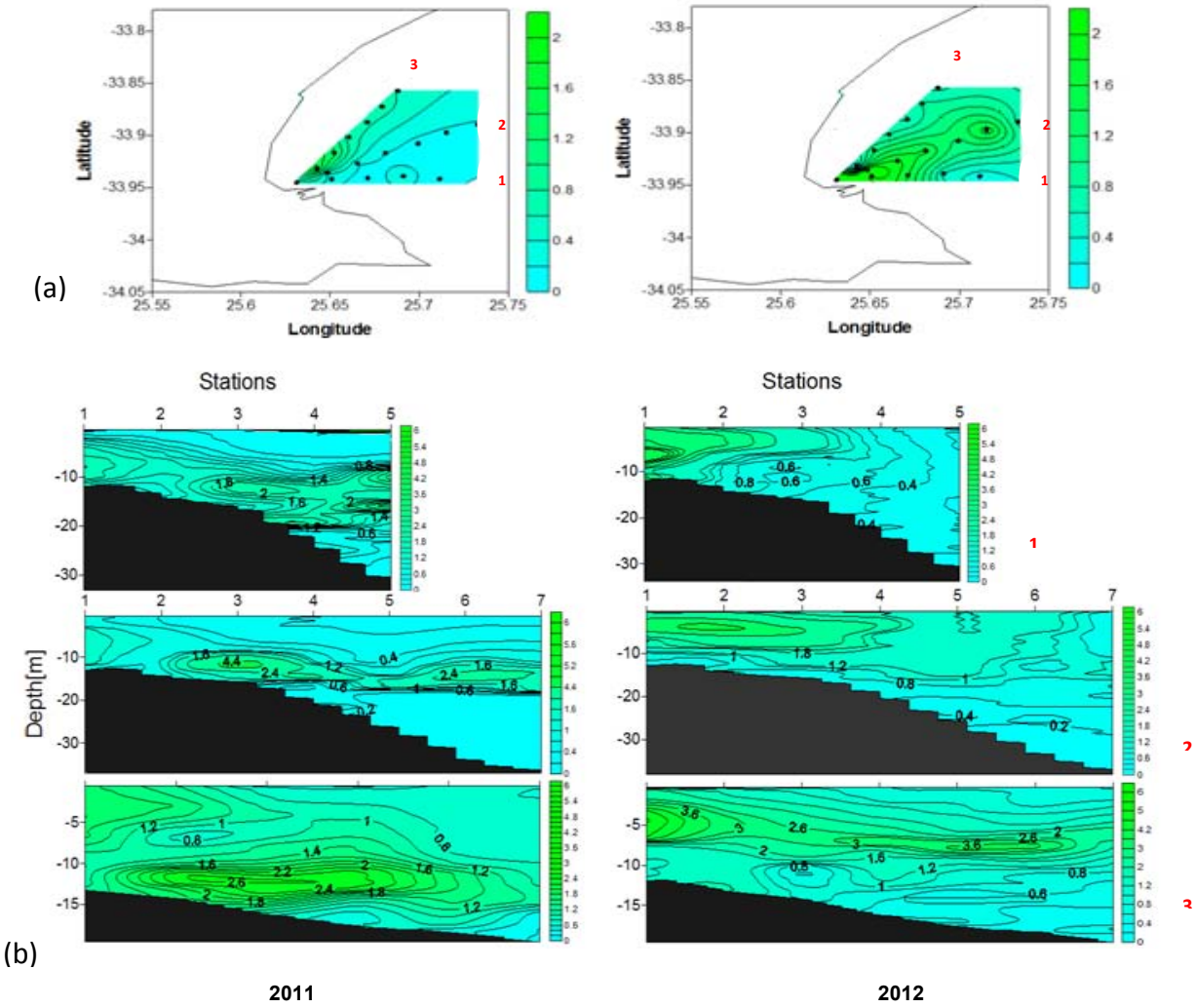

Figure 2.11: (a) Surface chlorophyll-*a* (mg.m^{-3}) distribution for all stations in Algoa Bay from 29 November to 01 December 2011(left panel) and 27-29 March 2012(right panel). **(b)** Vertical profiles of chlorophyll-*a* (mg.m^{-3}) for all stations in each of the three transects sampled in Algoa Bay in 2011 and 2012. Note three transects are represented by red numbers (1, 2 and 3).

Phytoplankton composition and abundance

Phytoplankton community structure was different between the two field trips. In early summer a total of 84 taxa was identified, most of them at genus level and some at species level. Out of those identified there were 44 diatoms, 34 dinoflagellates, 5 flagellates and 3 unknown species. Summarised cell concentration results showed that *Gonyaulax polygramma* and *Gonyaulax* sp. were the most abundant species (Figure 2.12a). In early autumn there were 77 microalgal species of phytoplankton identified in total. These included 47 diatoms, 24 dinoflagellates, 4 flagellates and 2 unidentified species. The summary of the results from mean concentration counts indicated that *Pseudo-nitzschia* sp. were the most abundant cells in early autumn (Figure 2.12b).

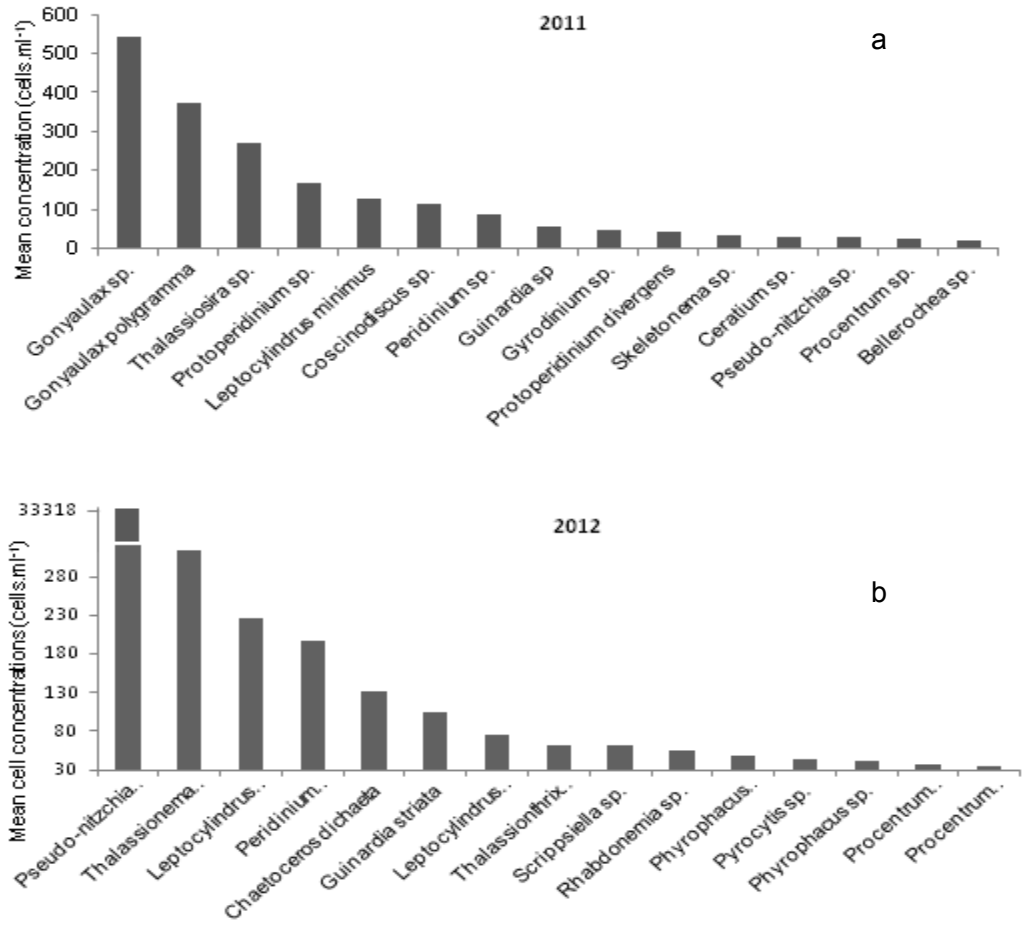

Figure 2.12: Phytoplankton species and mean cell concentrations (cells.ml^{-3}) for fifteen most numerous cells found in Algoa Bay in both 2011 (early summer) **(a)** and 2012 (early autumn) **(b)** fieldtrips.

Phytoplankton community structure

Phytoplankton community structure was examined through dendrograms and MDS plots. In early summer, five groups of samples were formed. NO_3 concentrations were superimposed on the samples to show spatial distribution and grouping of samples from each station or transect (Figure 2.13a). A similarity level of 30% was used to group the samples and concentration ranges of 0.01–0.04 $\mu M.L^{-1}$, 0.06-0.08 $\mu M.L^{-1}$ and 0.09-0.47 $\mu M.L^{-1}$ were used to classify samples to NO_3 concentrations (Figure 2.13b). Group-*a* showed a grouping of samples from stations closer to the shore with notable high NO_3 concentrations in a few samples. There was a strong grouping of samples in group-*b* from transect 2 stations, with samples with higher NO_3 concentrations and a few samples with low concentrations. Group-*c* had two samples from transect 1, both with higher NO_3 concentrations. In group-*d*, there were three samples from transect 2 with depleted NO_3 concentrations, and group-e also had two samples with low NO_3 concentrations.

SIMPER results were summarised to three groups in early summer, and showed that *Gonyaulax polygramma* and *Gonyaulax* spp. were the most abundant taxa in group 1 followed by *Peridinium* sp, *Leptocylindrus minimus* and *Thalassiosira* sp. (Figure 2.14). Other species like *Guinardia* sp., *Gyrodinium* sp. and *Coscinodiscus* sp. were among the most common species, because they were found in all three groups and most of the early summer samples. Group 2 had all the phytoplankton species found in group 1; however group 2 differed including *Alexandrium* sp., *Gonyaulax polygramma, Procentrium micans* and *Protoperidinium* sp. Group 3 differed from groups 1 and 2 with five different species; *Leptocylindrus minimus, Protoperdinium divergens, Pseudo-nitzschia* sp., *Thalassionema nitzchiodes* and *Rhizoselenia* sp. (Figure 2.14).

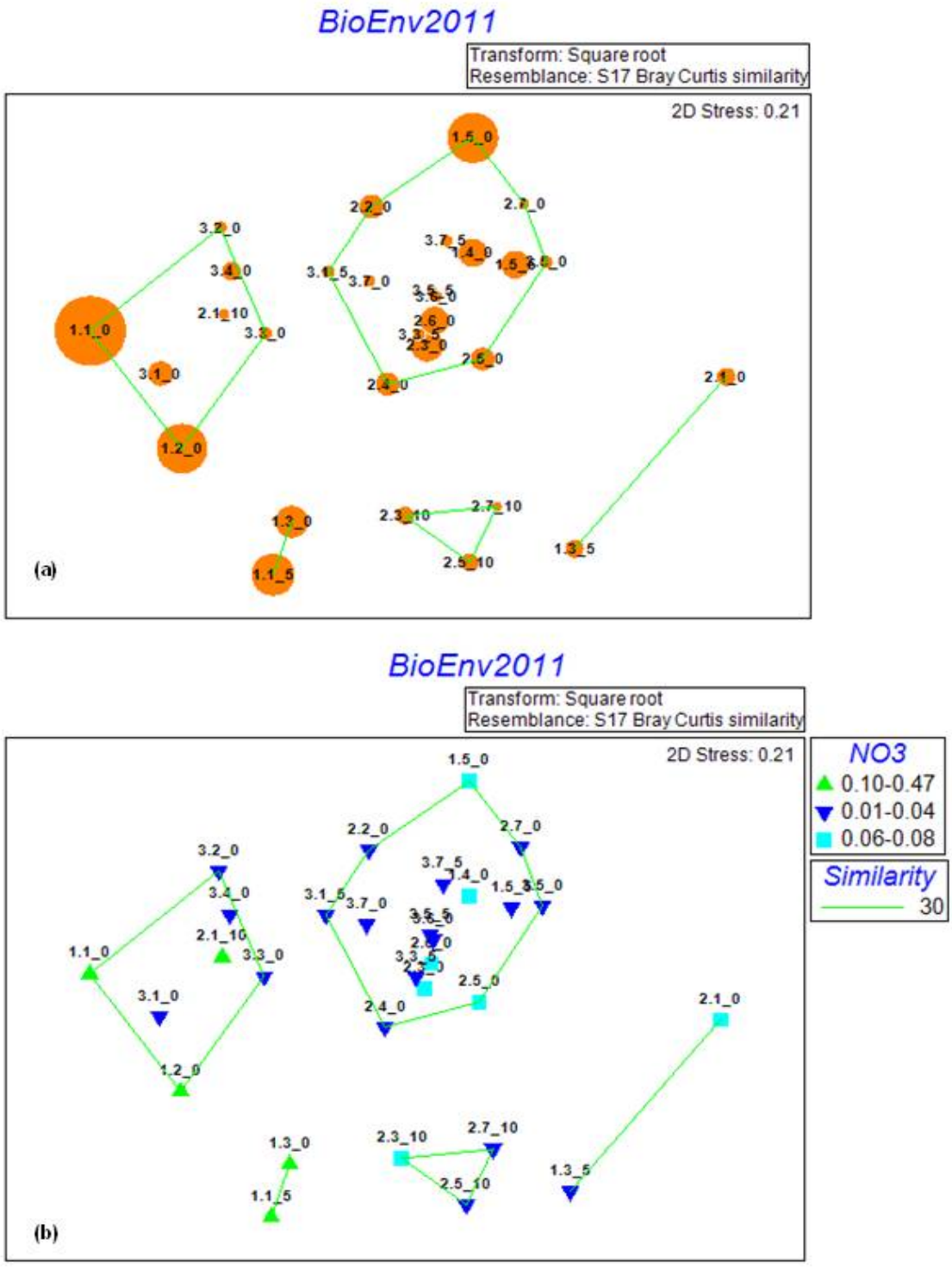

Figure 2.13: Multi-dimensional scaling (MDS) plot for samples in Algoa Bay in early summer. Bray-Curtis similarity was used for resemblance matrix. **(a)** Nitrate concentrations ($\mu M.L^{-1}$) ranging from 0.06-0.47 $\mu M.L^{-1}$ were overlaid on the samples and used as an environmental variable to explain nitrate concentration in each sample. **(b)** Sample grouping using 30 % level of similarity and NO_3 ranges of 0.01-0.04 $\mu M.L^{-1}$ (lower range); 0.06-0.08 $\mu M.L^{-1}$ (middle range); and 0.10-0.47 $\mu M.L^{-1}$ (upper range). Sample groups were denoted by: a, b, c, d and, e to show patterns of sample assemblages within nitrate concentration ranges. Note sample labels: transect.station_depth (m).

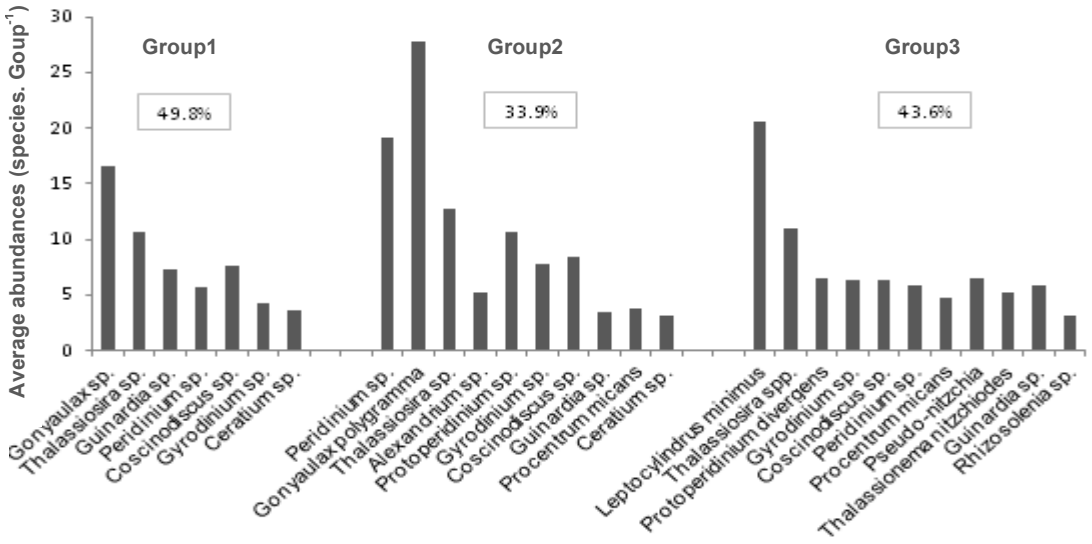

Figure 2.14: Summary of similarity percentages (SIMPER) analyses and average abundances of phytoplankton species for samples collected in Algoa Bay in early summer. Samples are grouped according to species composition to explain species dissimilarities/ similarities within samples.

The early autumn field trip showed five groups of samples, but other samples were not grouped at all (Figure 2.15a). NO_3 concentrations were superimposed on the samples to show the spatial distribution from each transect or station. A similarity level of 50% was used to group the samples and NO_3 concentration ranges of 0.02–0.09 0.12–0.46 and 0.51–1.43 $\mu M.L^{-1}$ were used to classify samples to NO_3 concentration (Figure 2.15b). Group-*a* had two samples from transect 1, with high NO_3 concentrations. Group-*b* consisted of most of the samples in transect 3, with depleted NO_3. In group-*c* there were three samples near the shore with high NO_3. Group-*d* had samples from transect 2 that had both high and low NO_3 concentrations. There were two samples from group-*e* that had depleted NO_3. Most of the samples closer to the shore had high NO_3 concentration while the rest were depleted (Figure 2.15).

SIMPER results for 2012 (Figure 2.16) indicated that *Pseudo-nitzchia* sp. was the most abundant species. The next few most numerous species were *Thalassionema elongatum, Peridinium exentricum, Chaetoceros dichaeta* and *Guinardia striata.* These species

accounted for higher average abundances. Groups in Figure 2.16 show that the group with range of 0.51–1.43 $\mu M.L^{-1}$ was similar to the group ranging from 0.12–0.46 $\mu M.L^{-1}$. *Leptocylindrus mimimus*, *Guinardia sp*. and *Scrippsiella sp*. distinguished the group ranging from 0.51–1.43 from 0.12–0.46 $\mu M.L^{-1}$ range. *Thalassiothrix longissima* and *Protoperidinium pyriforme* were only present in the 0.12–0.46 $\mu M.L^{-1}$ group range. The group range of 0.02–0.09 $\mu M.L^{-1}$ differed from the other two groups as it contained *Leptocylindrus danicus* and *Ceratium kofoidii* (Figure 2.16).

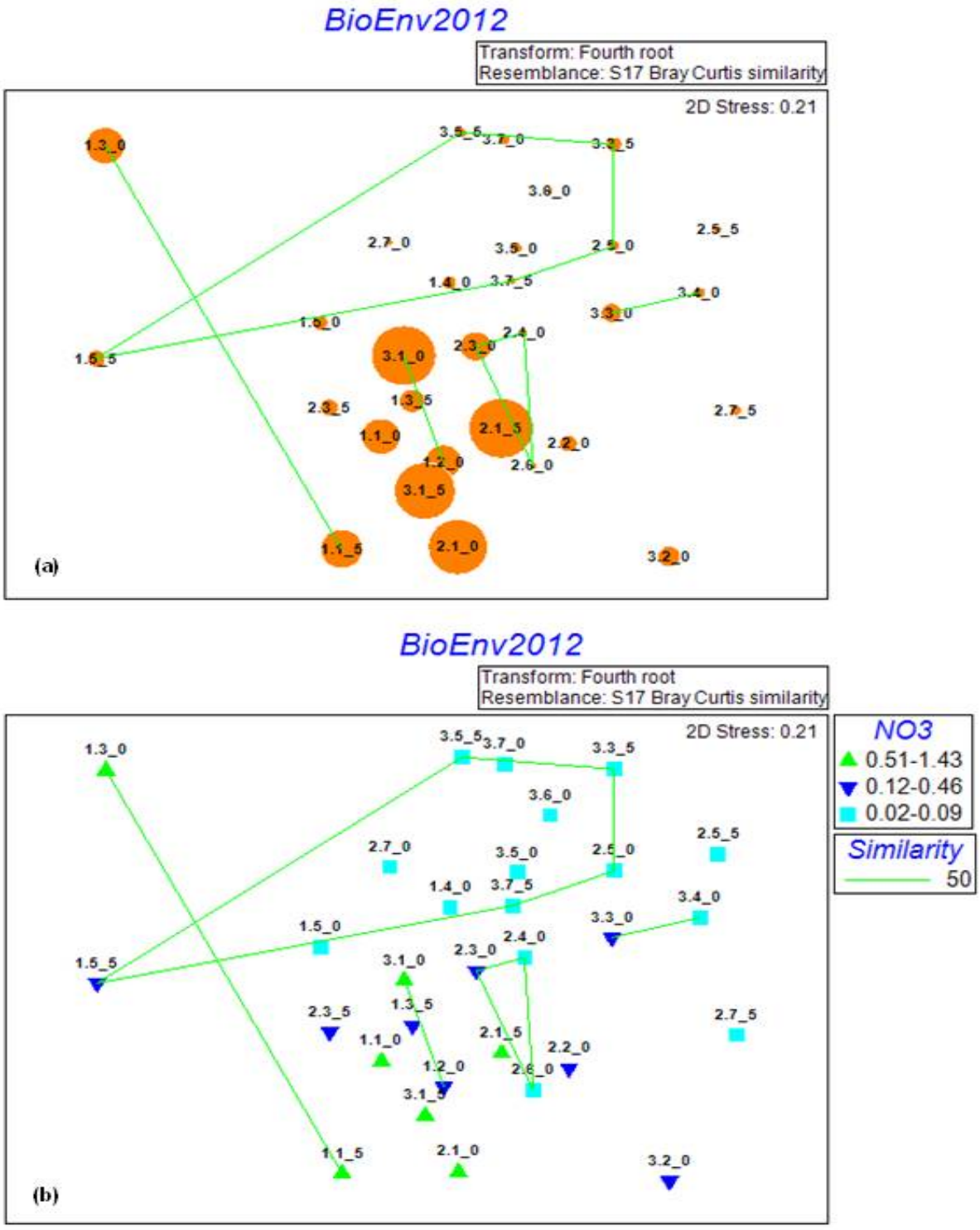

Figure 2.15: Multi-dimensional scaling (MDS) plot for samples in early autumn. Bray-Curtis similarity was used for resemblance matrix. **(a)** Nitrate concentrations ranging from 0.02 to1.43 $\mu M.L^{-1}$ were overlaid on the samples as environmental variables to explain nitrate concentration in each sample. **(b)** Sample grouping using 50 % level of similarity and NO_3 ranges of 0.02-0.09 $\mu M.L^{-1}$ (lower range); 0.12-0.46 $\mu M.L^{-1}$ (middle range); and 0.51-1.43 $\mu M.L^{-1}$ (higher range). Samples groups were denoted by: a, b, c, d, and e to show patterns in sample grouping to nitrate concentration ranges. Note the sample labelling: transect.station_depth (m).

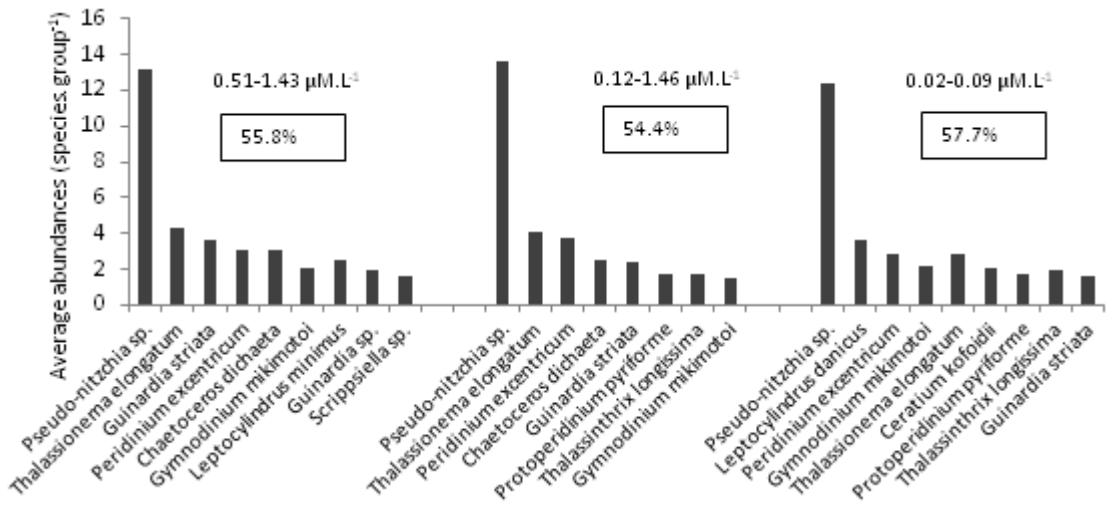

Figure 2.16: Summary of similarity percentage (SIMPER) analyses and average abundances for samples collected in Algoa Bay in early autumn. Nitrates (NO_3) concentration ranges were used as an environmental grouping factor to explain the proportion of species dissimilarities/similarities within the samples.

Discussion

Physical variables

There was a strong seasonal trend in sea surface temperature in Algoa Bay as indicated in the time series (Figure 2.2), where it was cooler in winter and warmer in summer. There was also a notable interannual difference in sea surface temperature with warmer waters present in 2012 than in 2011. According to Schumann *et al*. (1988) and Schumann *et al*. (2005), easterly winds are responsible for upwelling off Cape Recife. On the other hand, colder upwelled waters move into Algoa Bay as a result of westerly winds (e.g. Goschen and Schumann, 1995). Beckley (1988) also indicated that there were daily to annual temperature differences across Algoa Bay. A drop in temperature at Sundays River and wind-induced upwelling from Cape Padrone reach Cape Recife as a result of westerly wind movement (Goschen *et al*., 2012). The upwelling cell at Port Alfred was discovered by Lutjeharms *et al*. (2000), on the north east of Algoa Bay. Progressive winds (Figure 2.3a and b), indicated the dominance of south-easterly winds in summer with periodic south-westerly winds. The increase in dominance of south-easterly winds in summer, and throughout the year in the western sector of Algoa Bay has been reported as a common pattern in this region by Schumann *et al*. (2005) and Schumann and Martin (1991). The persistent occurrence of south-easterly winds is responsible for driving periodic upwelling and variability in SST in summer in the western sector of Algoa Bay.

Wind vectors measured during the field trips started off as north westerlies to stronger south-easterlies, with some minor wind reversals, and relaxations (Figure 2.4a). These winds then alternated between south-easterly and south-westerly winds. This indicated a temporal, short-term variability in wind events in coastal areas, also noted by Schumann *et al*. (2005). These wind events may have caused the algal bloom of the dinoflagellate *Gonyaulax polygramma* as indicated in (Figure 2.14) and led to higher abundances of *G. polygramma*.

This pattern is often influenced by increased solar radiation and reduced wind intensity in summer, which facilitates a stratified water column (Schumann *et al.*, 1982; Beckley, 1988; Schumann *et al*., 2005). This pattern was evident in the early summer field trip where there was a shallow thermocline sitting at 15 m (Figure 2.5a). Most dinoflagellate algal blooms are associated with species that cause harmful effects such as toxins and species biomass collapse due to oxygen reduction in the water (Pitcher *et al.*, 1998; Fawcett *et al.*, 2007).

Persistence of the south-easterly winds could have led to the establishment of an onshore movement of water from the bottom over the bay as it was also observed by Schumann *et al*. (2005). The non-persistent south-easterly wind patterns in early autumn led to a less stratified water column and mixed waters in the bay, where the thermocline was deeper and less visible compared to early summer (Figure 2.5b). The surface temperatures in early autumn were similar to those in early summer (Figure 2.5a). In early autumn south-easterly winds eroded the thermocline at the surface and led to a deeper thermocline at approximately 30 m. The interplay of winds and temperature indicated differences in the spatial variation in flow patterns in Algoa Bay, and distinct differences in phytoplankton species composition in the two field trips.

Chemical variables

According to Malone *et al*. (1996) phytoplankton productivity varies in relation to nutrient supply on different temporal and spatial scales. Algoa Bay is an open and relatively shallow bay but because it is predominantly a non-upwelling region, temperature and nutrient concentrations are less variable than found in upwelling regions. This was evident in terms of nutrients, especially phosphates [PO_4], silicates [SiO_4] and nitrates [NO_3], which are the most critical macronutrients for phytoplankton. Vertical profiles of nutrients in early summer indicated a dominant pattern of nutrient depletion at the surface and higher concentrations at greater depths.

According to Beckley (1988) and Schumann *et al*. (2005), an increase in wind intensity and minimised solar radiation in the early winter months enhances a homogenous water column structure. This could be the similar conditions in Algoa Bay for early autumn, where nitrate concentrations were notably high for samples closer to the shore (Figure 2.15), which also displayed stronger sample grouping to species composition on the MDS plots.

Lower concentrations of nutrients in the water column in Algoa Bay could be influenced by the hydrography of the bay, which is characterised by shallow stratified waters and minimal mixing. Nutrients for phytoplankton production become depleted in the euphotic layer. This occurs in western boundary environments in summer, when there is high solar radiation and less intensified winds on the continental shelf (McMurray *et al.*, 1992). This has been shown by lower concentrations of nutrients at the surface and higher nitrates and other nitrogen compounds at greater depths.

Nutrient concentrations in open and shallow bays, such as Algoa Bay, compared to complex systems, which are characteristic of heavily enriched estuaries, have a minor effect on phytoplankton production (Nixon *et al.*, 1986). Such bays have medium to high loading of nitrogen of 4.3 to 29.3 $g.m^{-2}.year^{-1}$ and low to moderate phosphate loading of 0.32 to 2.42 $g.m^{-2}.year^{-1}$ (Malone *et al*., 1996 and Boynton *et al*., 1995). Most enclosed bays are vulnerable to high enrichment because of increased residence time and consequent nutrient recycling within the system (Malone *et al*., 1996). Algoa Bay is not enclosed, as compared to an estuarine ecosystem, so nutrient enrichment, which can lead to eutrophication, is minimal. Therefore, a nutrient-depleted water column in Algoa Bay is normally dominant because of its shallow, warm surface layer and associated periodic phytoplankton blooms.

Temperature and nutrient relationships

Studies have shown that intense easterly winds enhance upwelling of deep nutrient rich waters to the surface along the coast of the Eastern Cape (Dali, 2010; Lutjeharms, 2006). In early summer, a strong thermocline, highly stratified waters, and stabilized water column were common features in the western sector of Algoa Bay. Nitrate concentrations and temperatures are related when upwelling has occurred (Waldron and Probyn, 1992; Probyn *et al*., 1994). This was a typical scenario in this study (Figure 2.9a). These patterns of nutrients may be driven by the fact that, in the western sector of the bay, upwelled patches of water periodically enter Algoa Bay from Cape Recife (Gouschen and Schumann, 1995), as illustrated in Figure 1.2.

In the early summer phosphate concentrations were lower than in early autumn (Figure 2.9b), when there was less stratification in the water column. This was noted by a higher concentration of nutrients near the surface due to reduced solar radiation and increased wind activity facilitating well mixed waters (Schumann *et al.*, 2005). There was a weaker relationship between SST and SiO_4 concentrations in the two sampling trips (Figure 2.9c), compared to the relationship of SST to NO_3 and PO_4.

Nitrogen and phosphorus can limit primary productivity of the ocean (Boyd *et al.*, 2000; Wu *et al.*, 2000; Sañudo-Wilhemy *et al.*, 2001; Brzezinski *et al.*, 2011). Nutrient limitation type depends on temporal and spatial distribution of dissolved nutrients (Tyrell, 1999; Weber and Deutsch, 2010). Uneven distribution was observed in the samples where there was high variability, mainly with low nitrate and phosphate concentrations for surface samples, and higher concentrations for deeper samples. Furthermore, it was an indication that conditions favoured algal growth, which had an impact on phytoplankton community structure in early summer. In early autumn the trend was similar, with less spatial variability and lower PO_4 concentrations at the surface and higher values at greater depths.

Nutrient limitation and seasonal variability for phytoplankton is high in coastal regions influenced by river run-off, causing changes in seasonal ratios of dissolved nutrients, especially nitrogen and phosphorous (Fisher *et al.*, 1992; Berman *et al.*, 2005). There were spatial differences when considering the NO_3 to temperature relationship, where in early summer there was a lower concentration of NO_3 and higher concentration in early autumn.

Generally, the stoichiometric composition of phytoplankton depends on the rate of carbon fixation per assimilated nutrient, which can be characterised as the atomic carbon to nitrogen to phosphorus (C:N:P) ratio. Atmospheric carbon enters the water as dissolved inorganic carbon and other chemical elements that drive phytoplankton production are formed through remineralisation (De La Rocha and Passow, 2007). It was noted that when total nitrogen versus PO_4 and SiO_4 were plotted (Figure 2.12a and b), nitrogen was generally limiting and the stochiometric ratio of nutrients was not stable. The average relationship in seston between C:N:P ratio is stable, ranging between 106:16:1 (Redfield 1958; Copin-Montegut & Copin-Montegut, 1983) and 166:20:1 (Sterner *et al.*, 2008). Phytoplankton shifts of C:N:P ratios can be driven by different factors such as light intensity and growth rates (Healey, 1985; Sterner *et al.*, 1997; Diehl, 2002; Klausmeir *et al*., 2004a Klausmeir *et al.*, 2004b).

Trommer *et al*. (2012) found that nutrient limitation for marine phytoplankton varies and changes over time, and nutrient limitation has less effect on marine phytoplankton than in a freshwater environment. This was evident in the early summer and early autumn trips, where the water column proved to be nutrient limited. There were differences between the two sampling periods in the species present and in which species were most abundant. Del Amo *et al.* (1997) noted similar conditions in the Bay of Brest (<50 m depth), during the summer of 1995, where a toxic bloom of dinoflagellates of *Dinophysis* spp. and *Gymnodinium mikimotoi (*formerly known as *Gymnodinium cf. nagasakiense*) were observed

to dominate the phytoplankton community. Such shallow bays are characterised as nitrogen limited marine environments; results in Algoa Bay showed a similar trend in term of species composition (Figure 12a & b), where flagellates of *Gonyaulax* sp. dominated in early summer. This implied the surface phytoplankton production in the open ocean is limited mainly by phosphorous, whereas in coastal sites it is limited by nitrogen (Trommer *et al*., 2012), as the results displayed a similar trend in spatial nitrogen distribution on the coastal region of Algoa Bay.

Phytoplankton composition and chlorophyll-*a* concentrations

Phytoplankton cells varied in size, and there was high diversity of species of phytoplankton in this region. The results from the time series indicated seasonal temperature variability (Figure 2.2), which influenced chlorophyll-*a* concentrations between the two summers. The median chlorophyll-*a* concentration was close to the mean value, with a range of 0.5 to 138.7 $mg.m^{-3}$.

Chlorophyll-*a* concentrations in the time-series were highly variable with periods of very high and low chl-*a* concentrations (Figure 2.2). This variability could have been driven by a temporal increase in occurrence of south-easterly winds in early summer and early autumn, inducing upwelling of nutrient rich waters on the continental shelf, as Schumann *et al*. (1988) noted the increase in an easterly wind component responsible for upwelling.

Sea-surface temperatures were similar in both field trips; the range was 17°C to 20°C in shallow waters or near surface and 13.5°C to 16°C for greater depths. The first fieldtrip was at the beginning of a warming period, with a slightly higher chlorophyll-a concentration than the second field trip at the end of warming period. Chlorophyll-a distribution has been known to be driven by substantial light penetration, a stratified system and stable water column due to wind relaxation; such has been noted by Schumann *et al.* (2005) as common seasonal events in the western sector of Algoa Bay.

Nitrate concentrations were higher in deeper and colder waters and lower at the surface. High chlorophyll-*a* concentrations were notable at 5-10 m depths and periodically at greater depths. Chlorophyll-*a* concentrations were higher at the stations closest to the shore (Figure 2.11a and b) for both early summer and early autumn.

Phytoplankton cell counts have showed higher values for *Gonyaulax polygramma* and *Gonyaulax* sp. (Figure 2.12a) in the early summer samples. In contrast, Algoa Bay samples in early autumn showed high concentrations of other phytoplankton cells, *Pseudo-nitzschia* sp. in particular was abundant in the samples (Figure 2.12b). Periodic wind patterns could have influenced the change in the dominance of species, driven by a shift from stratified waters in early summer to mixed waters at the surface with nutrients, and weaker south-westerly winds in early autumn.

According to Marshall (1980), open bays surrounded by rivers are generally dominated in winter by the centric diatom *Skeletonema costatum*. A shift occurs in spring when diatoms of *Cerataulina, Cyclotella,* and *Thalassiosira* species dominate (Marshall, 1980), indicating seasonal changes in phytoplankton community structure. In Algoa Bay some of these species were found in samples from both early summer and early autumn trips. However, *Cerataulina* was present in early autumn and *Cyclotella* sp. was in the early summer samples, and rare in both periods. Furthermore *Thalassiosira* species were found during both trips but more abundant in early summer. *Nitzschia, Coscinodiscus* and *Rhizosolenia* species are common in open bays (Marshall, 1980), but these species for Algoa Bay varied from sample to sample. *Coscinodiscus* species, in particular, were found in most samples, although sparingly. *Nitzschia* and *Rhizosolenia* were rare for both field trips.

Bays with similar hydrological features, such as freshwater inputs and depth, are comparable in terms of seasonal phytoplankton community assemblages (Marshall, 1980). In Algoa Bay the spatial phytoplankton composition in the early summer indicated dominance

of *Gonyaulax polygramma* and other *Gonyaulax* species (Figure 2.14), while in early autumn pennate diatoms of *Pseudo-nitzschia* species (Figure 2.16) were numerous in Algoa Bay.

In the early summer, phytoplankton samples showed low similarities in species composition (Figure 2.13b), with notably high nitrate concentrations in inshore samples, while the rest of the samples showed depleted nitrates (Figure 2.13 a). These are typical scenarios for episodic events relating to coastal upwelling in Algoa Bay. Schumann *et al* (1988) noted dominant easterly winds in summer favoured upwelling of nutrient rich waters off Cape Recife. The early autumn samples had similar species compositions for inshore samples (Figure 2.15b). The remaining samples offshore had low nitrate concentrations (Figure 2.15a).

The variability in water column structure such as stratification and stronger south-easterly winds with increased light intensity in the early summer enhanced the dominance of dinoflagellates as a result of red-tide formation, where *Gonyaulax polygramma* and other *Gonyaulax* species were numerous. According to Kim *et al*. (2006), *Gonyaulax polygramma* Stein blooms have been evident in Japan and South African waters. Molecular studies have demonstrated that this species is responsible for mass fish mortalities caused by a sudden lack of oxygen in water (Grindley and Taylor, 1962; Koizum *et al*., 1996; Morton and Villareal, 1998).

In early autumn, a homogenous water column structure with less intense solar radiation encouraged pennate diatoms of *Pseudo-nitzschia* species to dominate in the samples. Lelong (2012) indicated that *Pseudo-nitzschia* genus, gained more interest when the first amnesic shellfish poisoning (ASP) event was reported in 1987, in Japan, when people consumed blue mussels. These pennate diatoms are known to produce the neurotoxin, domoic acid (Bates *et al*., 1989). A molecular study provided evidence that *Pseudo-nitzschia multiseries* was the species that the mussels fed on and was responsible for the production of

domoic acid. This was proven through the death of people who ate these mussels (Bates *et al*., 1989; Pulido, 2008; Trainer *et al*., 2008).

Phytoplankton composition and community structure in Algoa Bay was strongly driven by spatial variability of environmental variables as the results have indicated. However, there are no distinct differences in phytoplankton biomass between the two sampling periods, as both indicated low chl-*a* concentrations. Such spatial variability in chl-*a* concentrations and shifts in phytoplankton community structure are not favourable to oyster production because not all phytoplankton species meet dietary requirements for oysters.

CHAPTER 3

Conclusion and recommendations

Phytoplankton composition in Algoa Bay is seasonally driven by wind dynamics, which influence surface seawater temperatures and nutrient concentrations in the water column. South-easterly winds in early summer of 2011 were persistent. A marked thermocline near the surface created suitable conditions for an algal bloom and there was an abundance of dinoflagellates e.g. *Gonyaulax polygramma*, with substantial nitrates inshore and low nitrate concentrations offshore

Temporal change in winds in the early autumn of 2012 influenced phytoplankton composition, where the south-easterly winds were less persistent and south-westerly winds alternatively caused a more homogenous water column structure with well mixed waters that created a shift to pennate diatoms of *Pseudo-nitzschia* sp. dominating within the bay.

Seawater temperature might not have had a great influence in terms of driving phytoplankton species composition because in both early summer and early autumn the seawater temperature range near surface was from 17 to 21°C. However, surface irradiance could influence phytoplankton spatial dynamics (Yool *et al*., 2007).

The relationship between nutrients and temperature was significant for nitrates [NO_3] in both early summer and early autumn periods; phosphates and silicates had a moderately significant relationship with temperature also. Ammonium and nitrite had no significant relationships with temperature that can be explained; however all nutrients and temperature relationships were negative. Total nitrogen to SiO_4 and PO_4 Redfield ratios indicated that Algoa Bay is nitrogen limited.

In Algoa Bay the phytoplankton composition is diverse; there were dominant, common, and different new species in both field trips. There was no environmental variable or sampling parameter that clearly explained phytoplankton species assemblages in both

sampling periods. However, in early summer (Figure 2.13b), species composition indicated a 30% grouping for species, which was relatively low compared to a 50 % grouping (Figure 2.15b) in early autumn. Nitrate concentrations in the samples were low in early summer (Figure 2.13a) and high in early autumn (Figure 2.15a). Among the fifteen most numerous phytoplankton species, there were five unique species in early summer and six species in early autumn (Figure 2.14 and 2.16). Some of the cells were not clearly identified and remained unknown.

The western sector of Algoa Bay is characterised by periodic seeping through of cold upwelled waters around Cape Recife, which drives seepage into the bay (Goschen and Schumann, 1995) and enhances phytoplankton productivity. However, there is still more that needs to be done in terms of understanding the biological interaction between phytoplankton productivity and the frequency of seepage of upwelled waters in Algoa Bay.

This study has indicated that strong south-easterly winds in early summer were dominant, but the relaxation of winds enhanced algal growth as the water column stabilised and an intensified thermocline developed at 5-10 m depth. In early autumn the less intensified fluctuation of the south-easterly and south-westerly winds caused a homogenous column structure and well mixed waters, with substantial dissolved nutrients, especially nitrates, which influenced the phytoplankton composition to be distinct from the early summer period. Time-series indicated temporal differences between summers of 2010/11 and 2011/12 in chl-*a* concentration and seawater temperature (Figure 2.2). The summer of 2010/11 was cooler with high chl-*a* concentrations and the summer of 2011/12 was generally warmer with low chl-*a* concentrations. Consequently, field trip analyses did not show as much spatial or temporal differences as the longer time-series had. This was probably because of the shorter and similar sampling periods and less variability in the sea surface temperatures, both having a similar SST range of 17–21 °C in the western sector of Algoa Bay.

This study can conclude that phytoplankton production in Algoa Bay is not hindered by temperature but by nutrient limitation, mainly influenced by the hydrography, with circulation dynamics of the system driven by the winds and light intensity, causing spatial variability in phytoplankton composition and biomass. Therefore, phytoplankton dynamics of spring to summer need to be investigated further within the bay to understand the mechanisms from shorter to longer time scales of variability in phytoplankton biomass and community structure.

It has been evident that summer of 2011/12 was not a good season for oyster culturing because of differences in phytoplankton communities with associated algal blooms. This could have caused production of the neurotoxic domoic acid as Bates *et al*. (1989) indicated that *Pseudo-nitzschia* sp. can cause amnesic shellfish poisoning. This summer period had lower chl-*a* concentration compared to the summer of 2010/11, showing that this period was not suitable for oyster production.

This study has made an effort to contribute to the knowledge base and potential decision-making process of Pacific oyster farming practices in Algoa Bay. Furthermore, the effort in understanding the marine environment dynamics and suitability for oyster culturing will allow more understanding on productive times for higher biomass and production in oysters, and location parameters at which the rearing of culturing facilities should be placed. Phytoplankton community structures in both early summer and early autumn show that environmental conditions can change phytoplankton composition at both temporal and spatial scales. This shows that the conditions were not compatible with Pacific oyster culturing during these periods. Furthermore, the assumption that Algoa Bay is a nutrient-limited area with relatively low phytoplankton biomass was proven and accepted.

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Appendices

Appendix 1: List of phytoplankton species and mean concentrations (cells.ml^{-1}) in Algoa Bay on the 29 November to 1 December 2011 (Early summer).

Species	N2971s10m	N2971s15m	N2971s20m	N2971s60m	N2971s65m	N2971s40m	N2971s50m	N2971s55m	N3072s10m	N3072s110m	N3072s20m	N3072s30m	N3072s130m	N3072s40m	N3072s50m	N3072s160m	N3072s60m	N3072s70m	N3072s710m	D113s10m	D113s15m	D113s20m	D113s30m	D113s35m	D113s40m	D113s50m	D113s55m	D113s60m	D113s70m	D113s75m
Amphora sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	37	0	0	0	0	0	0	0	0	0	0	0
Actinocyclus sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Azpetia sp.	23	0	0	0	0	0	0	0	0	0	0	18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Asterionellopsis glacialis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	147	0	0	0	0	0	0	0	0	0	0
Asteromphalus sp.	0	0	0	56	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Asteromphalus hookeri	0	0	0	0	0	0	0	0	0	0	0	18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bacteristrium sp.	0	23	0	23	0	0	0	0	0	0	0	18	0	0	0	0	0	0	18	0	0	0	0	0	0	0	0	0	0	0
Bacteriosira bathyomphala	0	0	0	0	0	0	0	0	0	166	0	0	0	0	0	0	0	0	0	18	18	0	0	0	0	0	0	0	0	0
Biddulphia sp.	0	0	0	0	0	0	23	423	0	0	0	0	18	18	0	0	18	0	0	0	0	0	0	0	18	0	0	0	0	0
Bellerochea sp.	0	0	0	0	685	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Coscinodiscus sp.	23	0	0	68	783	114	91	46	847	18	147	166	74	147	74	0	166	0	37	147	18	184	55	221	18	0	0	18	18	37
Chaetoceros socialis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	18	18	55	37	0	0	37	0	0	37	0
Cyclitndrotheca sp.	23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	18	0	0	0	0	0	0	0	0
Cyclitndrotheca closterium	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	37	0	0	0	0	0	0	0	0	0	0
Cyclotella sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	18	0	0	0	0	0	0	0	0	0	0	0	0	0
Eucampia cylindrocornis	0	0	183	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Eucampia cornuta	0	0	0	0	0	0	0	0	0	0	110	74	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Eucampia sp.	0	0	0	0	0	0	0	0	0	147	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fragilariopsis ehnrenbergi	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	18	0	0	18	0	0	0	0	0
Fragilariopsis sp	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Guinardia sp	0	23	388	0	56	46	0	0	0	147	37	18	18	405	74	18	55	37	0	92	0	0	37	55	0	0	55	74	55	18
Guinardia striata	0	0	0	0	0	593	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Guinardia deliculata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	74	0	0	0	0	0	0	0	0	0	0	0
Grammatophoria marina	0	0	0	23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Grammatophoria oceanica	0	0	0	0	0	0	0	0	0	18	0	0	0	0	0	0	0	0	0	18	0	0	0	0	0	0	0	0	0	0
Grammatophoria sp.	0	0	0	0	56	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	18	0	0	0	0	0	0	0	0
Gyrodinium sp.	114	137	160	68	504	23	23	0	0	37	18	18	18	18	18	0	74	0	0	37	18	0	55	18	18	18	37	55	18	0
Hemiaulus sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	37	0	0	0	0	0	0	0	626	0	0	0	0	0	0	0	0
Leptocylindrus sp.	0	0	0	0	0	23	0	0	0	0	0	74	0	0	0	0	0	0	147	0	0	0	0	0	0	0	0	0	0	0
Leptocylindrus minimus	1073	0	114	0	0	0	0	0	0	387	0	0	74	0	0	0	0	0	0	663	166	718	350	0	295	0	0	0	0	0
Leptocylindrus danicus	0	0	0	0	0	0	0	0	0	0	0	110	184	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Licmophora sp.	0	91	0	23	0	23	0	0	0	0	0	0	0	18	0	0	0	0	0	0	0	0	0	0	0	0	0	37	0	0
Licmophora ehrenbergi	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	18	0	0	0	0	37	0
Mastogloia sp.	0	0	0	23	0	0	0	0	0	0	0	18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Meuniera membranacea	0	0	0	0	0	0	0	0	0	0	74	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nitzchia sp.	0	68	68	23	0	0	0	0	0	0	18	0	0	0	0	0	0	0	0	92	18	55	0	0	0	0	0	0	0	0
Pseudo-nitzchia sp.	365	0	46	0	0	0	23	0	0	0	0	0	0	0	0	0	0	74	166	0	184	0	0	0	0	0	0	0	0	0
Rhizosolenia sp.	0	0	68	23	0	0	23	0	0	18	0	0	37	0	0	0	0	0	0	18	0	18	18	0	0	0	0	0	0	0
Scrippsiella sp.	0	0	0	0	0	0	23	23	423	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Skeletonema sp.	0	0	0	0	0	0	0	0	0	0	0	0	423	0	0	37	0	0	0	0	0	0	276	0	258	37	74	0	0	0
Thalassiosira hyperborea	0	0	0	0	0	0	0	0	0	0	0	0	92	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Thalassiosira sp.	46	0	23	23	280	228	593	160	2945	74	295	110	1012	74	37	74	55	92	202	18	350	166	276	9	221	129	110	74	313	166
Thalassionema nitzchiodes	0	0	114	23	0	0	0	0	0	74	0	0	0	18	0	0	0	0	0	92	0	0	166	0	0	0	0	0	0	0
Tricentrium sp.	0	0	0	0	0	0	0	0	0	0	0	0	18	0	0	37	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dinoflagellates																														
Alexandrium sp.	23	46	0	23	56	0	0	0	0	0	0	0	37	18	0	37	0	0	0	0	0	0	0	74	0	0	0	0	0	0
Ceratium sp.	0	46	0	23	56	0	0	23	423	0	0	37	0	18	0	0	92	0	0	0	18	0	0	37	0	18	37	55	18	0
Ceratium furca	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ceratium kofoidii	0	0	0	0	0	0	0	0	0	0	0	18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ceratium trichoceros	0	0	0	46	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dinophysis sp.	0	0	23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	18	0	0	0	18	0	18	0	0	0	0	0
Dinophysis acuminata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dactyliosolen sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	37	0	0	0	0	0	0	0	0	0	0	0
Dictyocha sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dictyocha fibula	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	18	0	0	0	0	0
Dictyocha octanaria	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ditylum sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	18	0	0	0	0	0	0	0	0	0	0
Gymnodinium mikimotoi	0	0	0	0	0	0	0	0	0	0	0	37	0	0	0	0	0	0	0	18	18	18	0	0	0	0	0	0	0	0
Gonyaulax sp.	0	0	0	0	0	457	639	571	10511	18	37	442	74	387	221	0	442	313	0	0	350	37	74	626	0	350	239	166	37	221
Gonyaulax polygramma	0	0	0	0	8506	0	0	0	0	0	0	110	1233	221	74	331	166	0	442	0	0	74	0	0	0	0	0	0	0	0
Noctiluca scintillans	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	18	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Oestrupia sp.	0	0	0	0	0	0	0	23	423	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Oestrupia musca	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Peridinium sp.	0	91	68	228	280	23	0	23	423	0	18	37	1675	18	166	350	0	18	202	92	92	18	129	37	18	74	37	37	37	18
Peridinium excentricum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Polykrikos sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	18	0	0	0	0	0	0
Plagiogramma sp	0	0	0	0	0	0	0	0	0	0	0	0	0	18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Protoperidinium sp.	0	137	114	91	1511	23	0	137	2522	0	110	0	0	0	0	0	0	0	18	0	0	55	0	295	18	0	18	37	0	0
Protoperidinium claudians	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Protoperidinium divergens	46	0	114	0	0	0	0	0	0	55	0	129	442	129	0	0	18	0	0	110	74	0	18	37	18	0	0	0	55	37
Protoperidinium oceanicum	0	0	0	0	0	0	0	0	0	0	0	18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Preperidinium sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	18	0	0	0	0
Preperdinium meunieri	0	0	0	0	0	0	0	0	0	0	55	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Procentrum micans	114	68	0	0	0	0	0	0	0	18	18	18	74	18	0	37	18	0	0	0	18	37	37	37	37	0	37	0	18	0
Procentruim rostratum	23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	18	18	0	0	
Procentrum gracile	0	0	0	0	0	0	0	0	0	18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Procentrum sp.	0	0	0	0	727	46	0	0	0	0	0	18	0	0	0	0	0	18	0	0	0	0	0	0	0	0	0	0	0	0
Pyrocytis sp.	0	0	0	0	0	0	0	0	0	0	0	0	18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pyrophacus horologicum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	37	0	0	0	0	0	0	0
Flagellates & others																														
Dunaliella sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Katodinium glaucum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lampricus sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	239	0	0	0	0	0	0	0	0
Rhabdonemia sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	18	0	0	0	0	0	0	0	0	0	0
Species Y	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	18	0	0	0	0	0	0	0	0
Species Z	0	0	0	0	0	0	0	0	0	0	0	0	0	18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Trchodesmium sp	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	37	0	0	0	0	0
Unkown cell.	0	23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mean Concentrations	22	9	17	9	150	19	24	12	220	10	13	16	60	26	9	11	13	6	13	19	17	26	22	17	11	9	8	7	7	6

Appendix 2: List of phytoplankton species and mean concentrations (cells.ml^{-1}) in Algoa Bay on the 27 to 29 March 2012 (Early autumn).

Species	M27T1st10m	M27T1st15m	M27T1st20m	M27T1st30m	M27T1st35m	M27T1st40m	M27T1st50m	M27T1st55m	M28T2st10m	M28T2st15m	M28T2st20m	M28T2st30m	M28T2st35m	M28T2st40m	M28T2st50m	M28T2st55m	M28T2st60m	M28T2st70m	M28T2st75m	M29T3st10m	M29T3st15m	M29T3st20m	M29T3st30m	M29T3st35m	M29T3st40m	M29T3st50m	M29T3st55m	M29T3st60m	M29T3st70m	M29T3st75m
Diatoms																														
Amphora sp.	0	0	0	0	0	0	0	0	0	0	0	0	18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Actinocyclus sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Azpeitia sp.	0	0	0	0	0	0	0	0	0	0	18	0	0	0	0	0	0	0	18	0	0	0	0	0	0	0	0	0	0	0
Asterionellopsis glacialis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Asteromphalus sp.	0	0	0	0	0	0	0	18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bacteristrium sp.	0	0	0	0	0	0	0	0	0	0	166	0	0	0	0	0	0	0	0	0	18	18	0	0	0	0	0	0	0	0
Bacteristrium bathyompha	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	18	0	0	0	0	0	0	0	0
Biddulphia sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bellerochea sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Coscinodiscus sp.	0	0	0	18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Coscinodiscus radiatus	18	0	55	0	55	0	0	92	74	18	0	0	18	0	147	18	0	18	0	0	0	0	0	0	37	0	18	0	37	
Chaetoceros sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	18	0	18	0	0	0	0	0	0	0	0	0
Chaetoceros dichaeta	368	497	387	0	129	0	166	55	479	387	0	110	37	0	0	331	295	0	258	0	110	184	0	0	129	0	0	0	0	0
Chaetoceros tortissimus	0	0	0	460	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Chaetoceros lorenzianus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	55	0	0	0	0	0	0	0	0	0	0	0	0
Chaetoceros socialis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	18	0	0	0	0	0	0	0	0	0	0	18	0	0	0	0
Cyclitndrotheca sp.	18	0	0	0	0	0	0	0	0	0	0	0	0	0	37	0	18	18	0	0	0	0	18	0	18	0	74	18	0	0
Cyclitndrotheca closterium	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	74	0	0
Cyclotella sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cochlodinium sp.	0	0	0	18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Corethron sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cerataulina sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	18	0	0	0	0	0	0	0	0	0	0
Cerataulina pelagica	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dactyliosolen sp.	0	0	0	0	0	0	0	0	0	0	18	0	0	0	0	0	0	0	0	18	0	37	18	0	0	0	0	0	0	0
Eucampia sp.	0	0	0	0	0	0	0	0	0	0	0	0	18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fragilariopsis sp	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	37	18	0	0	0	0	37	92	0	0	37	
Guinardia sp	0	0	0	0	0	0	0	0	239	147	0	166	92	0	0	0	0	0	0	184	37	0	0	18	0	0	0	0	0	0
Guinardia striata	74	147	534	368	74	110	147	92	92	184	110	18	55	258	0	0	202	129	0	258	221	0	0	18	0	37	0	18	0	0
Guinardia deliculata	147	0	0	0	18	74	0	0	0	0	0	313	0	0	18	0	0	0	0	0	0	37	0	0	0	74	0	110	37	
Grammatophoria marina	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Grammatophoria oceanica	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Grammatophoria sp.	0	18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	37	0	0	0	0	0	0	0	0	0	0	0
Gyrodinium sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	92	0	0	0	0	0	0	0	0
Hemiaulus sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	18	0	0	0	0	0	0	0	0	0	0	0	0	0
Katodinium glaucum	0	0	0	0	0	0	0	0	202	110	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Leptocylindrus sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	18	0	0	0	0	0	0	0	0	0	0	0	0	0
Leptocylindrus minimus	166	552	387	0	0	0	239	0	810	0	0	0	0	0	0	0	0	0	0	129	0	0	0	0	0	0	0	0	0	0
Leptocylindrus danicus	0	0	0	0	0	313	350	0	0	736	0	258	368	331	147	202	110	0	0	92	0	0	74	405	1104	129	37	1031	350	773
Licmophora sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Licmophora ehrenbergi	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lioloma pacificum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mastogloia sp.	0	0	0	0	0	0	0	0	0	0	0	202	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Meuniera membranacea	0	0	18	0	18	18	0	0	37	18	0	37	0	37	0	0	0	0	0	37	37	0	0	37	0	0	0	0	0	0
Noctiluca scintillans	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	202	0	0	0	0	0	0	0	0
Peridinium sp.	0	0	0	0	0	0	0	0	0	0	0	0	18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Peridinium excentricum	37	18	18	681	552	74	0	202	92	37	313	589	920	350	55	479	0	18	405	92	110	37	37	258	18	18	313	37	37	129
Polykrikos sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	55	0	0	0	0	0	0	0	0	0	0	0	0	0
Plagiogramma sp	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Proboscia sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	37	74	0	0	184	0	
Proboscia alata	0	0	0	0	0	0	0	0	0	0	0	0	0	18	0	0	0	0	0	0	0	0	0	0	37	0	0	0		
Pseudo-nitzchia sp.	99438	24961	58444	1723	67574	43350	11431	855	37883	36963	40607	54726	54873	34091	32913	12425	39245	18242	18150	38472	34514	45246	24758	38693	26709	21555	16788	15186	17101	33318
Rhizosolenia imbricata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Rhizosolenia sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	37	0	0		
Skeletonema sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Thalassiosira hyperborea	0	0	0	0	0	18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Thalassiosira eccentrica	18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	184	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Thalassiosira sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	18	18	0	0	0	0	0
Thalassionema elongatum	847	313	607	29	736	276	405	13	607	368	460	552	442	405	0	0	479	110	0	405	405	18	313	0	0	460	350	166	295	368
Thalassionema nitzchioide	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	37	0
Thalassionthrix longissima	0	0	37	0	0	0	0	0	258	239	110	18	0	129	37	166	202	0	166	0	0	37	92	0	239	37	0	74	0	37
Tricerentium sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	18	0	0	0	0
Dinoflagellates																														
Alexandrium sp.	0	0	0	295	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	55	0	0	0	0	0	0
Ceratium sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	239	221	129	258	74	0	0	0
Ceratium furca	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ceratium kofoidii	0	0	0	0	18	18	18	0	0	0	0	37	0	18	18	18	0	18	0	0	0	0	0	55	55	18	55	37	37	37
Ceratium declinatum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	18	0	0	0	0	0	0	0	18	0	0	0	0	0	0
Ceratium splineatum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	37	0	0	0	0	18	0	0	0	0	0	0	0	0
Dinophysis sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Gymnodinium mikimotoi	18	0	37	55	0	18	0	0	18	74	37	18	0	18	37	18	55	18	37	37	37	74	37	55	55	37	18	18	37	18
Gonyaulax sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Gonyaulax polygramma	0	0	0	0	0	0	0	0	0	0	0	0	37	0	0	18	0	0	0	18	0	0	0	0	0	0	0	0	0	37
Protoperidinium sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	313	0	0	0	0	0	18	74	0	0	0	0	0	0	0
Protoperidinium claudians	0	0	0	0	0	0	0	0	37	0	0	0	0	0	0	0	0	0	0	0	0	18	0	0	0	0	0	0	0	0
Protoperidinium pyriform	37	0	0	37	18	55	18	37	0	0	0	18	18	0	18	18	18	18	0	0	37	37	55	0	37	18	92	0	37	37
Protoperidinium conicum	0	18	0	0	0	0	0	0	0	0	18	0	0	0	18	0	0	0	0	0	0	0	0	0	0	0	18	18	18	
Preperdinium meunieri	0	0	37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	18	18	0	0	
Procentrium scutellum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Procentrum emarginatum	0	0	0	18	0	0	0	0	0	0	18	0	0	0	0	0	0	0	0	0	0	0	0	0	37	0	0	0	0	0
Procentrum compressum	0	0	0	0	0	74	0	0	0	18	0	0	0	0	18	0	18	0	0	0	18	0	0	0	18	37	0	0	0	0
Procentrum triestinum	0	0	0		0	0	0		0	0	0	18	0	0	0	0	0	0	0	0	0	0	0	0	0	37	0	0	0	0
Phyrophacus sp.	0	0	0	0	0	0	0	0	0	0	0	0	18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pyrocytis sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Phyrophacus horologicum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Rhabdonemia sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	92	0	0	0	0	0	0
Scrippsiella sp.	18	74	0	0	18	0	0	0	0	92	0	37	55	0	0	0	55	0	0	92	0	0	0	0	0	0	0	0	0	37
Flagellates & others																														
Dictyocha sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dictyocha octanaria	0	0	0	0	0	0	0	0	18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dunaliella sp.	0	0	0	0	18	0	0	0	37	18	18	0	37	18	0	0	37	0	0	0	18	18	18	0	37	18	0	0	0	0
Species B	55	0	0	0	37	0	0	0	184	166	0	37	0	0	37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Trichodesmium sp	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	18	0	0	0	0	0	0	0	0	0
Unkown cell C	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Unkown cell A	0	0	0	0	0	0	0	0	0	0	18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mean Concentrations	1101	289	658	41	753	483	139	15	446	430	455	619	622	388	364	155	444	203	207	432	389	501	280	434	312	248	196	182	199	380

Appendix 3

Nitrites (NO_2)

Nitrites had the lowest concentrations for both sampling trips; the surface concentration was from 0–0.1 µM.L^{-1} for early summer and ranged from 0–0.35 µM.L^{-1} for early autumn (Figure 1a). Vertical profiles indicated an even distribution for early summer ranging from 0–0.1 µM.L^{-1} with high concentrations at the greater depths and low concentrations at the upper depths. In early autumn there was less variability in distribution of nitrite concentrations where there were similar values in concentration ranges from 0.11–0.20 µM.L^{-1} (Figure 1b).

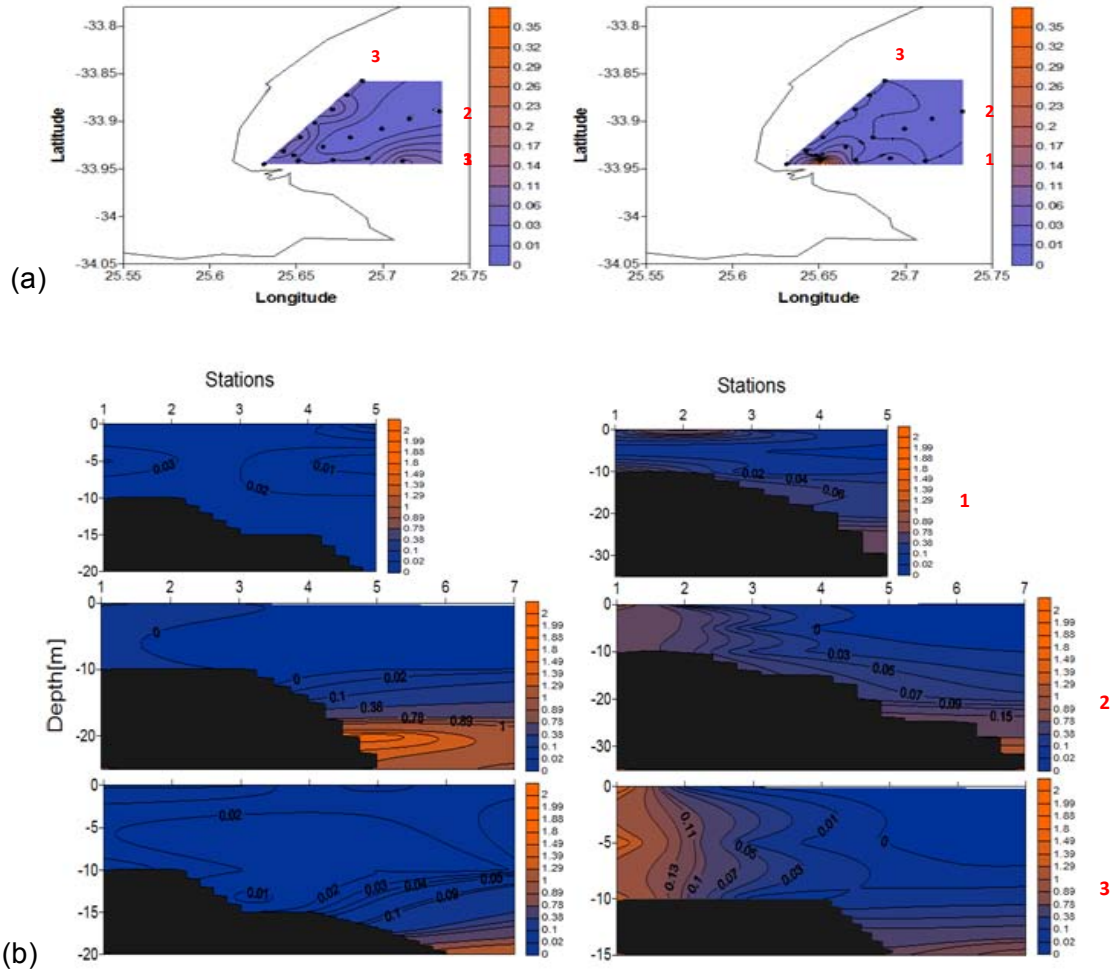

Figure 1: (a) Surface nitrite µM/L (NO_2) distribution for all stations sampled in Algoa Bay in early summer (left panel) 2011 and early autumn (right panel) 2012. **(b)** Profiles of nitrite µM.L^{-1} (NO_2) for all stations sampled. Nitrite profiles were taken according to transects 1, 2 and 3 each pair of the profiles represent each transects.

Appendix 4

Ammonium (NH_4)

Surface ammonium distribution ranged between 0–1 µM.L^{-1} for early summer and early autumn with different distribution patterns. In the early summer there were high concentrations values for onshore stations and offshore had lower concentrations ranging from 0–0.5 µM.L^{-1} and 0–1 µM.L^{-1} (Figure 2a). Ammonium vertical profiles showed an even distribution in concentration across the water column in early summer with 0–1.1 µM.L^{-1} range and 0.9–3 µM. L^{-1} for early autumn, also with lower concentration values near surface and higher at greater depths (Figure 2b).

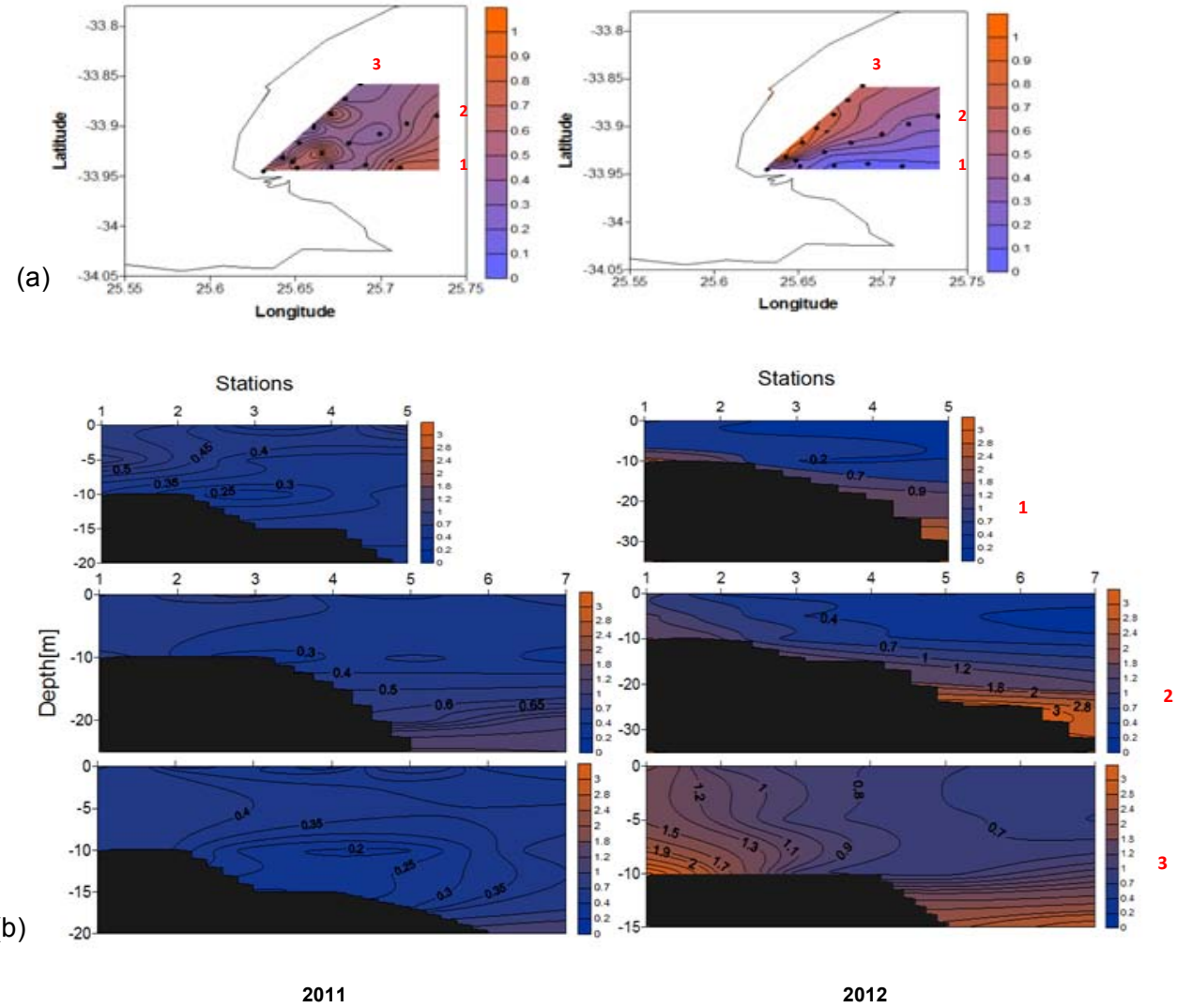

Figure 2: (a) Surface ammonium µM/L (NH_4) distribution for all stations sampled in Algoa Bay in early summer (left panel) and early autumn (right panel). **(b)** Profiles of ammonium µM/L (NH_4) for all stations sampled. Profiles were taken according to transects 1, 2 and 3 each pair of the profiles represent each transects.