An ADCP Study of Subtidal Scale Density-Driven Exchange in Saldanha Bay, South Africa

Submitted in Partial Completion of the Master of Science Degree
Helen Frances Stewart
Department of Oceanography,
The University of Cape Town
March 20, 2003

Revised June 18, 2003

An ADCP and water-column temperature study was conducted to determine the circulation aspect of subtidal-scale, density-driven exchange in Saldanha Bay, South Africa. Density-driven exchange conditions develop in response to synoptic-scale wind events in the southern Benguela region, even under light (<5m s^{-1}) wind conditions. During a density-driven exchange event, directionally opposing bi-level flow, similar to an estuarine system, develops in response to remote upwelling-favourable winds. The bi-level flow component occurs in two distinct bands, bayward at 0-9m height from bottom and seaward 15-20m height off bottom, and is very sensitive to changes in wind forcing. Observations of current behaviour are added to the four-phase conceptual model of density-driven exchange developed by Monteiro and Largier (1999). In addition, estimates of bay flushing based on ADCP current velocities and the four-phase conceptual model are calculated and implications of shelf water influx into Saldanha Bay are discussed.

Table of Contents

List of Figures

1. Introduction

1.1 Saldanha Bay

Saldanha Bay is the deepest and largest natural harbour in South Africa and is located approximately 100km north of Cape Town. It is roughly semicircular, bounded to the west by the Benguela upwelling system and to the south by Langebaan lagoon. It is separated into two distinct regions, the Outer Bay and Inner Bay, by a peninsula and the Marcus Island Causeway. Inner Bay, in turn, is divided into Big Bay and Small Bay by an artificial, 4km-shipping jetty whose construction began in 1975. Outer Bay is deeper and more influenced by the adjacent Benguela upwelling system. Big and Small Bays are more sheltered, shallower, and have a more coastal character. Langebaan Lagoon, to the south, is dominated by tidal influences. As Langebaan is generally less than 5m deep throughout, the depth of the summer thermocline, it can be considered separate from the Big Bay system (Monteiro and Largier, 1999).

Saldanha Bay as a whole is heavily influenced by the adjacent Benguela upwelling system, tidal flows, and winds. Sub-thermocline layers are formed of upwelled continental shelf waters (Spolander, 1996). A thermally stratified system exists in the bay during the August to May upwelling season, particularly from November to March (Monteiro and Largier, 1999; Weeks *et al*, 1991). A sharp thermocline develops between 5-10m depth as a result of strong seasonal insolation, ingress and egress of upwelled shelf water, and fluxes in synoptic-scale winds. This thermocline generally persists throughout the upwelling season, except during extremely strong wind events that mix the water column to depths of 10m or greater (Monteiro and Largier, 1999). During winter months, this thermocline breaks down because of lowered insolation and strong wind-induced mixing from winter storms. Salinity variation shows little variation throughout the system, and thus temperature can be used as a proxy for density within Saldanha Bay (Shannon and Stander, 1977).

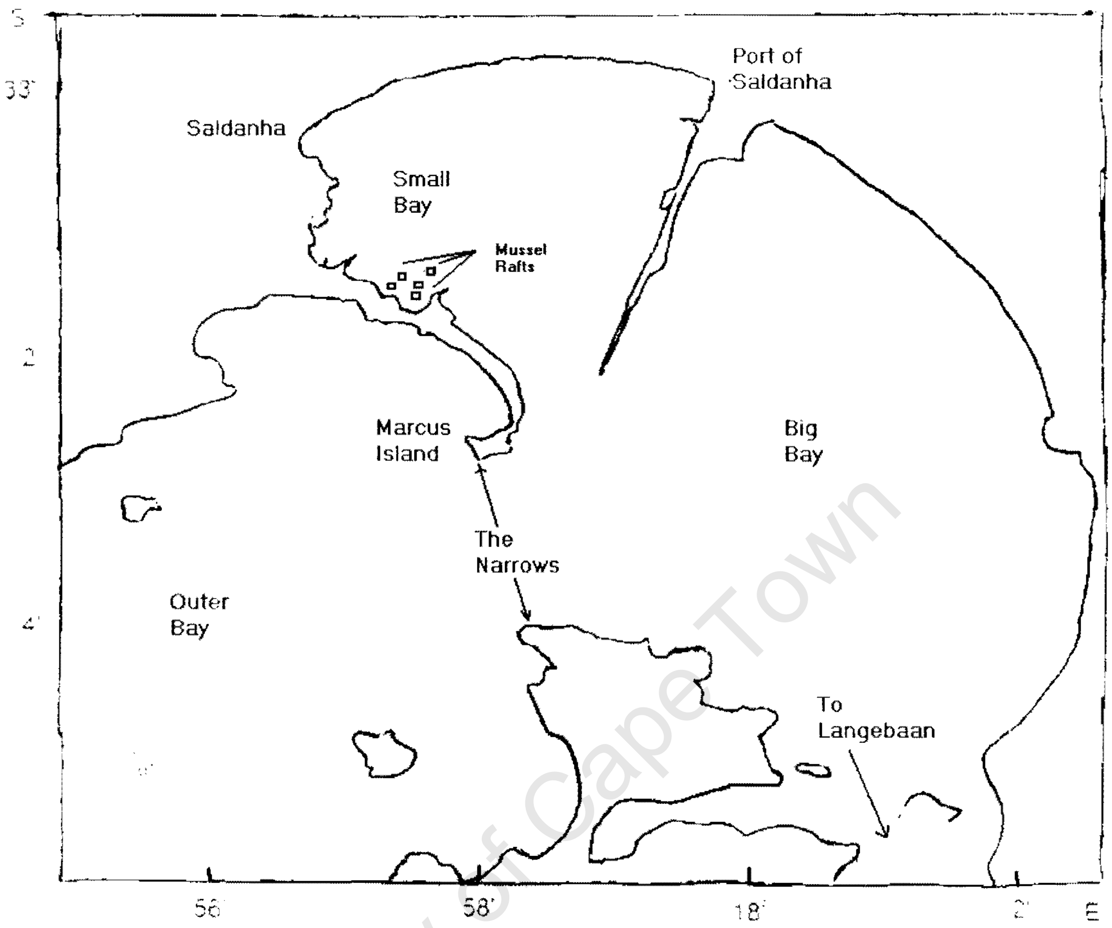


Figure 1. Saldanha Bay. Image adapted from Monteiro et al. 1998.

1.2 Historical Circulation Studies of Saldanha Bay

The foundation study of most recent research on the circulation of Saldanha Bay was conducted in 1974 by the Sea Fisheries Branch (Shannon and Stander, 1977). Monthly sampling procedures included water sampling by reversing thermometer, drift cards, drogues, and dye releases. During summer months, a shallow (5m) thermocline was observed at several sampling stations. This dataset was completed prior to the construction of the shipping jetty that divided Inner Bay. Surface-confined currents in the central part of both Inner and Outer Bay, the southern part of Inner Bay, and Langebaan Lagoon were found to be dependent on wind and tidal motion. In the northernmost section of Inner Bay, in what is now Small Bay, weak surface currents travelled clockwise along the north shore during both ebb and flood tide. Drogues deployed at 5m depth showed a similar pattern to the surface currents. Drogues deployed at 10 and 20 m and seabed drifters were released to profile the deeper areas of the bay. Data from the 10m and 20m drogues was sparse but indicated weak tidal flow (~5 cm s^{-1}) within the bay. Seabed drifters released in or near the mouth of Langebaan Lagoon travelled around Salamander Point and exited the bay to the north. Residence time was estimated to be 25 days, with tidal motion being the primary flushing mechanism (Shannon and Stander, 1977).

In 1975, construction on the shipping jetty began, followed by construction of a causeway linking Marcus Island to the mainland. The interior bay was divided into Big Bay and Small Bay, and circulation patterns of the bay system as a whole were greatly altered. The Sea Fisheries Institute environmental sampling program continued after construction of the jetty, until 1979. This historical data was analysed to provide post-construction circulation data (Weeks *et al*, 1991). This data showed that, in general, surface confined currents were primarily driven by wind, that tidal influences can be seen throughout the water column, and that current speed decreased with depth. At the surface and 5m depths in Outer Bay and Big Bay, tidally reversing flow is apparent. Surface current speeds were generally less than 12cm s^{-1}, with currents at 5 and 10 m less than 6cm s^{-1}. In Small Bay, the surface circulation is generally weaker and more variable than in Big Bay.

Following synoptic-scale wind events, a thermally stratified system develops as upwelled shelf water enters the bay (Monteiro *et al*, 1996; Monteiro *et al*, 1998; Monteiro and Largier, 1999). During the summer upwelling season (August-April), strong southeasterly winds drive coastal upwelling, which in turn causes bay temperatures to be greater than those of the adjacent ocean. In response, a tongue of cold, upwelled shelf water is advected into the bottom of Saldanha Bay and so intensifies the contrast between cold bottom and warm surface waters. This is the "active phase" of the density-driven circulation in the bay. After upwelling conditions cease, the coastal upwelling slackens off and the subthermocline bay water is now denser than the adjacent ocean. The cold bottom water then drains out of the bay into the ocean and stratification weakens. This is the "relaxation phase" (Monteiro and Largier, 1999). The onset of the active phase of the cycle may lag the onset of upwelling winds by 1.5 to 2.5 days and the onset of the relaxation phase may lag the decrease in upwelling winds by .5 to 1 day (Monteiro and Largier, 1999). Residence time of the upwelling intrusion is estimated at 6-8 days, roughly equivalent to the time between onset and cessation of synoptic-scale upwelling winds. Although the Monteiro and Largier study (1999) did not investigate the effect of coastal-trapped waves on the density-driven cycle in Saldanha Bay, a study by Nelson (2000) and by Probyn et al (2000) indicate that energetic coastal-trapped waves are a forcing factor of the cold bottom-water intrusion. In addition, the bay appears to respond to remote forcing factors, particularly in the Cape Columbine region (Probyn et al, 2000).

1.3 Industrial Activity in Saldanha Bay

As Saldanha Bay is home to several industries with differing requirements, often in conflict with one another, maintaining water quality in the bay is an important concern. Mariculture projects in Saldanha Bay are currently the focus of much investigation with the intention of increasing mariculture production in the bay. Culture of Spanish Mussels (*Mytilus galloprovincialus*) on rafts in Small Bay yields up to 3000 tons raw weight each year, and small-scale cultivation of oysters has occurred in the past (Probyn et al, 1999). Harmful algal blooms (HABs) occur frequently in the Benguela region late in the summer season, causing animal death either by algal toxin poisoning or by suffocation resulting from large regions of hypoxic or anoxic water (Probyn et al, 2001). Tourism interests also demand good water quality. The Saldanha Bay/Langebaan Lagoon system is home to a large casino resort, ecotourism interests (such as birdwatching and springtime wildflower trails), and more conventional seaside tourism. Proximity of the Small Bay mussel rafts and greater Saldanha/Langebaan system to a major deep-water port and fish-processing factories is thus a water-quality concern. The iron-ore terminal alone handles approximately 1.2 million metric tonnes of ore per annum, while the multipurpose terminal handles non-containerised cargo such as slag, steel pellets, and coking coal (Portnet, 2003). Spills or continuous, intentional discharges of any industrial chemicals including but not limited to slag cargo, marine diesel fuel, contaminated waste from the fish factories, or noxious liquids from either port or factories will have a deleterious effect on water quality, and has a potential deleterious effect on tourism and mariculture. Understanding the time-scales and mechanisms of water exchange in the bay is therefore necessary to success in the mariculture operation.

1.4 Study Objectives

In a small, enclosed embayment, maintaining good water quality in the face of natural and anthropogenic pollutants requires constant flushing with clean water from an external source. The most obvious flushing mechanism is tidal, although flushing may occur in other ways, including density-driven exchange. The density-driven flow of Saldanha Bay replaces older, warmer water residing in the bay with cold, nutrient-rich, oxygenated shelf waters. This oxygen and nutrient rich water is transported into both Big and Small bays during the density-driven exchange event, and the warm surface layer is enriched with these nutrients by entrainment. This continuous, upwelling season flushing removes anthropogenic substances from the bay, and may act to impede development of harmful algal blooms in Saldanha Bay (Probyn et al, 2000).

With this in mind, **the primary objective of this thesis is to further investigate and describe the subthermocline circulation in Saldanha Bay during periods of coastal upwelling and subsequent bottom-water intrusion**. Time-series ADCP, atmospheric and water-column temperature data are used to describe the intrusion, mixing, entrainment, and eventual draining away of upwelled shelf water into and out of Saldanha Bay.

2. Materials and Methods

2.1 Study Area

All instruments were moored in the Narrows region (between Marcus Island and the Donkergat peninsula, defining the southern boundary of the mouth of Saldanha) of Saldanha Bay, outside the shipping channel and adjacent to navigation buoy #2. This site was chosen to give data on bay processes as water intrudes into the Big Bay/Small Bay system, where most significant human industrial and recreational activity occurs. Although this is a single-point study in a complex system, the study location is spatially representative of the region and is thus suitable for the purposes of this study. Charted depth at deployment site is 24m at chart datum (SAN 1012). Position of the sampling area, shipping channel, and depth contours are indicated on Figure 3.

2.2 Sampling

The 2003 Saldanha Bay ADCP study was conducted from 16 Jan 2003-30 Jan 2003. Divers (including the author) observed a strong thermocline at approximately 8m from the surface, strong currents in the upper layer, very little noticeable current in the centre of the water column, and noticeable currents within 2m of the bottom while installing equipment (personal observation, 16/1). In addition, visibility above the 8m-depth thermocline was 3-4m, while visibility below the thermocline was less than 1m. The bottom was very flat and sandy, and no sand ripples were observed on the bottom.

Current data was collected by a RD Instruments Workhorse Sentinel ADCP. Individual current samples were taken every 6 seconds, with ensemble averaging every 15 minutes. Current direction is found using an internal magnetic compass reading adjusted to read true direction. Internal compass error was ±0.6° after calibration on January 13, 2003. ADCP data was collected in 1m bins from 0-24m height off bottom. Temperature, salinity, and pressure data is recorded by a Sea-Bird SBE 19 autonomous CTD, moored 3m above the water bottom. CTD sampling was conducted for 4-second intervals every 15 minutes. Water column temperature data was collected by an Aanderaa TR-7 thermistor string, collecting temperature recordings every 12 minutes. The TR-7 string was 11m long, with recording thermistors every meter, and attached to the CTD such that the thermistor string recorded temperatures at 4-14 meters above bottom (mab). The CTD and thermistor string were moored together, with the ADCP mooring located approximately 5m from the combination CTD/thermistor mount.

Hourly data on air temperature, barometric pressure, and surface winds were provided by the South African Weather Service at Geelbek Weather Station, located at the head of Langebaan Lagoon and approximately 10km from the sampling site. Although the weather station is not immediately adjacent to the coast, its proximity to the study site, orientation of the coastline in the direction of the prevailing wind, and low-lying topography make weather data at Geelbek suitable for the purposes of this thesis.

Figure 2. Mooring Diagram

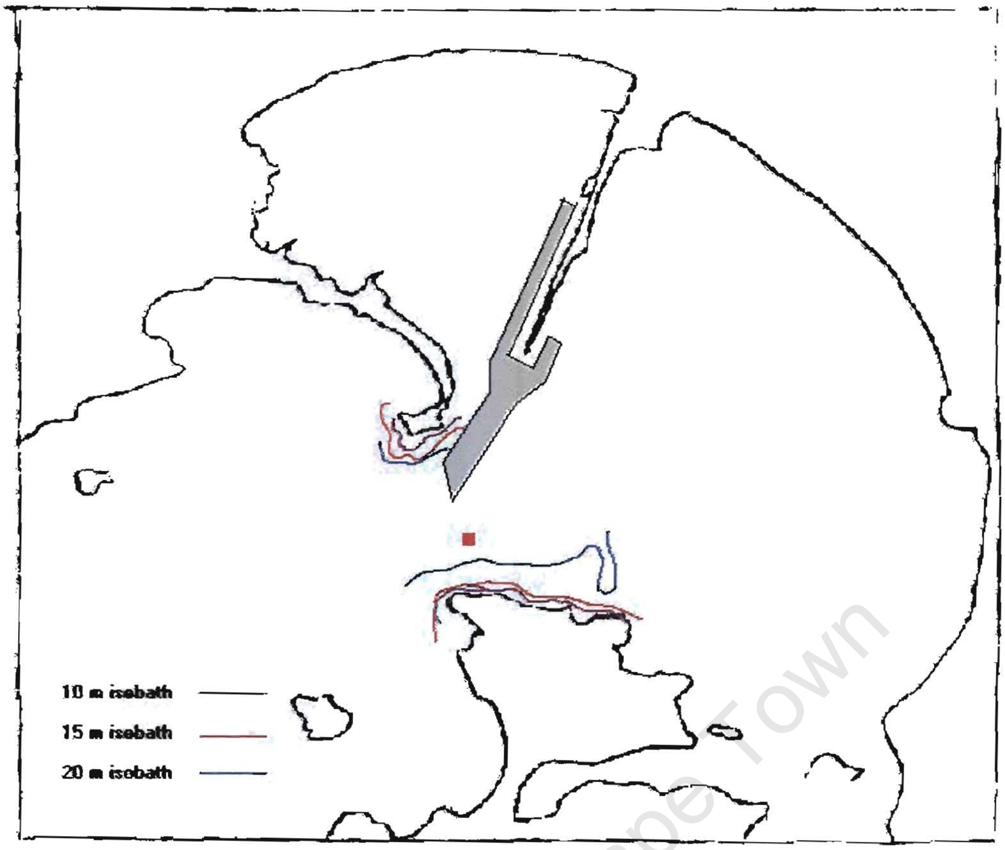


Figure 3. Location of study mooring (red square), shipping channel, and depth contours in the Narrows region of Saldanha Bay.

2.3 Data Processing

ADCP, CTD, and TR-7 data are averaged to 1-hour intervals and passed through the Doodson X0 tidal signal filter to obtain subtidal-scale data. The Doodson filter was designed to remove tidal signal from sea level data, although it is useful in the analysis of current and temperature data. When used for purposes other than sea level analysis, however, diurnal and higher-frequency variability may not be completely removed, as there are other sources of high-frequency variability (e.g. the effect of insolation on temperature). Several low-pass filters to be used on post-Doodson data were tested but were found to cause unacceptable decimation to the data. Observations are measured in meters above bottom rather than depth from the surface, with maximum ADCP observations at surface and maximum water-column temperature (from CTD and TR-7) at 14m meters above bottom (the length of the thermistor chain). Daily mean wind speed and direction are calculated from raw weather data.

3. Results

3.1 Atmospheric Observations

Atmospheric observations pertinent to this study can be divided into four main events: a weak, short-duration south-easterly wind event from 17/1-19/1 (Event A); a moderate, persistent south-easterly wind event from 21/1-26/1 (Event B), a strong, short-duration south-westerly wind event from 27/1-28/1 (Event C) and a weak, incompletely observed south-easterly wind event (Event D). (Figure 4a, 4b, 4c) Winds in event A are light (<4m s^{-1}) south-easterly, which persist for only 2 days before being curtailed by a one-day south-westerly event. There is no signal from event A in the air pressure time-series. Event B, characterised by moderate (5-8m s^{-1}) south-easterly to southerly winds that start strong and decline over time, is evident as a small decline in the barometric pressure signal. Event C signals a rapid end to the upwelling conditions of event B, an increase in wind speed, and shift in direction to the southwest. Following event C, a weak (<4m s^{-1} and decreasing) south-easterly wind event occurs.

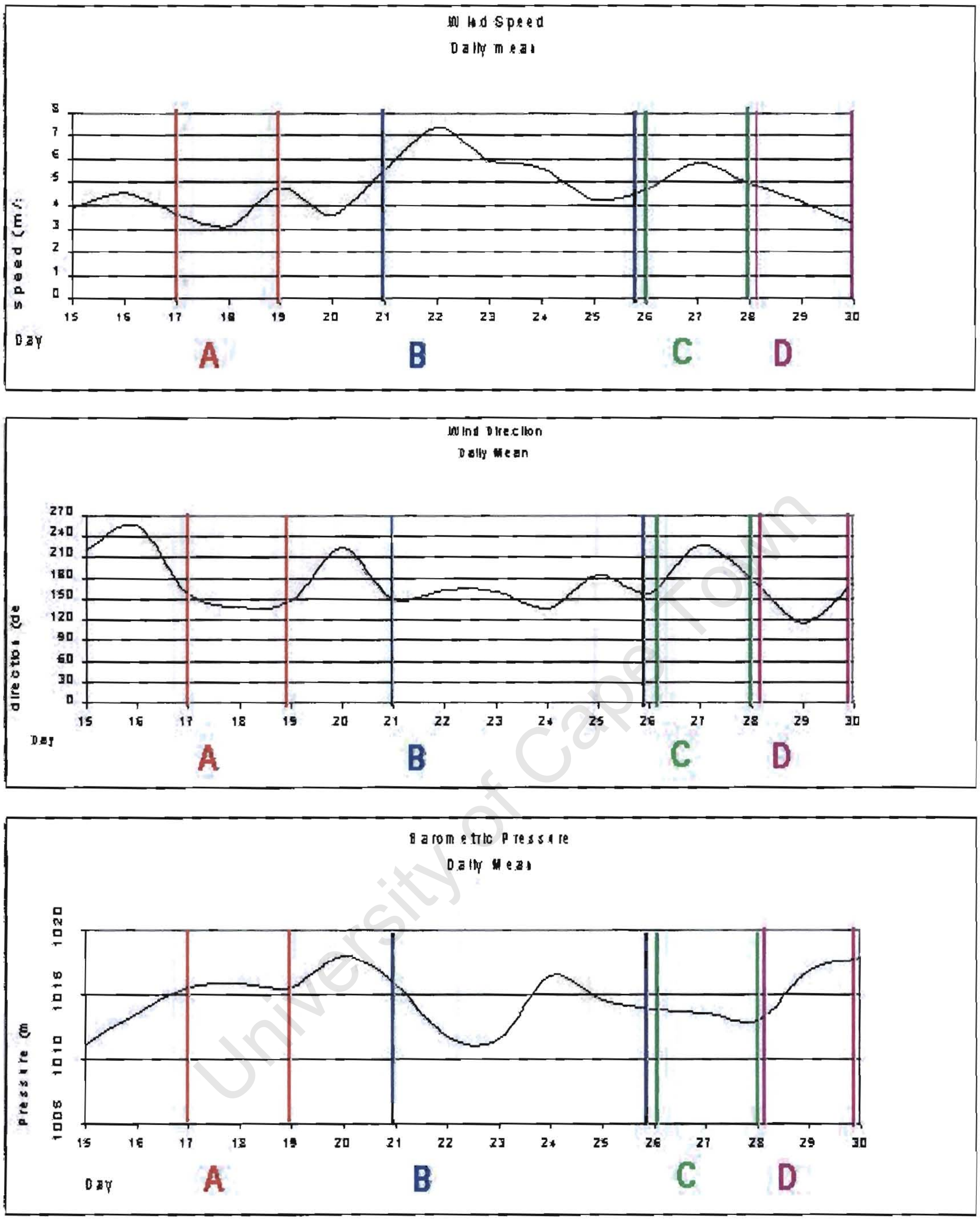


Figure 4a-c: Atmospheric observations during the sampling period. 4a. Wind speed, m s^{-1} (top). 4b. Wind direction. 4c. Barometric pressure, mm Hg. Synoptic scale events are indicated by event letter.

3.2 **Water Column Temperature Observations** (Figure 5)

During event A, recorded water column temperature decreases slightly from a minimum-maximum range of 10.5°-13.2° (3-14m height) on 17/1to a minimum-maximum range of 10.3°-12.8° on 19/1. Thereafter, water column temperatures rise before starting another decline that heralds the onset of event B. During the prolonged cooling period of event B, water column temperature drop from a minimum-maximum of 10.5°-13.5° on 20/1 to a minimum-maximum range of 9.2°-10.4° on 26/1. At the termination of event B and the onset of event C, water column temperature increased, such that by the end of the event (28/1) the water column temperature range had a minimum of 9.6 and a maximum of 11.7. Water temperature begins to decrease again during event D.

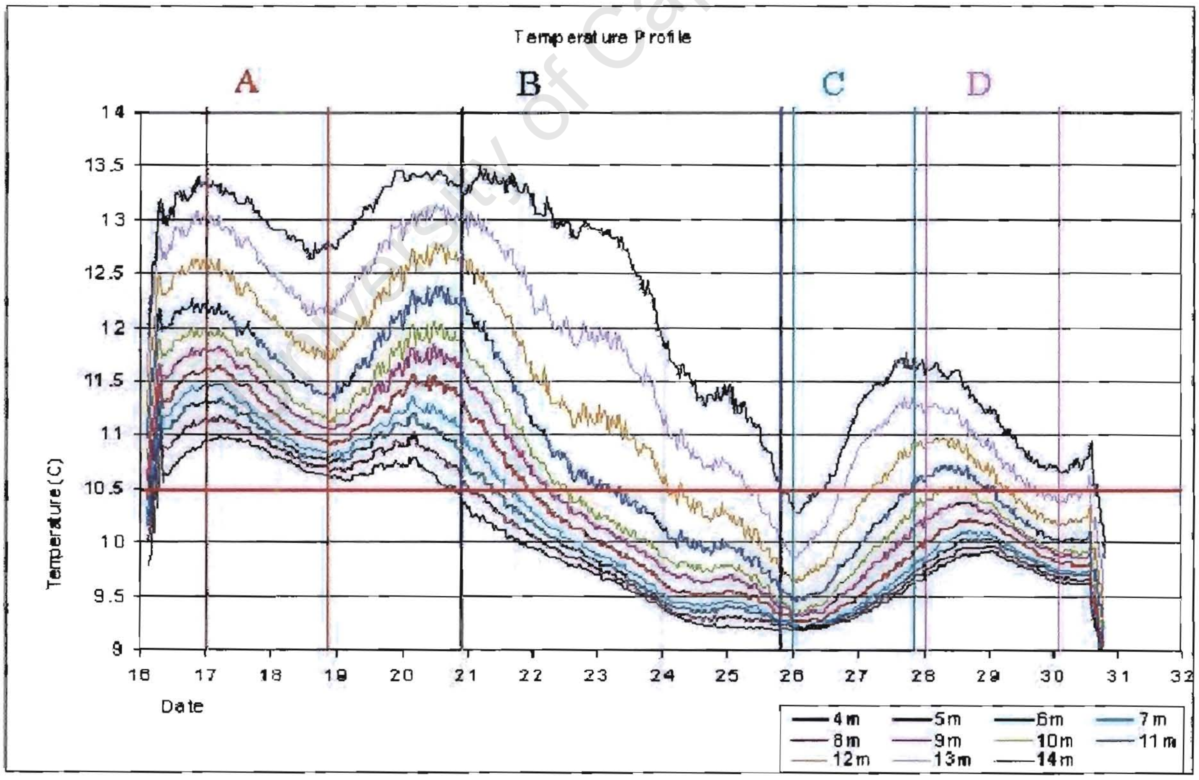


Figure 5: Water column temperature time series. 10.5° isotherm is shown in red. Level data refers to meters above bottom and not depth below surface. Synoptic-scale events are indicated by the event letter.

3.3 ADCP Observations

Bins are measured in meters above bottom (mab). Data from bins above 22mab are sparse and noisy, and data from below 3m falls into the ADCP blanking interval. Both are excluded from analysis. Observations are divided into east-west and north-south components. Due to the orientation of Saldanha Bay, water entering (leaving) the bay will have a stronger eastward (westward) component than north-south component. For the purposes of this study, east and north are defined as positive, while south and west are defined as negative.

East-West Flow (Figure 6)

During events A and B, opposing flow with respect to depth develops shortly after onset of south-easterly wind conditions. Water enters on the bottom (eastward flow) and exits between heights of 12-20mab (westward flow). During event A, velocity of water exiting the bay between 18-20mab is up to an order of magnitude greater than velocity of water entering the bay on the bottom. Currents are of similar magnitude and trend between 3-9mab and between 15-17mab. Currents between 10-15mab are weaker ($|u|<3\text{cm s}^{-1}$). During event B, (21/1-26/1) opposing flow with depth commences shortly after onset of upwelling winds. Bottom-level flow (0-9mab) increases as water column temperature decreases. Currents at both upper and lower levels decrease in velocity in response to a brief lull in winds on 24/1-25/1 before resuming strength the evening of 25/1. Starting 25/1, the thickness of currents flowing bayward increases to 15m, and the velocity at 16m decreases to near zero. Between 17-20mab, currents are again up to an order of magnitude greater than currents in the lower layer (0-15mab). With the commencement of south-westerly winds (Event C), current speed decreases to less than 3cm s^{-1} at all heights up to 19mab. Currents at 3m reverse direction entirely, becoming weakly negative. In the upper water column, currents at 19-20mab follow the general pattern of currents between 13-18mab, while currents above 20mab show strong wind influences (not shown). Bi-level opposing flow resumes on 28/1 with the onset of weak event D.

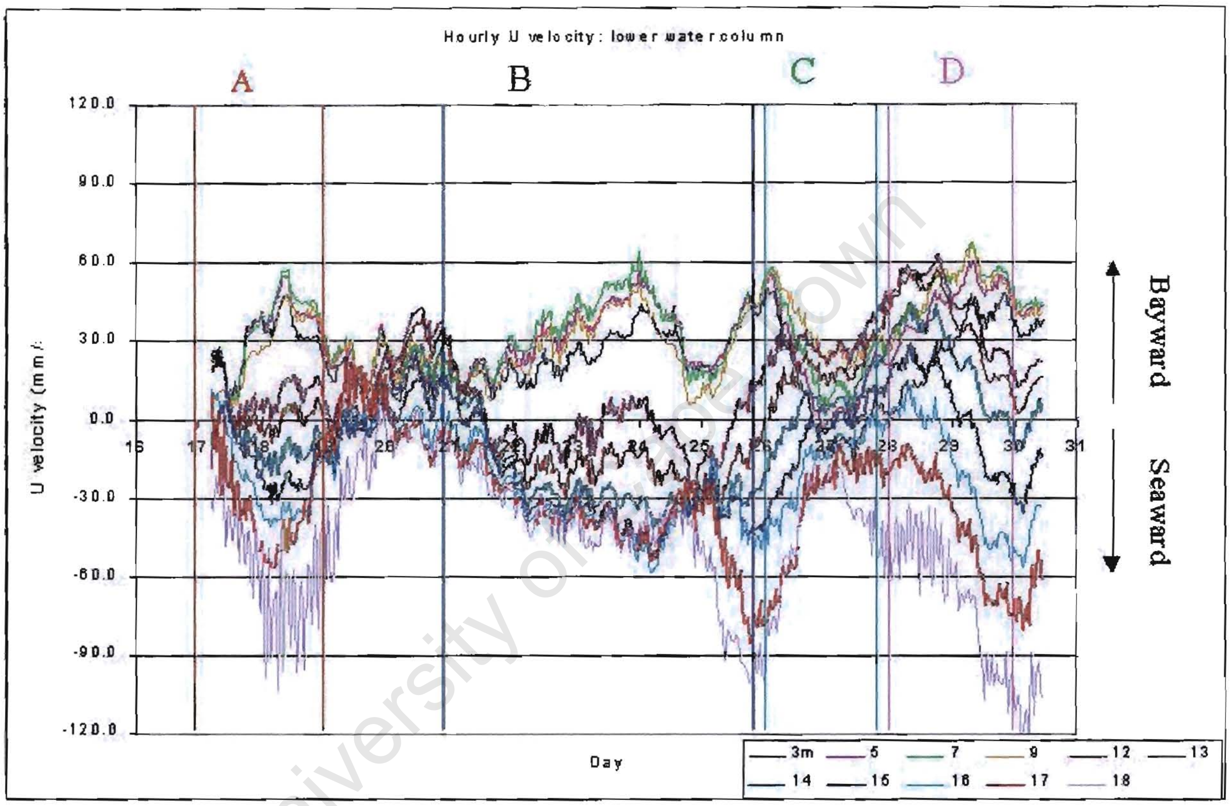


Figure 6. ADCP east-west velocities. East (bayward) is defined as positive flow and west (seaward) is defined as negative flow. Velocities are given in mm s^{-1}. Current bins are defined in meters above bottom and not depth from surface.

North-South flow (Figure 7)

During event A, current magnitudes from 0-16mab were small (<3cm s^{-1}) and change direction from flowing south to flowing north before the event was curtailed on 19/1. During the first part of event B (21/1-24/1), currents from 0-7mab are near zero.

Currents between 9-14mab are small (<3cm s^{-1}) and flowing south. Currents between 15-19mab are fairly uniform in magnitude and direction at –4.5cm s^{-1}. After the daylong lull in winds on 24/1-25/1, currents between 14-18mab reversed direction and flowed from south to north. Currents from 0-7mab remained small and southward-flowing. With the commencement of event C on 27/1, current speeds between 0-17mab remained small (<3cm s^{-1}), while current speeds at 18mab rapidly increased to similar magnitude of the surface layer (19-22mab) (not shown). The surface layer values are noisy and care should be taken in their analysis.

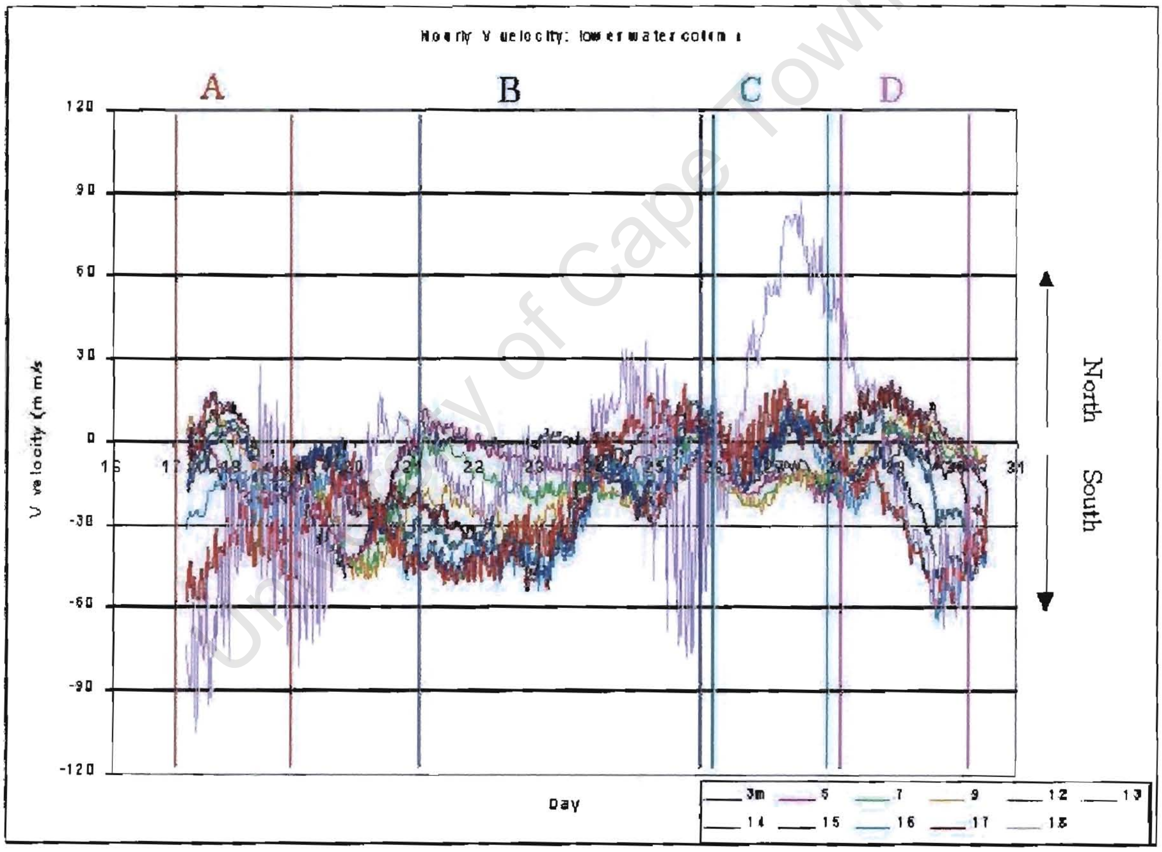


Figure 7. ADCP north-south velocities. North is defined as positive. Velocities are in mm s^{-1}. Current bins refer to meters above bottom and not depth from surface.

4. Discussion

4.1 Refining the Model

Monteiro and Largier (1999) presented a four-stage conceptual model of the density-driven exchange cycle in Saldanha Bay: Onset of upwelling-favourable winds and coastal upwelling, onset of cold bottom water intrusion, enhanced stratification, and upwelling winds relaxing/draining of cold bottom water. The bi-level flow observed during the 2003 sampling period was hypothesised by Monteiro and Largier (1999) and identified by Probyn et al (2000). Water flows southward and eastward into the bay on the bottom, and flows southward and westward out of the bay in the central water column. Thickness of the layer of recently upwelled shelf water is determined indirectly by both height of the 10.5° C isotherm and position of the zero *u* velocity contour. The position of the zero *u* velocity contour and order of magnitude changes in current speeds indirectly indicates the presence of a surface-layer thermocline.

During a density-driven exchange event, the water column can be divided into three distinct vertical zones (Figure 10a, 10b). These zones are, from bottom to surface: bayward current zone, seaward current zone, and surface mixed layer. Of these three layers, the bayward current zone and seaward current zone are composed of colder, upwelled water and the surface mixed layer is composed of thermally heated, wind mixed water. Thickness of the surface mixed layer is estimated to be 4-6m, depending on height of tide. Currents at the very bottom (0-9mab) flow as a fairly uniform band of bayward-flowing from onset of bottom-water intrusion until the bottom water begins to drain out of the bay. It is interesting to note that in this region, bayward flow is continuous throughout the study period. This flow is consistent with the strong bottom currents observed by divers at the commencement of the fieldwork phase of this study, despite the light winds on that date (personal observation, 16/1). It is possible that during a prolonged relaxation or reversal of synoptic-scale upwelling winds currents in this layer do reverse direction. This requires further investigation.

Immediately below the thermocline, there exists a similar band of seaward-flowing water (15-20mab) during the intrusion event. Unlike the bayward current zone, the seaward current zone becomes markedly less homogeneous during maximal intrusion of bottom water and during the draining phase. During the initial intrusion of upwelled water, both bayward and seaward zone u velocities have similar magnitude but opposite direction. After the bottom water intrudes to a depth of greater than 11m, however, the seaward currents immediately below the thermocline increase in velocity to compensate for the volume of water entering at the bottom. Currents in the seaward and bayward current zones are very responsive to changes in the wind field, with little to no apparent lag between change in wind field and change in currents in these zones.

Although the literature suggests a lag time of 1.5-2 days between onset of upwelling-favourable winds and onset of density-driven exchange, current observations do not support such a time lag. Water exchange begins rapidly after onset of upwelling-favourable winds, evidenced by the height of the 10.5° isotherm rising 7m on the first day of event B and by the rapid draining of cold water from Saldanha Bay following the onset of event C (Figure 9). Rather, the apparent lag time may be the time it takes for the thickness of the upwelled shelf water to exceed the thickness of the bayward current zone and penetrate into the mixing zone. Event A is not apparent in the 10.5°

isotherm plot, but visible as a decreasing and levelling out of the zero *u* velocity contour. Events B, C, and D are visible in both the 10.5° isotherm trace and the zero *u* velocity contour.

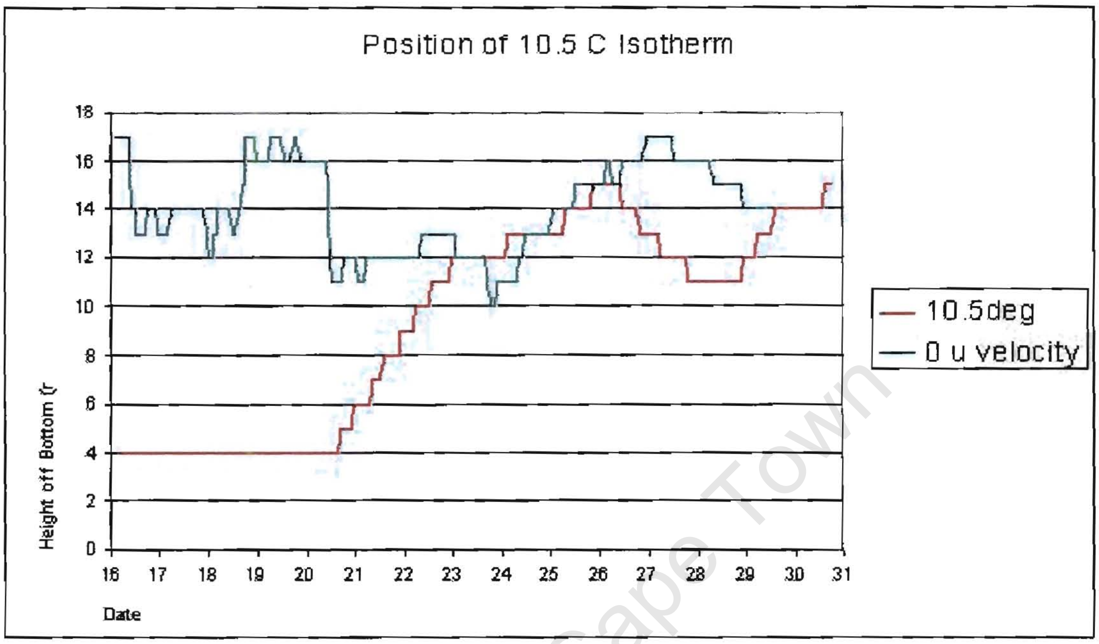
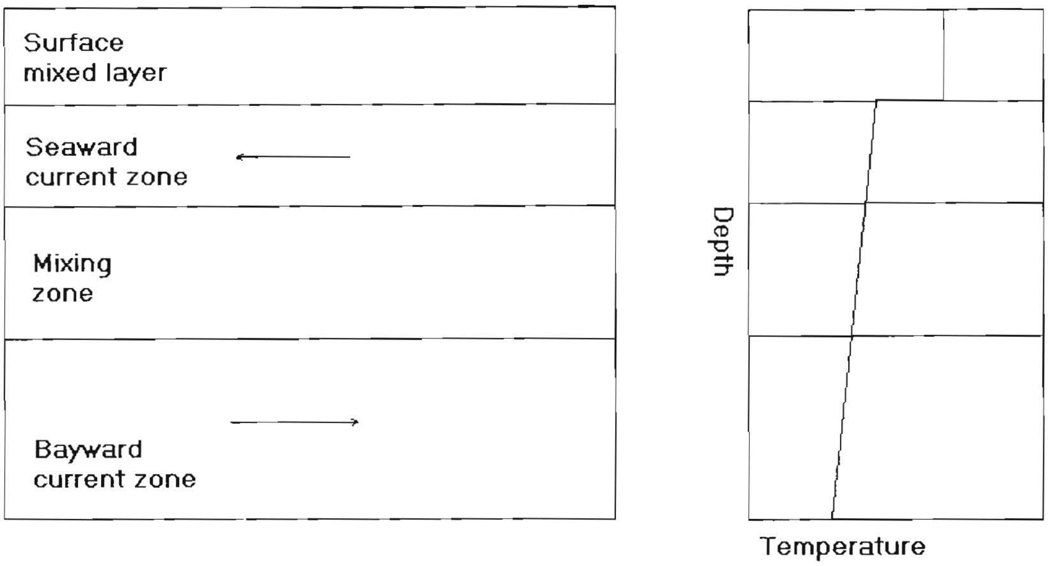


Figure 9. Position of 10.5° isotherm and zero *u* velocity contour. Event A is visible as a drop in the zero *u* velocity contour; events B and C are visible in both isotherm position and zero *u* velocity position.

Recalling that the 10.5° isotherm is used as an index of the thickness of the recently upwelled shelf water, it is evident that during the strong event B the thickness of the upwelled water layer corresponds to the position of the 0 *u* velocity contour. This implies that while cold, recently upwelled water is entering the bay, cold relict water is leaving the bay. The behaviour of the surface mixed layer with respect to the lower layers requires further investigation and will not be discussed here.



Figures 10a-10b. 10a. Stratification zones in Saldanha Bay during a density-driven exchange cycle. 10b. Temperature-depth plot of Saldanha Bay during a density-driven exchange cycle. Strata are shown for reference.

With the above in mind, we can now qualitatively incorporate the bi-level flow pattern into the conceptual model of density-driven exchange in Saldanha Bay designed by Monteiro and Largier (1999). Detailed analysis of the dynamics of this conceptual model are beyond the scope of this thesis and will be left for further investigation.

1. Onset of synoptic-scale upwelling winds (Figure 11)

At onset of synoptic-scale upwelling winds, outward (westerly) flow in the seaward current zone commences. The magnitude of both currents is similar, with velocities in the seaward current zone being somewhat larger (less than an order of magnitude) and trending more to the south as it exits the bay.

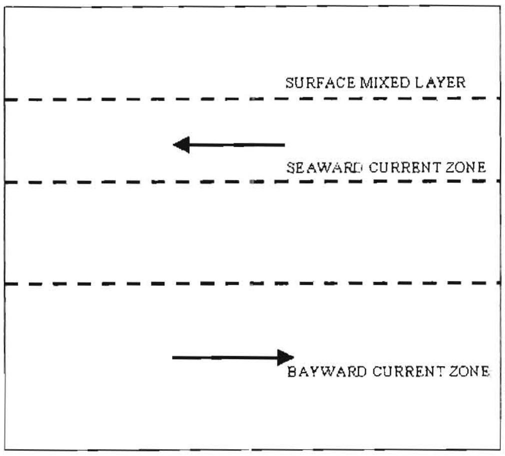


Figure 11: Phase 1 of density-driven exchange cycle. The height of the 10.5° isotherm is less than the thickness of the bayward current zone.

2. Intrusion of cold bottom water (Figure 12)

Although bottom water begins to intrude less than 6 hours after onset of upwelling-favourable winds, the largest rate of intrusion occurs 1-2 days after onset; in other words, when the thickness of the recently upwelled water intrusion exceeds the thickness of the bayward current zone. Currents in the bayward and seaward current zones remain vigorous and of similar magnitude, increasing in velocity as wind speed increases.

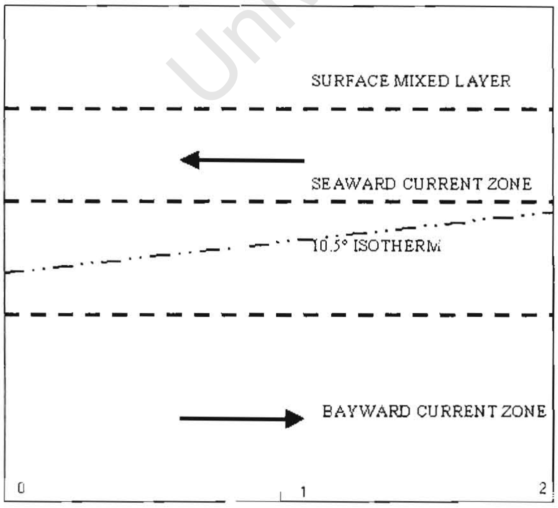


Figure 12: Phase 2, density-driven exchange cycle. Dot-dashed line indicates change in position of 10.5° isotherm over time (days from start of phase).

3. Increased stratification (Figure 13)

Here the thickness of the upwelled shelf water intrusion reaches its maximum. In response, currents in the seaward current zone increase in magnitude such that they are an order of magnitude greater than the currents in the bayward current zone. Shear between the two layers leads to increased vertical velocities at the interface of the upwelling intrusion and seaward current zone and at the interface of the seaward current zone and surface mixed layer. In response, maximum entrainment of cold bottom water into the surface layer occurs.

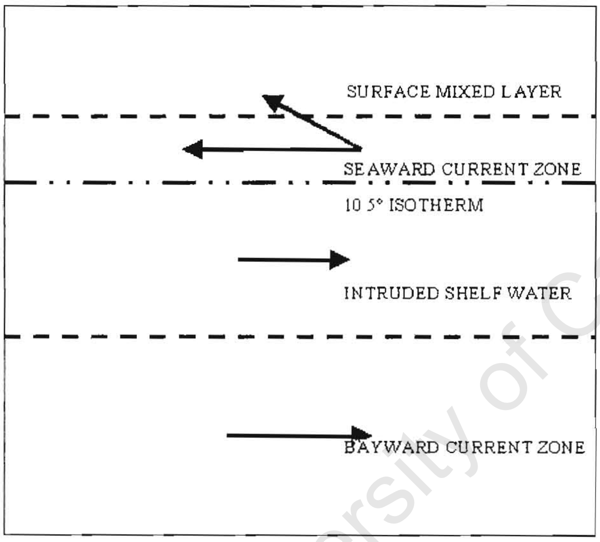


Figure 13: Phase 3, density-driven exchange cycle. The 10.5° isotherm has reached its maximum height.

4. Draining of bottom water (Figure 14)

After cessation of upwelling-favourable winds, the thickness of the upwelling intrusion begins to decrease as bottom-layer currents reverse and drain out of the bay. Although velocities in both bayward and seaward zones decrease almost immediately following a wind relaxation, currents in the seaward current zone may remain up to an order of magnitude larger than currents in the bayward current zone. The literature suggests that after cessation of the upwelling wind event, currents at all depths below the thermocline flow bayward (Monteiro and Largier, 1999). This draining leading to an isothermal bay may be short-circuited by onset of another south-easterly wind event shortly (1-2 days) after the termination of the previous event. However, results of this study show continuing bayward flow even after cessation of an upwelling wind event. This must be incorporated into any future model.

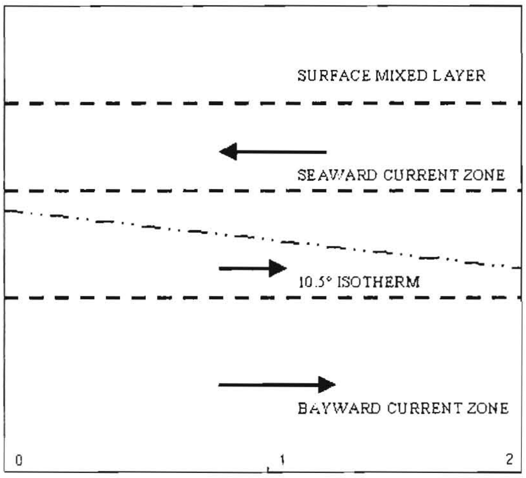


Figure 14: Phase 4, density-driven exchange cycle. The height of the 10.5° isotherm is decreasing over time (days from start of phase).

4.2 Estimates of Bay Flushing Time

While by no means definitive, this study has shown that bi-level flow associated with density-driven exchange can occur in Saldanha Bay even under light wind conditions provided the wind is from the southeast. Over the course of the sampling period, three density-driven exchange events occurred, separated from each other by less than 3 days in each case. This combined with the continuous observed inflow of shelf water in the bayward current zone suggests that the fourth stage of the conceptual model by Monteiro and Largier is frequently short-circuited, and influx of cold, clean, nutrient-rich bottom water into Saldanha Bay occurs near constantly during the upwelling season.

In a short, weak density-driven exchange event such as event A, current speeds remain small and the thickness of the upwelled water intrusion is approximately equal to the thickness of the seaward current zone. In this case assume that the bayward current velocity during a density-driven exchange event is constant at 3cm s^{-1}, the seaward current velocity is equal in magnitude and opposite in direction, and that the thickness of the bayward and seaward current zones are each 9m thick, and that the distance between Marcus Island and the Donkergat peninsula is 1.8km. Also assume the currents in the bayward and seaward current zones are moving as a slab and do not vary with spatially. Then over a 3-day period, approximately $125.9\times10^6 m^3$ of recently upwelled water enters Inner Bay and replaces older, warmer upwelled water. Neglecting entrainment, this short, weak event is capable of flushing 20% of Inner Bay (using the estimated total volume of Inner Bay to be $596.2\times10^6 m^3$, from Monteiro and Largier, 1999). Including the estimated entrainment rate of $20\times10^6 m^3$ per day (Spolander, 1996; Monteiro and Largier, 1999), then 31% of the volume of Inner Bay is replaced during a weak, 3-day density-driven exchange event. It is likely, however, that entrainment occurs at a slower rate during the weak wind events; therefore the conservative flushing estimate of 20% of Inner Bay volume during a weak, curtailed wind event is held.

In a strong, persistent density-driven exchange event such as event B, current speeds in the upper layer increase as the thickness of the upwelled water intrusion (and hence the bayward current zone) is greater than the thickness of the seaward current zone. Assume that the same conditions as for the weak, short-duration event hold true, except that bayward current zone is 13m thick and average bayward current velocity is 4.5cm s^{-1}, moving as a slab into Inner Bay. Then over a persistent 6-day density-driven exchange event, excluding entrainment $377.9 \times 10^6 m^3$ of cold bottom water enters the bay. Including entrainment, 84% of the water residing in Inner Bay is replaced. Using these rough, somewhat large estimates of water transported into Inner Bay, a conservative estimated flushing time of Inner Bay is approximately 12-15 days during a weak density-driven exchange event and 8 days during a strong event.

4.3 Implications of Shelf Water Influx on Industry in Saldanha Bay

The near-constant flushing with cold, nutrient-rich shelf water is of particular importance to tourism and mariculture interests, and lesser importance to shipping and industrial (e.g. steel, fish-processing) interests. Frequent influx of nutrients over a time-span of several days, particularly of nitrate (NO_3^-), provides a favourable environment for new production. Estimated daily production of 0.63g C m^{-2}, where transfer of NO_3^- across the thermocline is considered to be a limiting factor, in turn provides a rich environment for the culture of filter feeding organisms, namely oysters and mussels (Monteiro et al, 1998). Further up the food chain, this production provides the foundation of the Saldanha/Langebaan Lagoon ecosystem that is the focus of ecotourism in the area. Also, the removal of nutrient-enriched surface waters through the density-driven exchange process has been implicated in the low occurrence of harmful algal blooms in Saldanha Bay (Probyn et al, 2000). This density-driven exchange and flushing of the bay then assures the good water quality necessary for both of these industries.

Of particular interest to mariculture in Saldanha Bay is the possibility of advection of anoxic or hypoxic, or toxic (from noxious algal species) water into the bay. While wind-driven oxygen uptake in the surface layer may be sufficient to prevent oxygen stress, sedentary organisms in the lower layers of the water column are susceptible to damage and/or death from low oxygen conditions. Further, disruption of production during a low-oxygen event could increase the stress on the organism. Influx of anoxic or hypoxic water could occur during a density-driven exchange event, where anoxic shelf water upwells, or following harmful algal bloom and bayward wind conditions (e.g. event C). While there is no way to prevent occurrence of anoxic water entering the bay, understanding the process and the time needed to flush the bay of anoxic, hypoxic, or toxic water from the culture area may improve response to an incident.

For light and heavy industry such as pelagic fish processing, shipping, and steel production, the main advantage to industry gained through density-driven exchange is pollution control. Should a spill of a noxious chemical occur in the stratified regions of the bay, the rapid flushing time increases the chance that polluted waters from the spill are removed in a short (<14 days) time span. This natural bay flushing in combination with proper pollution-control and prevention procedures may in maintaining a high level of water quality within both Big and Small Bays. It is important to note, however, that in shallow areas (<5m depth) of the Saldanha/Langebaan system, there is no subthermocline layer and thus flushing associated with a density-driven exchange event does not extend to the shallow regions. In these regions tidal flushing estimates of 20-25 days apply (Shannon and Stander, 1977).

5. Conclusions

Observations of water column temperature and ADCP data support the hypothesis of Monteiro and Largier (1999) and Probyn et al (2000) that subtidal-scale, subthermocline currents in Saldanha Bay during a density-driven exchange event are expressed as directionally-opposing bi-level flow. This flow is very sensitive to fluctuations in upwelling-favourable winds, with response time between onset of winds and onset of bi-level flow on the order of hours. With the water column current data, volume transport during a density-driven exchange event is estimated and an existing conceptual model of the density-driven flow is refined. The cycle of intrusion, entrainment, replacement, and draining of cold, nutrient-rich bottom water has important implications for water quality and industry in Saldanha Bay.

Acknowledgements

Financial and technical assistance was generously provided by the CSIR-Stellenbosch and the University of Cape Town. I wish to thank Drs Pedro Monteiro, Howard Waldron, and Geoff Brundrit for their supervision and assistance. Finally I send a great heartfelt thank-you to my friends and family for believing that I could.

References

1. Largier, J. (2000). Stratification and baroclinic circulation in Saldanha Bay. p. 1; 10th Southern African Marine Science Symposium (SAMSS 2000): Land, Sea and People in the New Millennium – Abstracts
2. Monteiro, P.M.S. and Largier, J. (1999) Thermal stratification in Saldanha Bay (South Africa) and subtidal, density-driven exchange with the coastal waters of the Benguela upwelling system. *Estuarine, coastal and shelf science* 49, 877-890
3. Monteiro, P.M.S., Spolander, B., Brundrit, G., and Nelson, G. Shellfish culture in the Benguela system: estimates of nitrogen driven new production in Saldanha bay using two physical models. *Journal of Shellfish Research* 17, 3-13
4. Nelson, G. (2000). Shelf waves as a control over the flow, temperature and nutrient supply in Saldanha Bay, South Africa. 10th Southern African Marine Science Symposium (SAMSS 2000): Land, Sea, and People in the New Millennium—Abstracts.
5. Portnet: Saldanha Iron Ore and Saldanha Multi-Purpose Terminals. Government Public-Information Publication. http://www.saponet.co.za/sun/ext/pub/default.asp
6. Probyn, T.A., Pitcher, G., Pienaar, R., and Nuzzi, R. (2001) Brown tides and mariculture in Saldanha Bay, South Africa. *Marine Pollution Bulletin* 42(5), 405-408.
7. Probyn, T.A., Pitcher, G.C., Monteiro, P.M.S., Boyd, A.J., and Nelson, G. (2000). *Physical processes contributing to harmful algal blooms in Saldanha Bay, South Africa.* South African Journal of Marine Science 22, pp 285-298

8. Probyn, T.A.., Pollock, D., Pitcher, G., Anderson. R., and Bailey, J. (1999). MCM shellfish overview. http://www.environment.gov.za/mcm/econom/maricult/overview.htm
9. Spolander, B. (1996). Entrainment in Saldanha Bay. Unpublished MSc thesis, University of Cape Town. 66pp.
10. Weeks, S., Boyd, A.J., Monteiro, P.M.S., Brundrit, G. (1991)The currents and circulation in Saldanha Bay deduced from historical measurements of drogues. *SA Journal of Marine Science* 11, 525-535
11. Weeks, S., Monteiro, P.M.S., Nelson G., Cooper, R.. (1991) A note on wind-driven replacement flow of the bottom layer in Saldanha Bay, South Africa: Implications for pollution. *SA Journal of Marine Sci*ence #11, 579-583.

List of Revisions

1. Throughout manuscript: Replace "survey" with "study"
2. Throughout manuscript: Replace "density-driven mixing" with "density-driven exchange"
3. Throughout manuscript: Dates in original are written in US convention; in revised thesis are written in South African convention.
4. Throughout manuscript: Change "height above bottom" and "m height" to mab.
5. Page 10, paragraph 1: Sentence now reads: "Spills or continuous, intentional discharges of any industrial chemicals including but not limited to slag cargo, marine diesel fuel, contaminated waste from the fish factories, or noxious liquids from either port or factories will have a deleterious effect on water quality, and has a potential deleterious effect on tourism and mariculture."
6. Page 11, paragraph 1: omit "or excessive rainfall" from sentence 2.
7. Page 12, paragraph 1: Add "defining the southern boundary of the mouth of Saldanha" to the parenthesised description of the location of the Narrows.
8. Page 12, paragraph 1, sentence 2 now reads: Divers (including the author) observed a strong thermocline at approximately 8m from the surface, strong currents in the upper layer, very little noticeable current in the centre of the water column, and noticeable currents within 2m of the bottom while installing equipment (personal observation, 16/1).
9. Page 12, paragraph 2: omit "(hereafter 1/16-1/30 in the conventions of this paper)" from sentence 1.
10. Page 13, paragraph 1, sentence 9: Sentence now reads "The TR-7 string was 11m long, with recording thermistors every meter, and attached to the CTD such that the thermistor string recorded temperatures at 4-14 meters above bottom (mab)."
11. Page 13, paragraph 2: Add the sentence "Although the weather station is not immediately adjacent to the coast, its proximity to the study site, orientation of the coastline in the direction of the prevailing wind, and low-lying topography make weather data at Geelbek suitable for the purposes of this thesis."
12. Page 14, paragraph 1: Add "The Doodson filter was designed to remove tidal signal from sea level data, although it is useful in the analysis of current and temperature data. When used for purposes other than sea level analysis, however,

diurnal and higher-frequency variability may not be completely removed, as there are other sources of high-frequency variability (e.g. the effect of insolation on temperature). Several low-pass filters to be used on post-Doodson data were tested but were found to cause unacceptable decimation to the data."

13. Page 14, paragraph 1: Change "height off the bottom" to "meters above bottom."
14. Page 15, paragraph 1: Change "height off the bottom" to "meters above bottom."
15. Page 17: Change figure caption to read "Atmospheric observations during the sampling period."
16. Page 18, paragraph 1: Change "22m height" to "22mab." Change last sentence to read "bins are measured in meters above bottom (mab)" and move this sentence to the beginning of the paragraph. Add the sentences "Observations are divided into east-west and north-south components. Due to the orientation of Saldanha Bay, water entering (leaving) the bay will have a stronger eastward (westward) component than north-south component. For the purposes of this study, east and north are defined as positive, while south and west are defined as negative." at the end of the paragraph.
17. Page 20, paragraph 1: Add the sentence "The surface layer values are noisy and care should be taken in their analysis" to the end of the paragraph.
18. Pages 21: Omit observations of ADCP vertical velocity, including Figure 8.
19. Page 22, paragraph 2, sentence 1: change sentence to read "During a density-driven exchange event. . ." Change last sentence to read "It is interesting to note that in this region, bayward flow is continuous throughout the study period. This flow is consistent with the strong bottom currents observed by divers at the commencement of the fieldwork phase of this study, despite the light winds on that date (personal observation, 16/1). It is possible that during a prolonged relaxation or reversal of synoptic-scale upwelling winds currents in this layer do reverse direction. This requires further investigation."
20. Page 23, paragraph 1: Change 1st sentence to read "Immediately below the thermocline, there exists a similar band of seaward-flowing water (15-20mab) during the intrusion event." Omit last 2 sentences.
21. Page 24: Add the following paragraph: "Recalling that the 10.5° isotherm is used as an index of the thickness of the recently upwelled shelf water, it is evident that during the strong event B the thickness of the upwelled water layer corresponds to

the position of the 0 *u* velocity contour. This implies that while cold, recently upwelled water is entering the bay, cold relict water is leaving the bay. The behaviour of the surface mixed layer with respect to the lower layers requires further investigation and will not be discussed here."

22. Page 25, paragraph 1 now reads "With the above in mind, we can now qualitatively incorporate the bi-level flow pattern into the conceptual model of density-driven exchange in Saldanha Bay designed by Monteiro and Largier (1999). Detailed analysis of the dynamics of this conceptual model are beyond the scope of this thesis and will be left for further investigation."
23. Page 25, paragraph 2: Change first sentence to read "At onset of synoptic-scale upwelling winds, outward (westerly) flow in the seaward current zone commences." Omit last sentence.
24. Page 26, paragraph 1: Omit last 2 sentences.
25. Page 27, paragraph 2: Paragraph now reads "After cessation of upwelling-favourable winds, the thickness of the upwelling intrusion begins to decrease as bottom-layer currents reverse and drain out of the bay. Although velocities in both bayward and seaward zones decrease almost immediately following a wind relaxation, currents in the seaward current zone may remain up to an order of magnitude larger than currents in the bayward current zone. The literature suggests that after cessation of the upwelling wind event, currents at all depths below the thermocline flow bayward (Monteiro and Largier, 1999). This draining leading to an isothermal bay may be short-circuited by onset of another south-easterly wind event shortly (1-2 days) after the termination of the previous event. However, results of this study show continuing bayward flow even after cessation of an upwelling wind event. This must be incorporated into any future model."
26. Page 28, paragraph 2, sentence 3 now reads: "This combined with the continuous observed inflow of shelf water in the bayward current zone suggests that the fourth stage of the conceptual model by Monteiro and Largier is frequently short-circuited, and influx of cold, clean, nutrient-rich bottom water into Saldanha Bay occurs near constantly during the upwelling season."