Driving Mechanisms of the Port Alfred upwelling cell inshore of the Agulhas Current

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1 Abstract

The presence of a semi-permanent upwelling cell, with a surface expression more than 40 % of the time has previously been described inshore of the Agulhas Current in the vicinity of Port Alfred, South Africa. This study employs a combination of in-situ mooring data, hydrographic cruises and satellite remote sensing in order to investigate the nature and variability of this upwelling cell, as well as to investigate possible driving mechanisms. The study takes place over a period of 11 months. Special focus is given to the subsurface variability due to its possible implications for the greater Agulhas Bank environment.

Upwelled water was found to be present on the shelf 85% of the time, highlighting the importance of subsurface variability in this area. The main timescales of variability were observed at 50-70 days, 8-12 days and 4-6 days.

Upwelling was found to be maintained by continuous processes, driven by the interaction of the Agulhas Current with the changing bathymetry at Port Alfred. This upwelling is modulated by the effects of mesoscale features on the inshore edge of the current. While not a primary driver of upwelling, wind events were observed to have an effect on inshore bottom temperatures as well as the surface expression of the upwelling cell. A high degree of variability in was observed, with bottom temperatures at three mooring site fluctuating through a range of approximately 10° C. Future directions include further theoretical and idealised modeling studies to separate out the exact mechanisms of topographically driven, site-specific upwelling. The range of mesoscale interactions of the Agulhas Current with the shelf circulation also require further observational study.

2 Literature Review

2.1 The Agulhas Current

The Agulhas Current is the Western Boundary current of the Indian Ocean. It manifests itself as a narrow, fast-flowing jet that closely follows the continental shelf from south of the Delagoa bight in the region of 27°S to the southern end of the Agulhas Bank at 40°S (Lutjeharms, 2006; Gordon, 1985). On separation from the shelf, the current is carried by its inertia to the region of zero wind stress curl where it retroflects back into the South West Indian Ocean (de Ruijter et al., 1999a). The Agulhas is a relatively narrow (~100km in width) and extremely fast flowing current with currents of up to 2.5 $m.s^{-1}$ being recorded on its inshore edge. It should also be noted that the Agulhas is unusual in that little or no seasonality has been observed in its flow (Lutjeharms, 2006; Krug and Tournadre, 2012).

The effect of bathymetry on the trajectory of the Agulhas Current has been examined by Speich et al. (2006)using a modeling based approach. It was shown that the current is sensitive to changes in both the depth and shape of the bottom bathymetry, with significant effects on both the volume flux and meandering behaviour of the current being seen when bathymetry was altered.

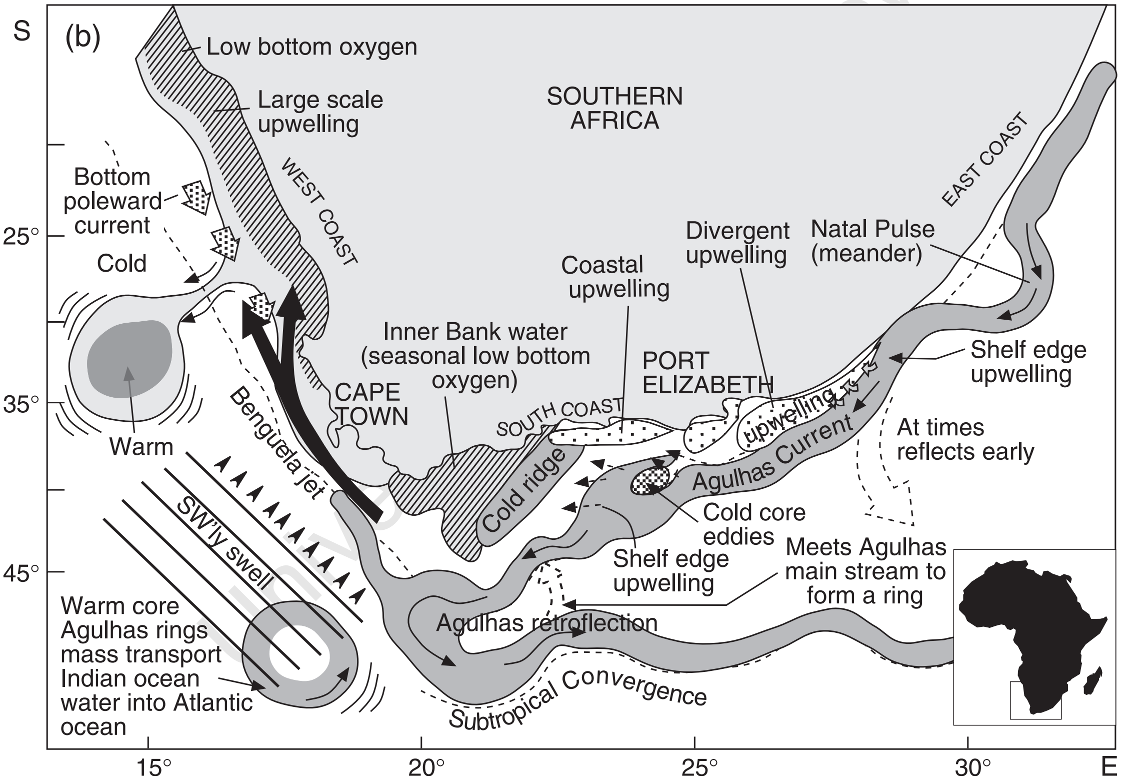

Fig. 2.1: Schematic view of Southern Africa showing the Agulhas Current system and highlighting the importance of shelf processes on the Agulhas Bank (from Roberts (2005)).

The Agulhas Current can be seen as being divided into distinct Northern and Southern parts, each with a different set of characteristics. The Northern part, extending from 27°S to approximately the latitude of Port Elizabeth (approximately 34°S) can be considered to have a relatively stable trajectory, an unusual characteristic for a Western Boundary Current. The only exception to the stable path of the Northern Agulhas Current is the area of anomolously shallow shelf in the Natal bight, which has been identified as a centre of cyclogenisis, crucial for the generation of many features in the Agulhas Current, such as Natal Pulses (de Ruijter et al., 1999b) and breakaway Durban Eddies (Roberts, 2010).

The southern part of the current follows a far more variable path, due to the change in the bathymetric profile of the shelf region. The northern region of the Agulhas follows the narrow, deep shelf, which broadens with distance south, resulting in is an increase in the size and amplitude of meanders and mesoscale features. These, as well as other shear-edge phenomena, become more common as the shelf broadens out onto the Agulhas Bank, a region of wide shallow continental shelf which has a complex relationship with the Agulhas Current itself (Largier and Swart, 1987; Swart and Largier, 1987; Lutjeharms, 2006; Jackson et al., 2012).

The Agulhas Bank is known to be of critical importance to the life cycles of many of the South Africa's commercially harvested marine species, such as chokka squid and sardine, whose life cycles and distribution are highly sensitive to small environmental changes driven by the physical dynamics of the Agulhas Bank (Roy et al., 2007).

Recently attention from the scientific community are now focusing on the effect of the Agulhas Current and it's leakage on the Atlantic Meridional Overturning Circulation (AMOC) and thus on world climate (Beal et al., 2011). However, since the 1980's and early 1990's relatively little attention has been paid to the effects of the Agulhas Current on the inshore circulation around the east coast of Southern Africa.

The physical conditions of the Agulhas Bank have been examined by Swart and Largier (Swart and Largier, 1987; Largier and Swart, 1987) who focused on the thermocline structure and sources of bottom water from both the eastern and western extremities of the bank. The water masses on the Agulhas Bank tend to be highly stratified, with a well developed thermocline (temperature differences of 8-10° C over 10m depth have been observed) deepening toward the west. This thermocline is thought to be advectively controlled in the east, with the western part of the Bank becoming more seasonal as atmospheric conditions play a greater role in maintaining the thermocline.

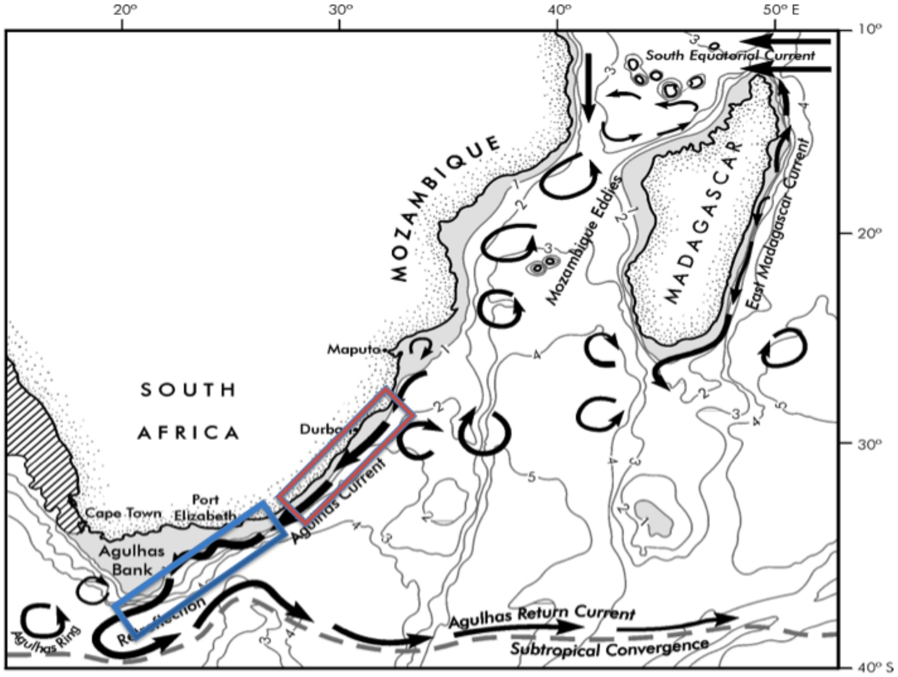

Fig. 2.2: Schematic showing circulation in the Greater Agulhas system and highlight the northern (red box) and southern (blue box) regions. Note the location of Port Alfred in between these two regions (from Lutjeharms (2006)).

2.2 Mesoscale features of the Agulhas Current

Lutjeharms et al. (1989) described the shear features and boundary phenomena of the Agulhas Current using a 10-year record of satellite imagery along with data from two hydrographic research cruises. A key finding of this study was the change in the meandering behaviour of the Agulhas Current downstream of Port Elizabeth, with meanders increasing their amplitude at this point and at the same time producing warm plumes that were reported to advect onto the shelf. Of further interest were the influence shear-edge eddies and their plumes had on the upwelling of very cold (10°C) water up to depths of 100m. The effect of these border eddy features have also been studied in both the Gulf Stream (Churchill et al.,

1986) and South Brazil Currents (Campos et al., 2000). These small cyclonic features have been shown to have distinct upwelling and downwelling sectors, with upwelling occurring on the leading edge of the meander, a cold dome in the centre and then a downwelling sector on the trailing edge of the meander. Of main importance is the ability of these mesoscale features to transport bottom waters across the front at the inshore edge of the Western Boundary Current, thus transporting new water up onto the shelf - similar to the dynamics observed on the Agulhas Bank.

The most notable transient feature in the Agulhas Current is the large solitary meander known as the Natal Pulse (Lutjeharms and Roberts, 1988), it is generally accepted that these large meanders are the dominant mode of variability in the Agulhas Current (Lutjeharms, 2006). These Natal Pulses are thought to develop from instabilities in the Natal Bight, (de Ruijter et al., 1999b) which then propagate downstream, increasing in amplitude. Pulse generation is intermittent, with an average of 1.6 Natal Pulses per year thought to pass Port Elizabeth (Rouault and Penven, 2011) although previous studies have quoted a higher number of 4-6 Natal Pulses per year (de Ruijter et al., 1999b; Lutjeharms and Roberts, 1988).

It should be noted that the passage of a Natal Pulse past the point where the shelf begins to widen, just upstream of Port Elizabeth in the region of Port Alfred, seems to result in an increase of shear edge features, however this does not hinder the passage of the Pulse itself down the whole length of the current (Lutjeharms and Roberts, 1988). However, some of this disagreement seems to be caused by a difference in the criteria used to define a 'Natal Pulse' rather than the actual number of solitary meander features.

Schumann and Brink (1990) identified the importance of coastal trapped waves in the near-shore circulation of the Agulhas Current. They established that for a limited area of the South and East coasts of South Africa, large amplitude coastal trapped waves propagate from west to east. These coastal trapped waves are thought to be primarily wind-generated and propagate up the coast as far East as Port Elizabeth or East London where they begin to be influenced by the Agulhas Current. It is interesting to note that Gill and Schumann (1979) also proposed a theoretical mechanism whereby the propagation of internal waves would be inhibited by the minimum in shelf width occurring off Port Alfred (see Figure 4.1 for bathymetry). The coastal-trapped waves observed by Schumann and Brink were associated with barotropic current reversals over the shelf off East London, with each reversal having a duration of a few days.

The most recent study concerning the coastal circulation and the effect of mesoscale dynamics inshore of the Agulhas Current was that of Roberts et al. (2010) in connection with the effect of the coastal circulation on the Natal Sardine run. Of particular interest to this study was the discovery of the so-called 'Durban Break-away Eddies' - smaller cyclonic eddies generated in the Natal Bight, which do not display the characteristics of a Natal Pulse but rather are flattened and elongated against the coast. These lee-trapped cyclonic eddies cause warm plumes of water to migrate onto the shelf. Unlike Natal Pulses, these Durban Break-away eddies do not grow in offshore extent but rather flatten and elongate against the coastline. This feature occurs at a higher frequency than the Natal Pulse, with a break-away eddy being generated every 10-15 days and has been reported to be responsible for current reversals on the shelf (Roberts et al., 2010). An upwelling cell was also identified in the region of Port St Johns, approximately halfway between Durban and East London. An inshore counter-current was also observed.

In conclusion, four main mesoscale features have identified (1.Natal Pulse's, 2. border and shear-edge eddies, 3. coastal trapped waves and now 4. Durban Break-away Eddy) as responsible for driving changes in the coastal circulation inshore of the Agulhas Current. All of these phenomena can be responsible for current reversals on the shelf and most of the time are linked to upwelling activity. However, the exact dynamics and results of these features remain largely unknown.

It should be noted that in considering the passage of mesoscale features past Port Alfred it can sometimes be difficult to draw conclusions from the literature, as most work on the subject considers the Northern and Southern parts of the Agulhas Current separately. Port Alfred lies in the transition between these two and thus could be assumed to experience a combination of northern and southern Agulhas type features.

2.3 Water Masses of the Southern Agulhas region

The water mass configuration on the Southern Agulhas Current as discussed in Lutjeharms (2006) consists in the top 200m of Tropical Indian Surface water with a temperature warmer than 16° C. On the inshore edge of the Current, at a depth of around 200m, is a core of South Indian Subtropical Surface Water which is easily identified by its clear salinity maximum (> 35.3 psu). Lying below this, as well as inshore is South Indian Central Water, with temperatures between 6° C and 14° C and originating from a depth of around 800m. Below this lies North Atlantic Deep Water. Antarctic Intermediate Water, Red Sea Water, Tropical Thermocline Water and Sub-Antarctic Mode Water have also been observed in the Agulhas Current, but in relatively small volumes. For a historical temperature-salinity plot of the water masses present in the Agulhas Current system, please refer to Figure 2.3.

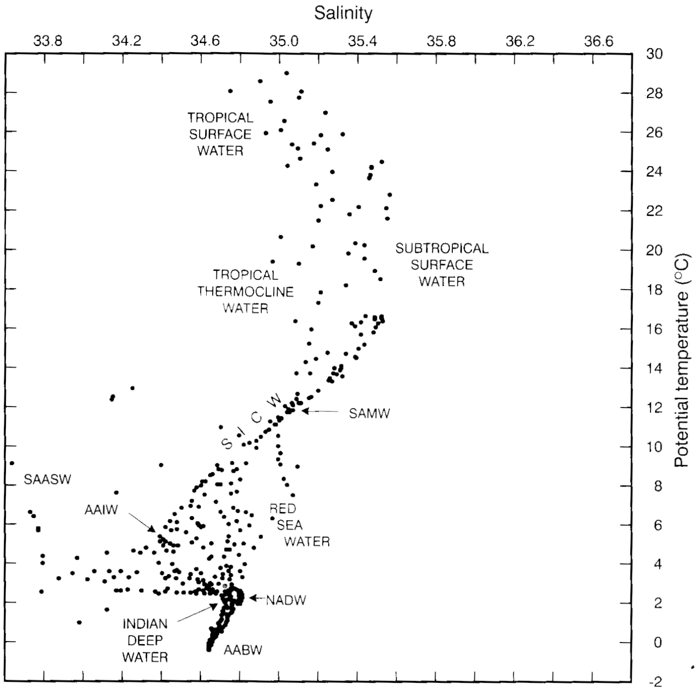

Fig. 2.3: Temperature-Salinity relationships in the Agulhas Current (from Lutjeharms (2006)).

2.4 Upwelling in the coastal Agulhas system

It is generally accepted that there are three main sites along the Agulhas Current where site-specific upwelling have been reported to occur inshore of the core of the current (Lutjeharms, 2006). These are the Port Alfred upwelling cell (Lutjeharms et al., 2000b), in the Natal Bight (Lutjeharms, 2006; Roberts et al., 2010) and the 'Cold Ridge' on the central Agulhas Bank (Swart and Largier, 1987). The Port Alfred and Natal Bight upwelling cells are thought to be driven mainly by the Agulhas Current itself (Lutjeharms et al., 2000b; Lutjeharms, 2006) while it has been proposed that the Cold Ridge could be the result of advection of cold water from the Port Alfred upwelling cell onto the Agulhas Bank, where it is brought to the surface via wind-driven processes (Lutjeharms, 2006). The site-specific upwelling off both Port Alfred and Natal takes place at a location where the bathymetry undergoes a fairly radical change, from a very narrow, steep shelf, to a wider shallower one. Gill and Schumann (1979) proposed a theoretical mechanism using a potential vorticity argument, whereby the narrowest point of the continental shelf exerts a hydraulic control on the flow downstream of it. The widening of the shelf downstream then causes a change from sub-critical to super-critical flow, resulting in the interface outcropping at the surface. Thus this mechanism would allow surface expression of upwelling in the absence of both wind-driven upwelling and mesoscale features. It is important to note however, that upwelling may only occur at locations with the correct shelf configuration i.e. at Port Alfred and on the Natal Coast just south of Durban (in the case of the Agulhas Current, for other examples see section 1.2) and that the intensity and extent of the surface expression will be dependent on the strength and position of the Agulhas Current.

2.5 Dynamically driven upwelling inshore of Western Boundary Currents

Geographically well-defined upwelling cells have been identified on the inshore edge of many Western Boundary Currents. Including the Agulhas Current (Lutjeharms et al., 2000b), Brazil Current (Campos et al., 2000; Palma and Matano, 2009), East Australia Current (EAC) (Roughan, 2004; Oke and Middleton, 2000), East Madagascar Current (Lutjeharms and Machu, 2000) and Kuroshio Currents (Lutjeharms, 1993). There has also been work carried out on site specific upwelling in the Gulf Stream, but this seems confined to more localised cells downstream of Capes and is thus not as applicable to this study (Blanton et al., 1981).

Several mechanisms have been proposed as the primary driving force of these upwelling cells. These include upwelling inducing winds, divergence brought about by meanders as well as the cyclonic eddies associated with these meanders (Campos et al., 2000). The effect of Ekman veering in the bottom boundary layer has also been explored (Oke and Middleton, 2000; Roughan, 2004). Gill and Schumann (1979), also proposed a mechanism by which a Western Boundary Current flowing over a changing bathymetry would cause upwelling on its inshore edge. They argued that the changes in potential vorticity drive changes in the structure of an inertial jet current, resulting in upwelling being induced at the site where a Western Boundary Current moves from a minimum in shelf width to a wider shelf and applied this to the Agulhas Current.

In the East Australia Current upwelling is driven by interactions of the current with the bottom boundary layer (BBL) downstream of the point where the EAC separates from the coast. In an intensive field study(Roughan, 2004), upwelling was observed to increase as the axis of the current jet moves onshore, leading to increased bottom friction and Ekman pumping onto the shelf in the BBL. The encroachment of the EAC onto the shelf results in a temperature drop in the BBL of up to 5° C. In an idealised modeling study of the same region, Oke and Middleton (2000) investigated the processes in the BBL. It was identified that while stratified flow over a sloping shelf should not lead to effective, current driven upwelling due to the thermal wind relation acting to reduce the along-shelf velocity to zero and thus shutting down transport in the BBL. However, the thermal wind relation assumes geostrophy, therefore in a region where the alongshore current accelerates due to variations in the topography, the shutdown time of flow in the BBL is increased, thus allowing persistent current-driven upwelling to take place. Based on theory, they suggest a direct relationship between along-shelf transport and the amount of cold water which is upwelled inshore of the current.

In the South Brazil Current, it has been observed that upwelling activity has a distinct seasonality. Campos et al. (2000), using a combination of hydrographic data and numerical simulations using the Miami Isopycnic Coordinate Ocean Model (MICOM). concluded that upwelling in the Southeast Brazil Bight was associated with cyclonic meanders of the Brazil Current. This upwelling was observed to be seasonal and controlled by a combination of shelf-break upwelling, driven by cyclonic meanders, and coastal wind-driven upwelling, which combine to produce a strong mechanism capable of bring cold South Atlantic central water up from depth greater than 200m to the surface. The seasonality observed in upwelling activity was attributed to seasonal changes in the wind fields, and thus seasonal changes in the wind-driven components of the upwelling mechanism. A later study using a suite of numerical simulations (Palma and Matano, 2009) found that in addition to the upwelling driven by coastal, wind-driven upwelling, there is also upwelling as a result of a persistent feature of the regional circulation due to changes in the orientation of the coastline and alongshore bottom topography. The mechanism for this persistent upwelling was suggested to be a simple one whereby changes in the alongshore bottom topography influences the alongshore pressure gradient, thus via geostrophy resulting in onshore flow along the bottom and shelf-break upwelling. It was also suggested that this mechanism could work in synergy with that put forward by (Oke and Middleton, 2000) in the East Australian Current, as discussed above.

3 Introduction

Examination of historical cruise data and satellite SST has established that the area off Port Alfred is a centre of kinetically-driven shelf-upwelling activity on the Eastern Agulhas Bank, with upwelling reported to have a surface expression 40% of the time (Lutjeharms et al., 2000b). The effects of this upwelling cell can be seen clearly in the satellite images of chlorophyll A concentrations, with very high concentrations of chlorophyll being found over the continental shelf to the East of Algoa Bay (33.7994° S, 25.7697° E). (Figure 3.1)

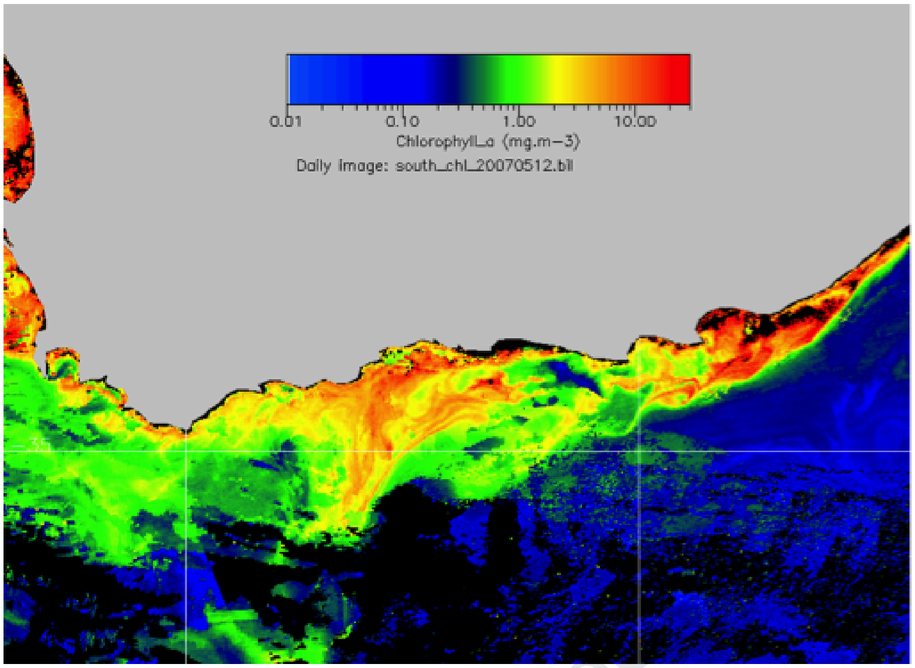

Fig. 3.1: Satellite image showing daily Chlorophyll A concentrations (mg.l^{-1}) along the South coast of Southern Africa. Note the the effect of the Port Alfred upwelling cell, resulting in high productivity to the east of Algoa Bay.

It has been suggested that this semi-permanent upwelling cell is driven by the Agulhas Current itself (Lutjeharms et al., 2000b), although the exact variability, frequency and extent of upwelling activity has yet to be understood. It has also been hypothesised by Lutjeharms (2006) that water upwelled at Port Alfred may be advected westwards onto the Agulhas Bank therefore becoming a key supplier of bottom water to the highly stratified Agulhas Bank region.

A recent study (Goschen et al., 2012), using 100 days of coastal data from between 2m and 70m depth, concluded that upwelling in the region was mostly wind-driven, although it was found that the region off Port Alfred was less responsive to wind-driven upwelling than sites further West. Goschen et al. (2012)also challenged the use of the term 'cell' when describing the upwelling area off Port Alfred.

Although environmental conditions on the Agulhas Bank have been identified as being of crucial importance to the spawning behaviour of many commercially important species

(Roy et al., 2007), very little work has been undertaken on the sources of this variability since the pioneering work carried out by Largier and Swart (Swart and Largier, 1987; Largier and Swart, 1987). A recent conflicting study (Jackson et al., 2012) could not find evidence that cold bottom water on the Agulhas Bank in fact originated at Port Alfred.

It is possible that variability in the supply of cold, nutrient rich water from the Port Alfred upwelling cell could have a substantial effect on conditions associated with the Agulhas Bank and thus on the spawning activity of fish and invertebrate species in the area. It is therefore important to understand both the short-term and inter-annual variability of upwelling activity off Port Alfred as a first step towards understanding the impact this may have on the Eastern Agulhas Bank region. Although the nature of the surface expression of the Port Alfred upwelling cell has been described using satellite sea surface temperature (Lutjeharms et al., 2000b; Lutjeharms, 2006), the subsurface processes which bring cold water up onto the shelf to supply the upwelling cell have yet to be examined. In addition, the possibility that cold nutrient-rich water advected westwards from the Port Alfred upwelling cell is a key driver of thermocline variability on the Agulhas Bank makes the subsurface transport of cold nutrient rich water from depth at Port Alfred critical factor in determining environmental conditions for biological activity on the Agulhas Bank.

Many of the processes in the Agulhas Current system, especially mesoscale features, occur on relatively short timescales of days to weeks, it is attempted in this study to understand the processes that take place in a single year which will then enable other years to be more easily understood. The eventual goal would be to also gain an understanding of the inter-annual variability, but this is somewhat out of the scope of this study.

It should be noted that as shelf-slope upwelling is mainly a subsurface phenomenon, it is important to make liberal use of both synoptic, in the form of ship-board surveys, and time series, in the form of oceanographic moorings in order to gain a more complete picture of the various processes at work as it is possible that many of the dynamics of the system are not visible to satellite imagery. Whilst there is a base of theory about the drivers of semi-permanent upwelling cells in Western Boundary Currents (Campos et al., 2000; Oke and Middleton, 2000; Gill and Schumann, 1979; Palma and Matano, 2009; Condie, 1995), with the added effects of coastal wind-driven upwelling and mesoscale eddies and meander features it can prove difficult to isolate the exact mechanisms of shelf-break upwelling (Campos et al., 2000; Roughan, 2004).

Previous cruise data show the presence of cold water on the shelf slope with varying degrees of outcropping. However a detailed examination of the subsurface processes that supply this upwelling cell and their interactions with the mesoscale variability of the Agulhas Current has yet to be carried out. This study seeks to answer two basic questions, using a combination of historical cruise data, remote sensing and three in-situ current-meter moorings. These results will then be compared to theory and case studies and other Western Boundary Currents, namely the South Brazil and East Australian Currents to assess the possibility of a common mechanism for semi-permanent upwelling cells inshore of Western Boundary Currents.

In order to gain an improved descriptive understanding of the Port Alfred upwelling cell and more specifically the sub-surface dynamics driving it, this study seeks to address the following questions:

- **How often does shelf-edge upwelling occur?**

The frequency of cold water intrusions up the shelf at Port Alfred is examined from bottom temperature data from 3 mooring sites. The range of temperatures over an 11-month period is identified and the main frequencies of variability are investigated, as is the total period of time that upwelled water is present on the shelf.

- **What are the main possible driving mechanisms of this upwelling?**

Full water column ocean currents are examined along the width of the shelf and associated with bottom temperatures and the passage of mesoscale features. The relationship between surface currents, bottom currents and bottom temperatures during an encroachment of the Agulhas Current onto the shelf is examined in a case study.

- **How do mesoscale, current-driven and other factors combine to control the variability of the Port Alfred upwelling cell?**

Satellite Imagery is examined in order to place context onto events observed in the ocean current and temperature records taken from moorings. A schematic framework is developed from a visual analysis of daily satellite sea surface temperature images in an attempt to identify different modes of upwelling in the Port Alfred system, linked to the passage of mesoscale features.

These results will then be compared to theory and case studies and other Western Boundary Currents, namely the South Brazil and East Australian Currents to assess the possibility of a common mechanism for semi-permanent upwelling cells inshore of Western Boundary Currents.

4 Methods

In order to gain a more complete understanding of the nature of the Port Alfred upwelling cell and in an attempt to gain an understanding into the main driver and sources of variability in the system, a three-pronged strategy has been used. Firstly, hydrographic cruise data from three cruises of the FRS Algoa has been used to give snapshots of the structure and water mass characteristics of the area over 2005 and 2006. Secondly a dedicated array of three ADCP current meter moorings was used in order to give an 11 month time series of full water column currents and bottom temperatures, and thirdly, satellite sea surface temperature and altimetry products have been used in order to gain insight on the state of the greater Agulhas Current as a whole, and the mesoscale events directly affecting the Port Alfred upwelling cell. The focus in interpreting these data has been strongly on understanding how changes in the sub-surface structure of the cell are affected by the Agulhas Current and it's associated features and also on assessing the extent to which these sub-surface changes are expressed on the surface. One of the difficulties of working in a coastal region such as the Port Alfred upwelling cell is caused by the relative shortcomings of remotely sensed satellite data when compared to larger scale, open-ocean studies due to the small spatial scales considered and the proximity of the coastline. Thus the use of in-situ data, such as that from hydrographic cruises, oceanographic moorings and land-based weather stations has been given preference. However, where appropriate, satellite remote sensing data has been used in order to represent the greater state of the Agulhas Current, in order to quantify the effect of large-scale variability of the current itself on upwelling activity off Port Alfred.

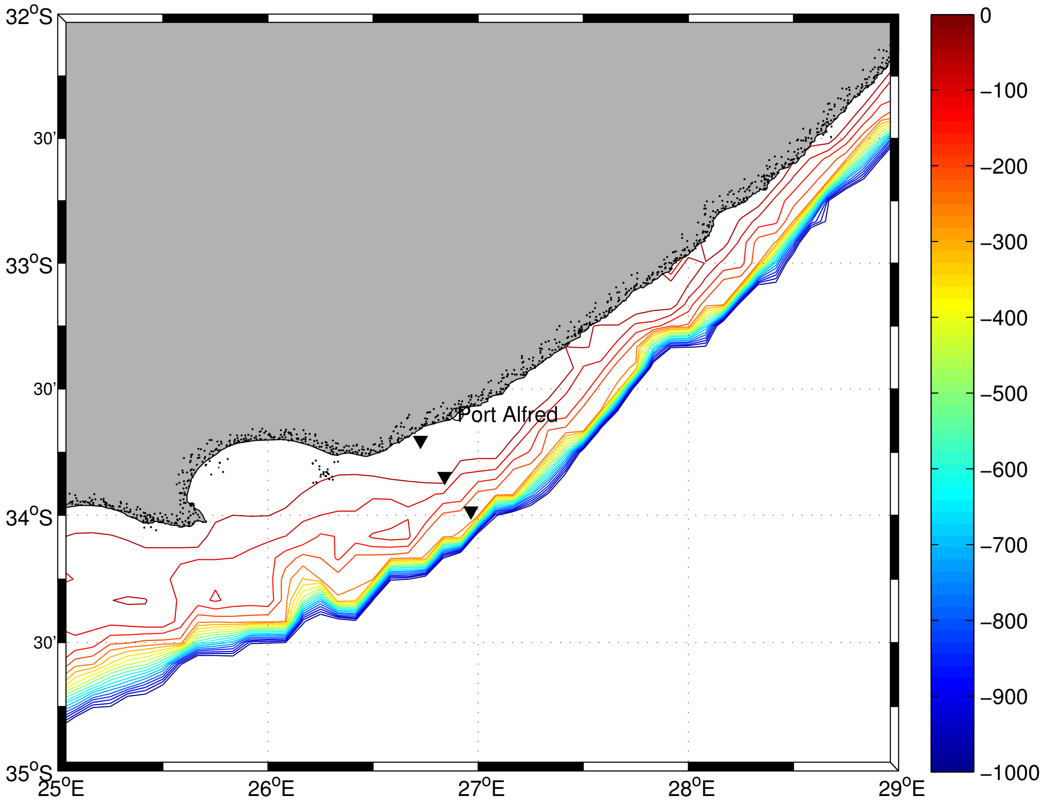

Fig. 4.1: Chart of the bathymetry of the area surrounding the Port Alfred upwelling cell, with the inshore, mid-shelf and offshore mooring site locations marked by black triangles.

4.1 Hydrographic Cruises

A regular CTD line off Port Alfred has been maintained by the Dept. of Environmental Affairs. During the 2005-2006 period on which this study focuses, three cruises took place, namely ALG 135, 139 and 147 in May 2005, September 2005 and April 2006 respectively. The location of this transect is shown by the black dots in Figure 4.2. CTD sections were plotted using Ocean Data View (Schlitzer, R., Ocean Data View, http://odv.awi.de, 2013).

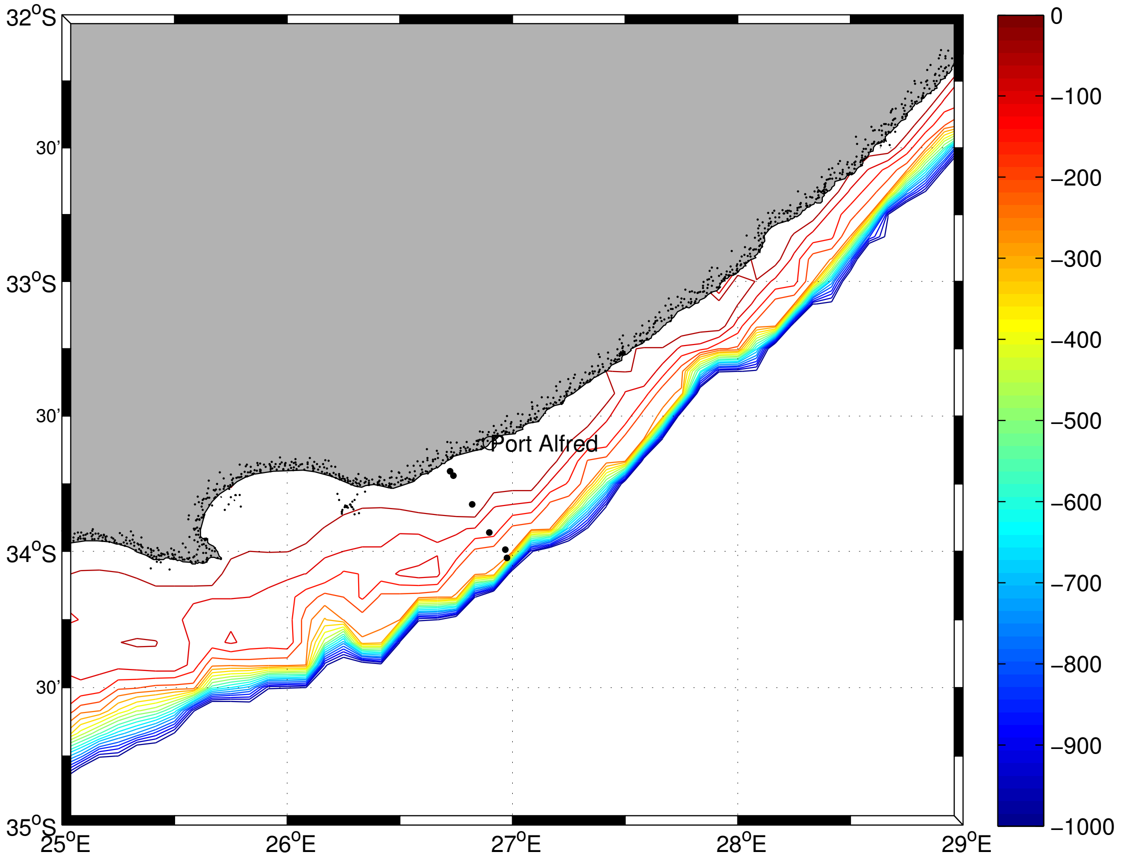

Fig. 4.2: Chart showing the position of the stations on the Port Alfred CTD transects used in the study. Individual stations are shown by black dots (transect was repeated in May2005, September 2005 and December 2006)

4.2 Moorings

Three Acoustic Doppler Current Profiler (ADCP) moorings were deployed off the coast in the region of Port Alfred for a period of 11 months, from May 2005 to April 2006. These ADCP's were bottom-mounted, looking upward and so allow the currents throughout the whole water column to be measured. Each ADCP also carries a temperature sensor, allowing accurate bottom temperatures to be recorded at each site.

All three mooring sites consisted of a bottom mounted ADCP. At the inshore site a Teledyne RDI 300kHz ADCP was deployed at a depth of 31m at a position 33° 42.2702'

S, 26° 43.4901' E, which places it approximately 3.6km offshore. The ADCP was moored using an anchor weight, two mini-Benthos acoustic releases and a flotation package, which maintained the sensor head 2m above the seabed. The instrument recorded data for a period of 11 months, from May 2005 until April 2006. The instrument sampled once every 30 minutes, using an ensemble of 120 pings. The entire water column was sampled using 15 bins, with each bin being 2m in length. Average temperature at the sensor was also recorded, at 30-minute intervals.

At the mid-shelf site another Teledyne RDI 300kHz ADCP was deployed in the same way as at the inshore site, this time in 76 metres of water at a position 33° 50.8085' S, 26° 26 50.4204' E, approximately 23 km offshore. The ADCP was moored in the same manner as the inshore mooring and sampled the entire water column using 50 bins, with each being 2m in length. Again, the instrument was configured to sample at an interval of 30 minutes with an ensemble of 120 pings and also recorded bottom temperatures averaged over 30 minutes.

The offshore site was placed so as to be on the edge of the shelf-break and in a position generally associated with the inshore edge of the Agulhas Current. It was placed in 175 m of water at a position 33° 59.027' S, 26° 57.904' E, placing it approximately 42 km from the coast. This mooring consisted of a 190 kHz Nortek ADCP moored in the same way as the mid-shelf and inshore moorings. The entire water column was sampled using 75 bins, each 2m in length. Bottom temperatures were also recorded at this site using the ADCP's temperature sensor.

Data was processed using a combination of RDI and MATLAB 2010b software. Surface data was discarded, as well as those bins in which the data was less than 75% 'good' (Gordon, 1996).

The inshore and mid-shelf moorings were serviced in September and December 2005, whilst the offshore mooring was serviced in September 2005 and recovered in December 2005.

4.3 Wind Data

Hourly wind data was obtained from the South African Weather Service (SAWS) for the Port Alfred Airport weather station. This weather station is located at 33°33'32"S, 26°52'52"E, which places it 84m above sea level. The station is located 2km from the coast and 20km from the inshore site of the Port Alfred mooring array used in this study. Wind speed and direction was recorded hourly for the study period May 2005 to April 2006. These hourly data were then converted to U and V components averaged daily, rotated into along and across-shore components and plotted in MATLAB. Due to the probable inaccuracy of the wind data from Port Alfred Airport, no attempt was made to calculate wind stress, as the alongshore wind speed provides enough evidence for the questions posed by this study, i.e. whether is the wind promoting upwelling or downwelling and its relative strength. Thus the Port Alfred Airport wind data is appropriate for the purposes of providing a context of the effects of wind on upwelling activity off Port Alfred in this study.

4.4 Remote sensing

The daily level 3 sea surface temperature (SST) product from NASA's Moderate Resolution Imaging Spectrometer (MODIS) was accessed via the UCT Remote Sensing Unit's website (www.afro-sea.org.za) and plotted using m_map (www.eos.ubc.ca/~rich/map.html) in MATLAB 2010b. The optical wavelengths at which the MODIS sensor operates cannot penetrate cloud and therefore due to the large ocean-atmosphere fluxes in the Agulhas region (Rouault et al., 2000)large areas of each image are masked by cloud. Thus a while a continuous data set is not available, some images were useful for use as case studies. A five-year record (2005-2010) was also analysed in order to produce the schematic seen in Figure 6.1. It was also found that it was far better to use a daily product from a single sensor than one of the merged products such as the GHRSST MURSST, which proved to have too much smoothing in the coastal areas to be useful for the purposes of this study. Altimetry data from Aviso is also shown in Figure 5.18 in order to track the position of the core of the current. For details of this method please refer to Rouault and Penven (2011).

5 Results

The Port Alfred upwelling cell is a semi-permanent zone of upwelling that exists inshore of the Agulhas Current. It has an approximate spatial extent from 32°S to 34°S and has been reported to have a surface expression 40% of the time. However, the variability and true extent of this upwelling cell and its effects on the surrounding region, especially in the supply of nutrients to the Agulhas Bank, are not known. Here an approach employing a combination of hydrographic cruise data, a dedicated mooring array and satellite remote sensing is used to assess this upwelling cell and identify its main driving mechanisms.

5.1 Hydrographic sections

The variability of the Port Alfred system is illustrated using three CTD transects taken during cruises of the FRS Algoa over the period May2005 to April 2006. This data follows on from previous work and historical sections, which showed the presence of slightly warmed South West Indian Central Water on the shelf, with bottom temperatures sometimes as low as 9°C (Lutjeharms et al., 2000b; Lutjeharms, 2006) and highlights the typical features of the Port Alfred upwelling cell in terms of its water mass characteristics. A key characteristic of the upwelling cell identified in these sections is the distinct active and inactive configuration of the temperature and salinity structure over the shelf region. In an inactive configuration, most of the water overlying the shelf is warmer than 20°C, with temperature and salinity characteristics typical of South Indian Subtropical Surface Water which is overlaid with warmer, fresher Tropical Indian Surface Water, a situation typical of the inshore edge of the Agulhas Current. In the active configuration the 20°C isotherm reaches the surface at the shelf edge, with all water inshore of it being cooler than 20°C. This inshore water also shows lower salinity values in the region of 35.2 psu, indicative of slightly warmed South Indian Central Water (refer to Figure 2.3 for historical temperature-salinity plot).

The hydrographic portion of this study seeks to confirm and update the findings of these previous studies using recent cruise data, in order to give a solid background knowledge of the changing temperature and salinity structure over the shelf during different phases of upwelling.

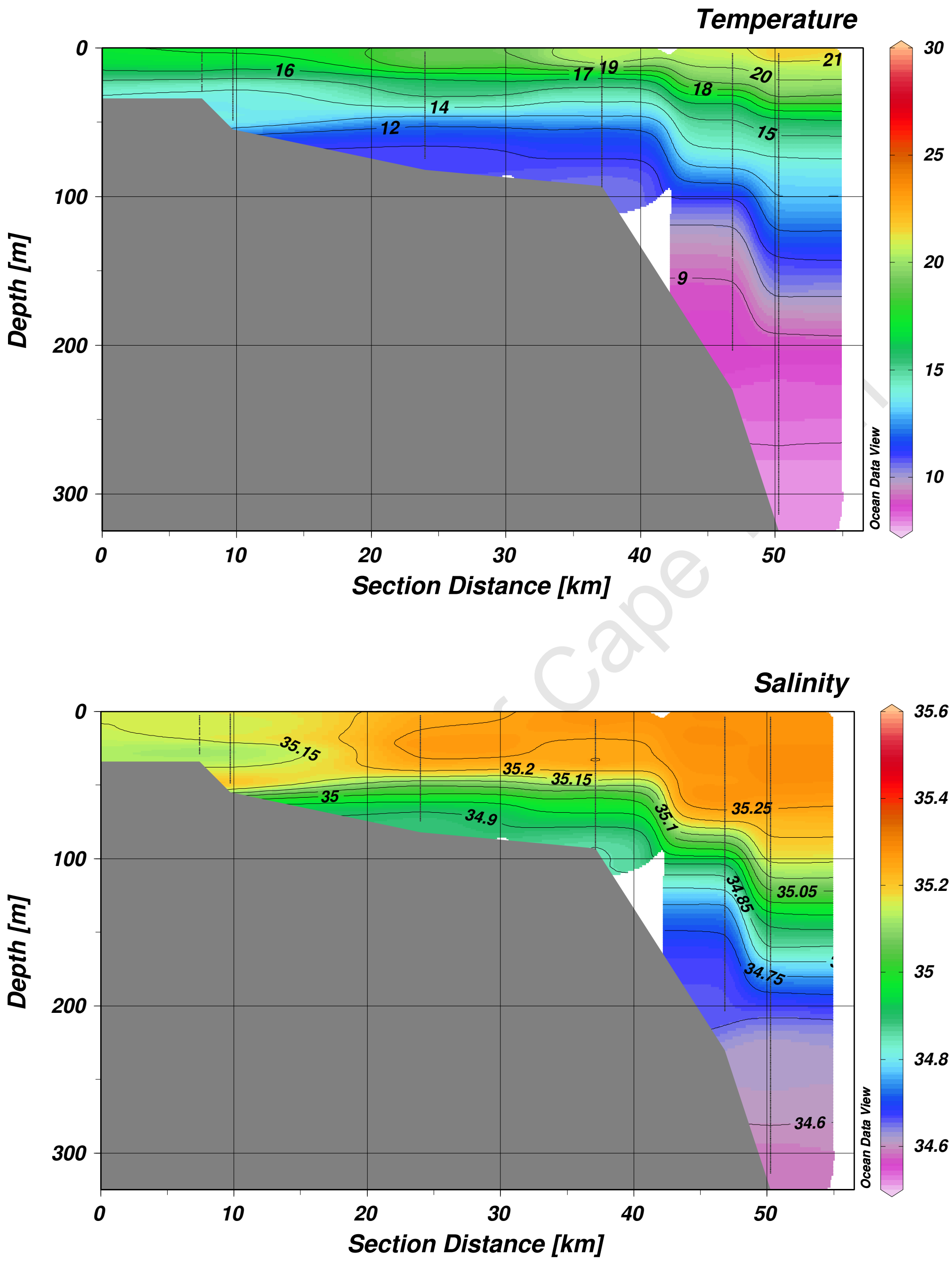

Fig. 5.1: CTD sections of temperature (top) and salinity (bottom) taken on 5th of May 2005

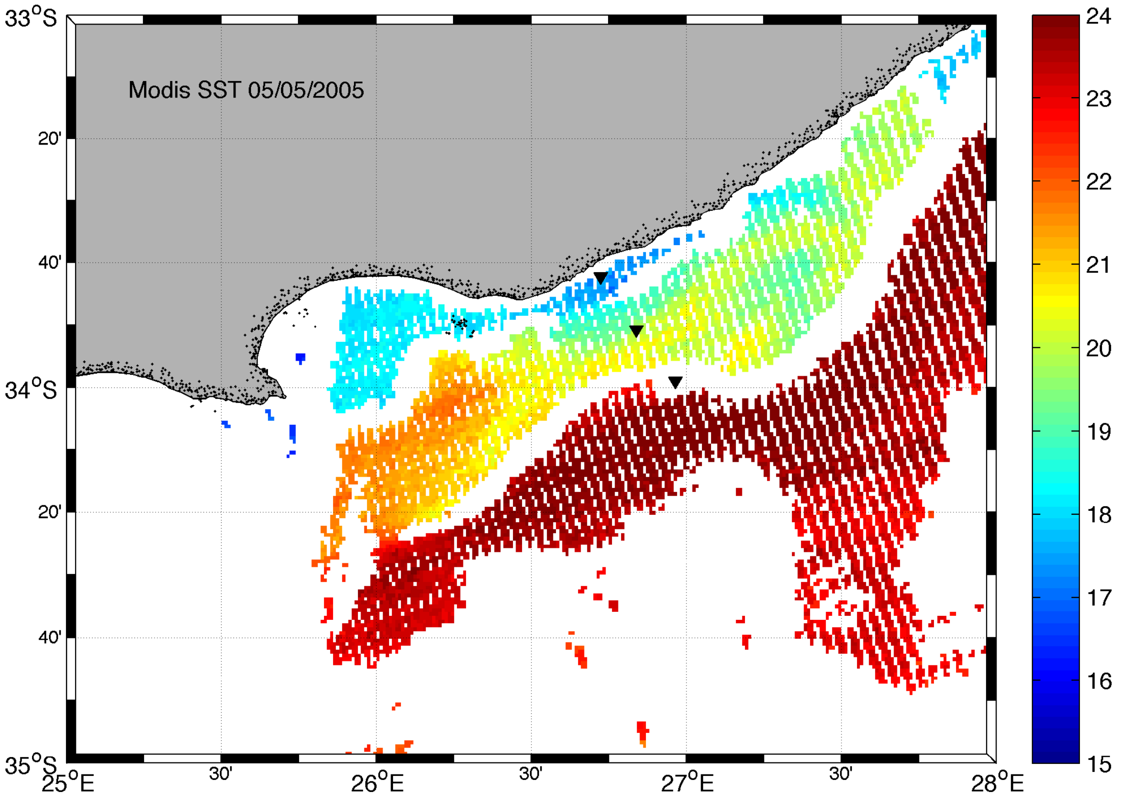

Fig. 5.2: Satellite image of sea surface temperature from MODIS on the 5th of May 2005

FRS Algoa cruise 135, May 2005

The CTD section taken off Port Alfred during the cruise ALG 135 on the 5th of May 2005 is shown in Figure 5.1. There is a strong stratification of temperature, with the 15°C isotherm placed within 30m of the surface all the way over the shelf. Over the offshore part of the shelf (more than 25km from the coast) surface temperatures are around 20°C, whilst inshore there is a slight cooling, with the 17.5°C isotherm outcropping between 15 and 20km from the coast. Nearer the shelf break it can be observed that there is a tilting of the isotherms, with water as cold as 12°C being intruded along the bottom right up onto the shelf within 10km of the coast. This indicates the presence of cold water on the shelf in this region, even in a period where surface upwelling is not particularly active. The salinity section closely follows the patterns observed in temperature. However, it should be noted that the inshore surface waters are slightly fresher than those offshore (~35.2psu as opposed to ~35.4psu). It could be suggested that the current is in an offshore position during this section as the temperature and salinity maxima usually associated with the inshore edge of the Agulhas Current are not visible in this section. An examination of the temperature-salinity characteristics of the stations on the Port Alfred transect from May 2005 (Figure 5.7) reveal temperatures ranging from 7.5°C to 22°C and salinities from 34.6 to 35.25 psu. Of interest is the broad range of salinities in the surface waters (from 35.1 to 35.3 psu). Further examination of this reveals that the inshore stations have fresher surface water than the offshore stations.

An examination of the SST image from the MODIS satellite on the 5th of May (Figure 5.2) shows a small meander feature passing Port Alfred, with a distinct temperature front being visible between the warm Agulhas Current water (temperature above 23°C) and the cooler inshore water. A small region of very cold (below 16°C) water is seen to outcrop against the coastline to the east of Algoa Bay.

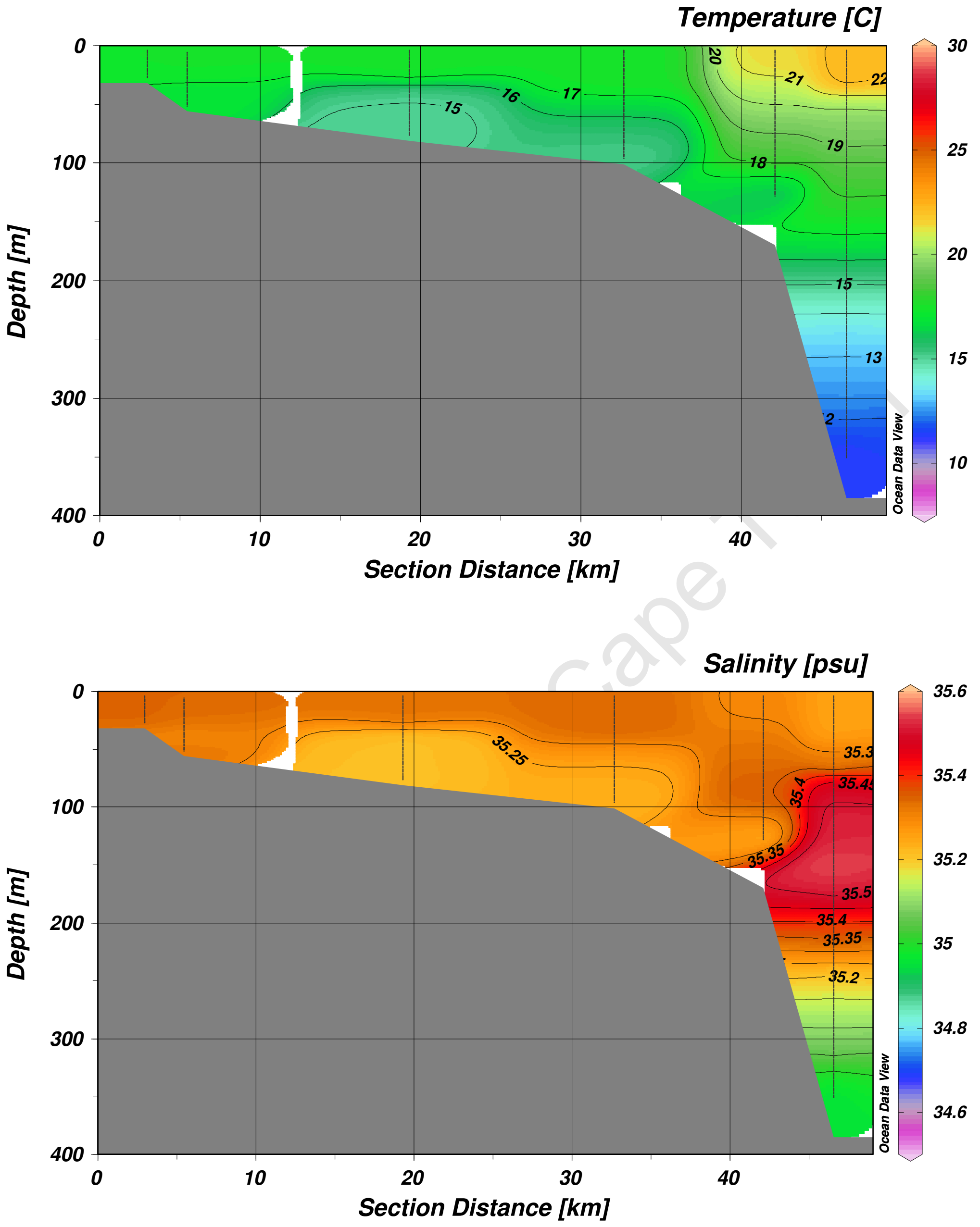

Fig. 5.3: CTD sections of temperature (top) and salinity (bottom) taken on the 11th of September 2005

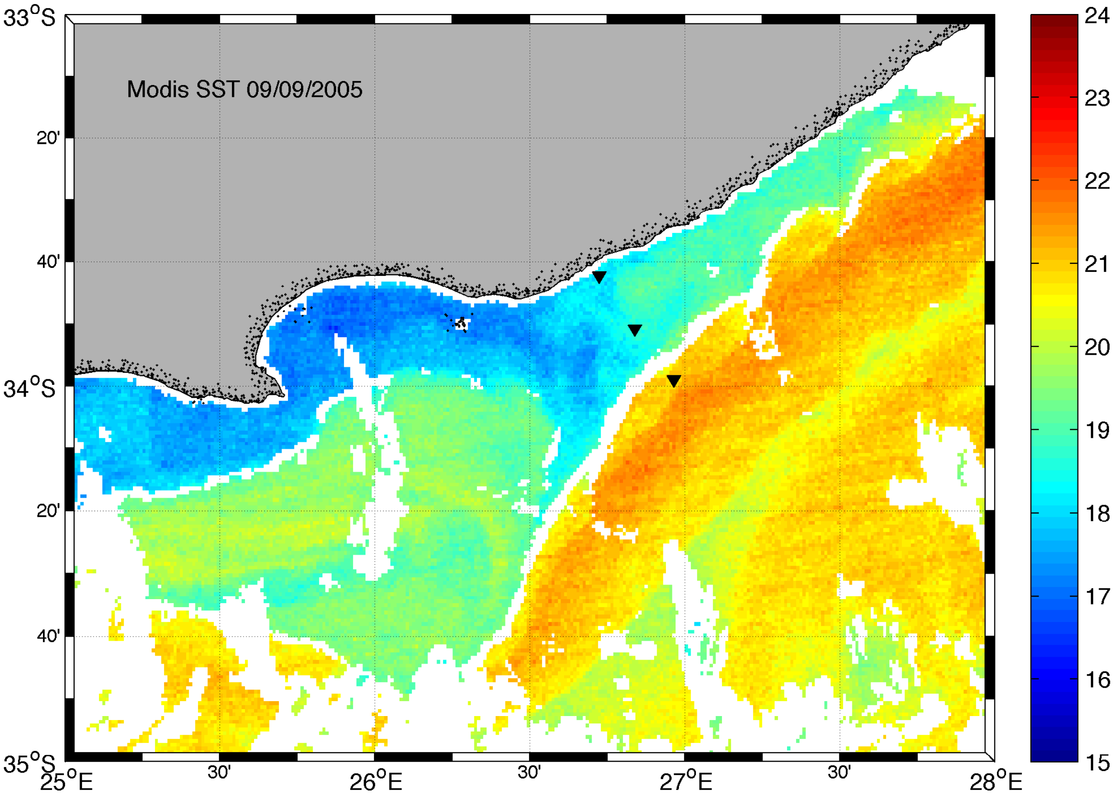

Fig. 5.4: Satellite image of sea surface temperature from MODIS on the 9th of September 2005, showing active upwelling just prior to the BBL shutdown observed in the September 11th CTD section.

FRS Algoa cruise 139, September 2005

A CTD section taken during the cruise ALG 139 on the 11th of September 2005 is shown in Figure 5.3. There is a distinct temperature front situated 40 km offshore separating the inshore waters with a temperature of around 17°C from the warmer offshore waters of the current itself which are warmer than 20°C. Also to be noted is the intrusion of a dome of colder (less than 15°C), fresher, water up the shelf between 10 and 40km offshore. The Agulhas Current seems to be in a more inshore position in comparison to the section taken in May of the same year (Figure 5.1), with temperatures in excess of 22°C being observed in the region of 50km from the shore, indicative of the current itself and a subsurface salinity maximum with salinities of greater than 35.4 psu visible offshore of 40km from the coast. Surface temperatures over the shelf are fairly uniform without strong stratification compared to other sections taken in this region. The dome of cooler, fresher water over the shelf noted above is visible in a temperature-salinity plot of this section (see Figure 5.8) as being 0.2psu fresher than the offshore waters of the same temperature range (15°C-17°C). The daily MODIS image for the 11th of September was contaminated by cloud, as was the 10th of September, thus Figure5.4 shows MODIS SST for the 9th of September. The image shows the a relatively cool Agulhas Current (temperature less than 23°C) beginning the encroachment onto the shelf which is observed in the CTD section observed in Figure 5.3. A meander is also visible passing to the south east of Algoa Bay.

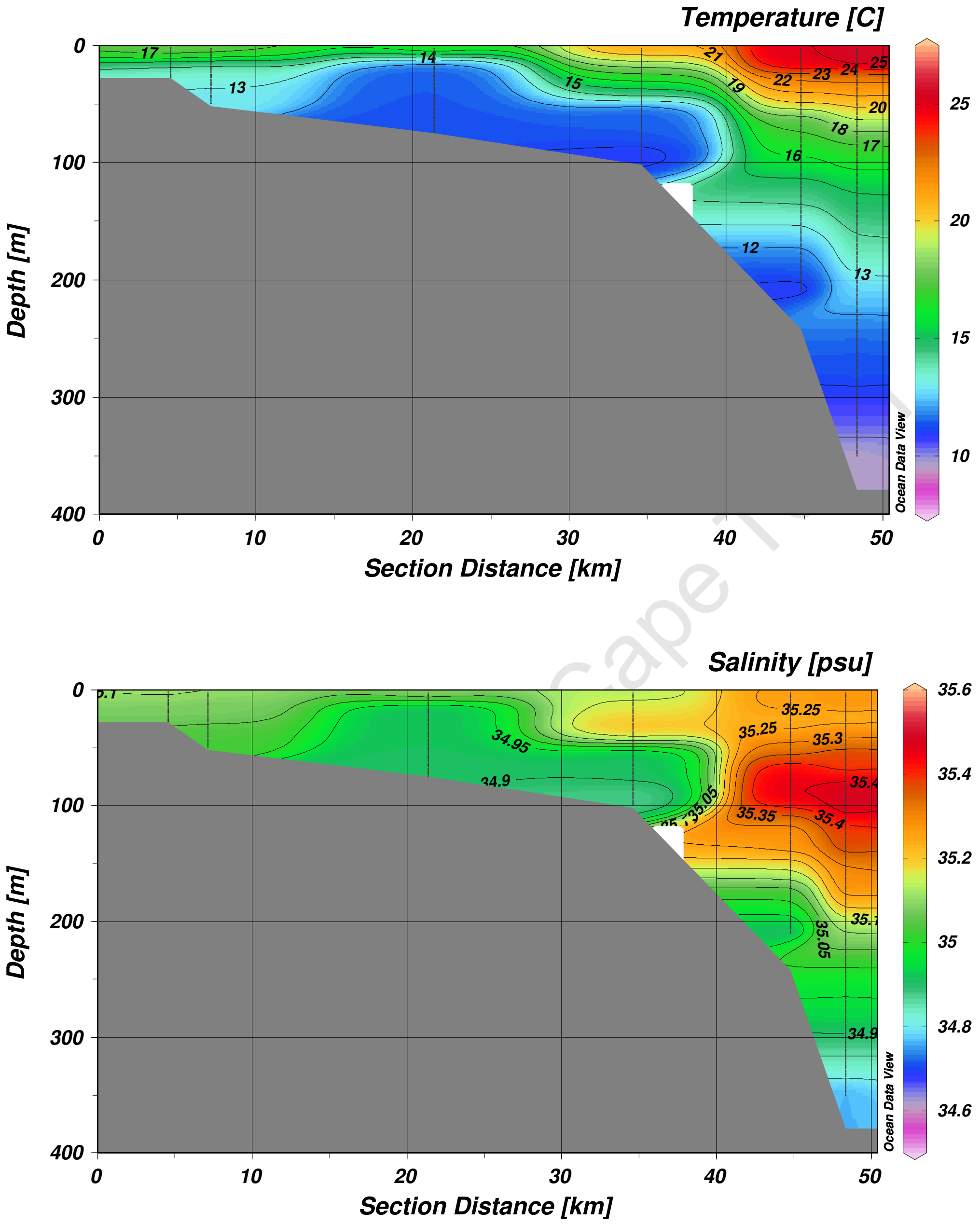

Fig. 5.5: CTD section of temperature (top) and salinity (bottom) taken on 10 April 2006.

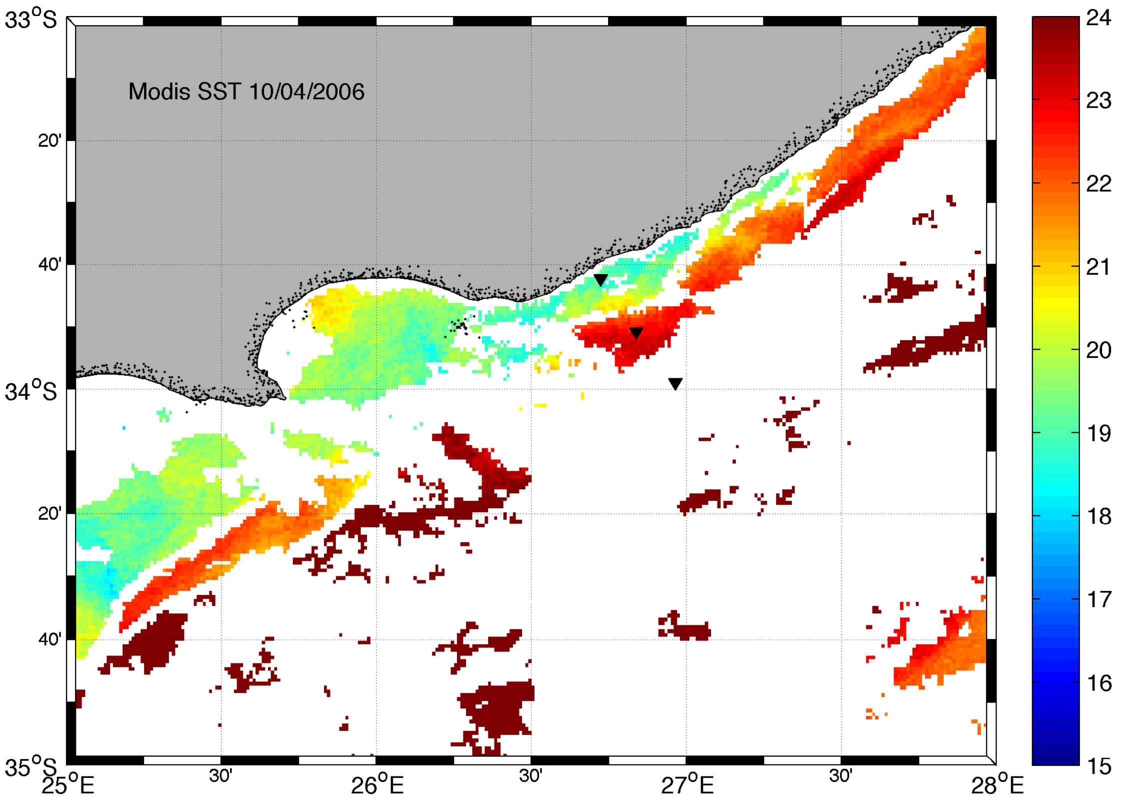

Fig. 5.6: Satellite image of sea surface temperature from MODIS on the 10th of April 2006.

FRS Algoa cruise 147, April 2006

A third section was taken by the Algoa on the cruise ALG147 on the 10th of April 2006. This section presents a similar situation to the section taken in September of the previous year, however the salinity and temperature gradients are far greater, presenting an 'active' upwelling situation. The temperature and salinity sections shown in Figure 5.5 show a very different situation to that in a similar period of the previous year (refer to Figure5.1). The current is visible around 50km offshore, with the 17.5° isotherm outcropping at the surface about 30km offshore, far further offshore than in the two previous sections. There is also a marked intrusion of cold (less than 12°), fresh (less than 35psu) water up the shelf region, extending very close to the surface between 15 and 30km offshore. As observed in the previous section (September 2005, see Figure 5.3) there is a strong sub-surface salinity maximum (above 35.4 psu) below the current. This is usually indicative of South Indian Subtropical Surface Water. However, this salinity maximum does not extend beyond the shelf break. Temperature-salinity plots from the all three cruise sections are shown in figures 5.1, 5.3 and 5.5. Of particular interest is the difference in salinity observed between the inshore and offshore surface water of a similar temperature, with inshore stations showing fresher salinities than the offshore stations. Although this is visible in all three temperature-salinity plots it is particularly apparent in the section taken in April 2006, where the inshore surface water shows low temperatures (below 15°) and salinities similar to those observed in South Indian Central Water, indicating active upwelling of water up the shelf from below 400m. The daily MODIS SST image for the 10th of April shows what appears so be a narrow, intense Agulhas Current lying very close inshore along the shelf (Figure5.6). Once again a strong temperature from is observed between the warm Agulhas Current waters offshore and the narrow band of cooler water inshore.

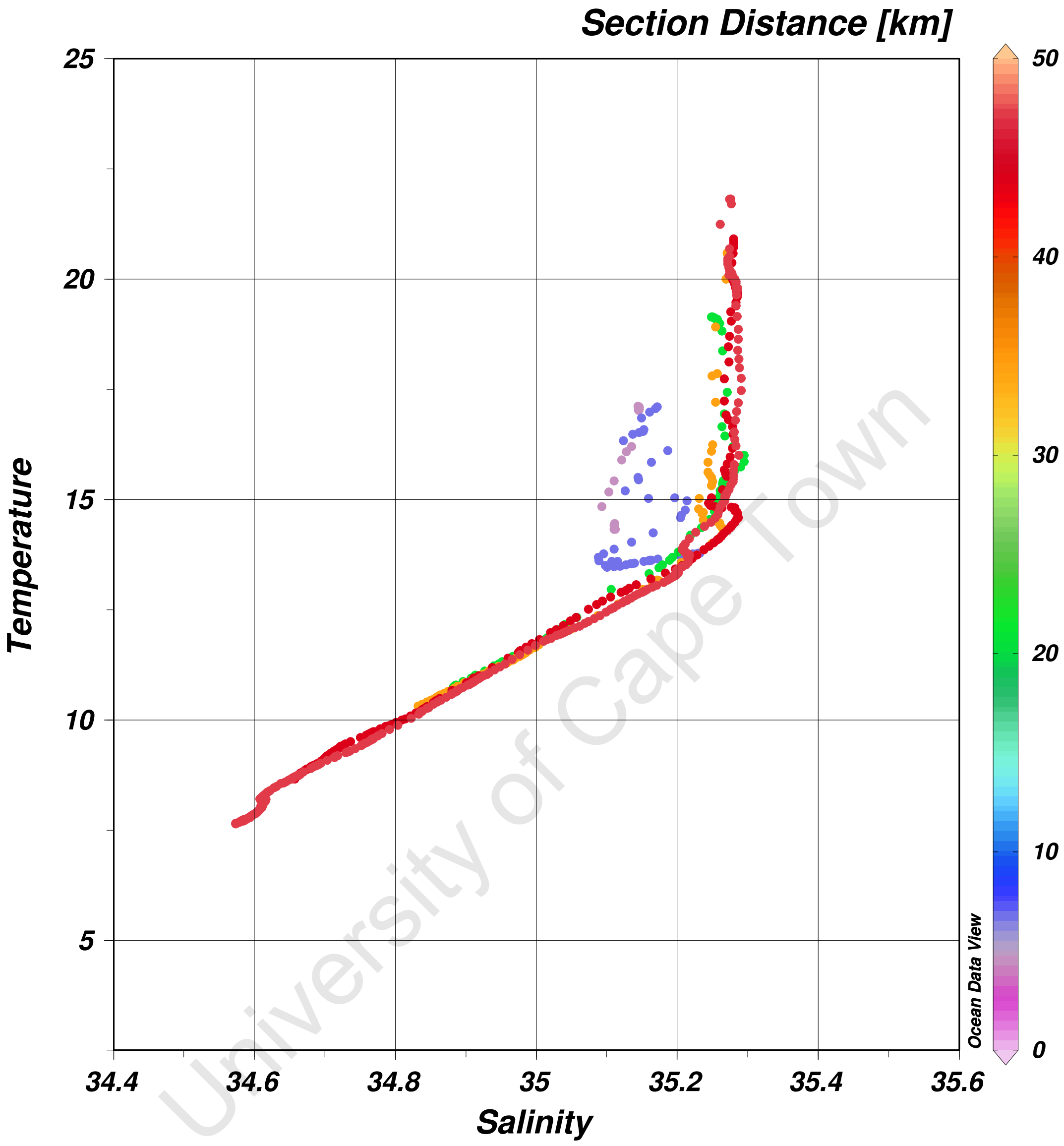

Fig. 5.7: Temperature-Salinity (coloured with distance from the shore) plot of Port Alfred Mooring line transect from FRS Algoa cruise 135, May 2005.

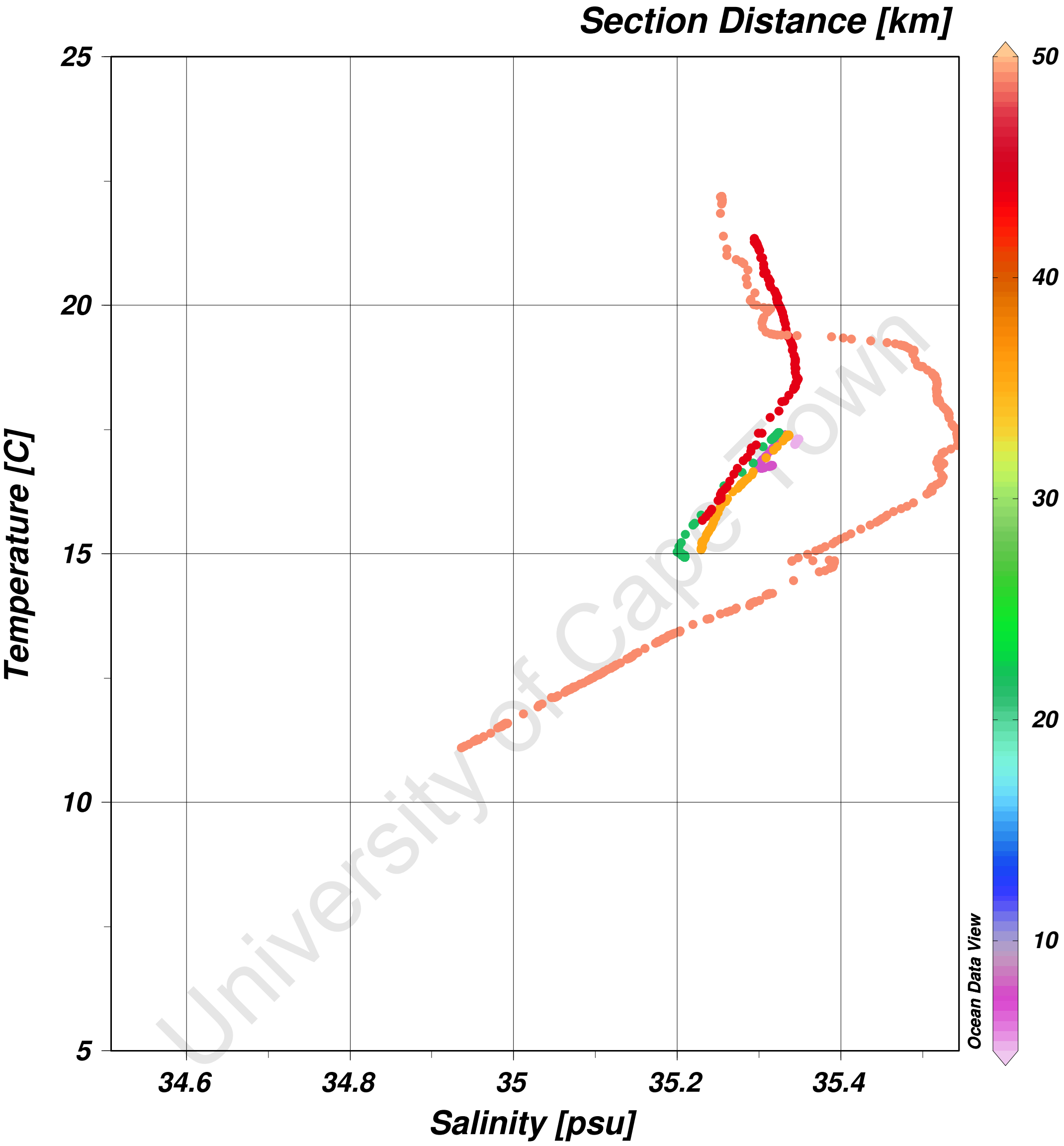

Fig. 5.8: Temperature -Salinity(coloured with distance from the shore) plot of Port Alfred mooring line transect from FRS Algoa cruise 139, September 2005.

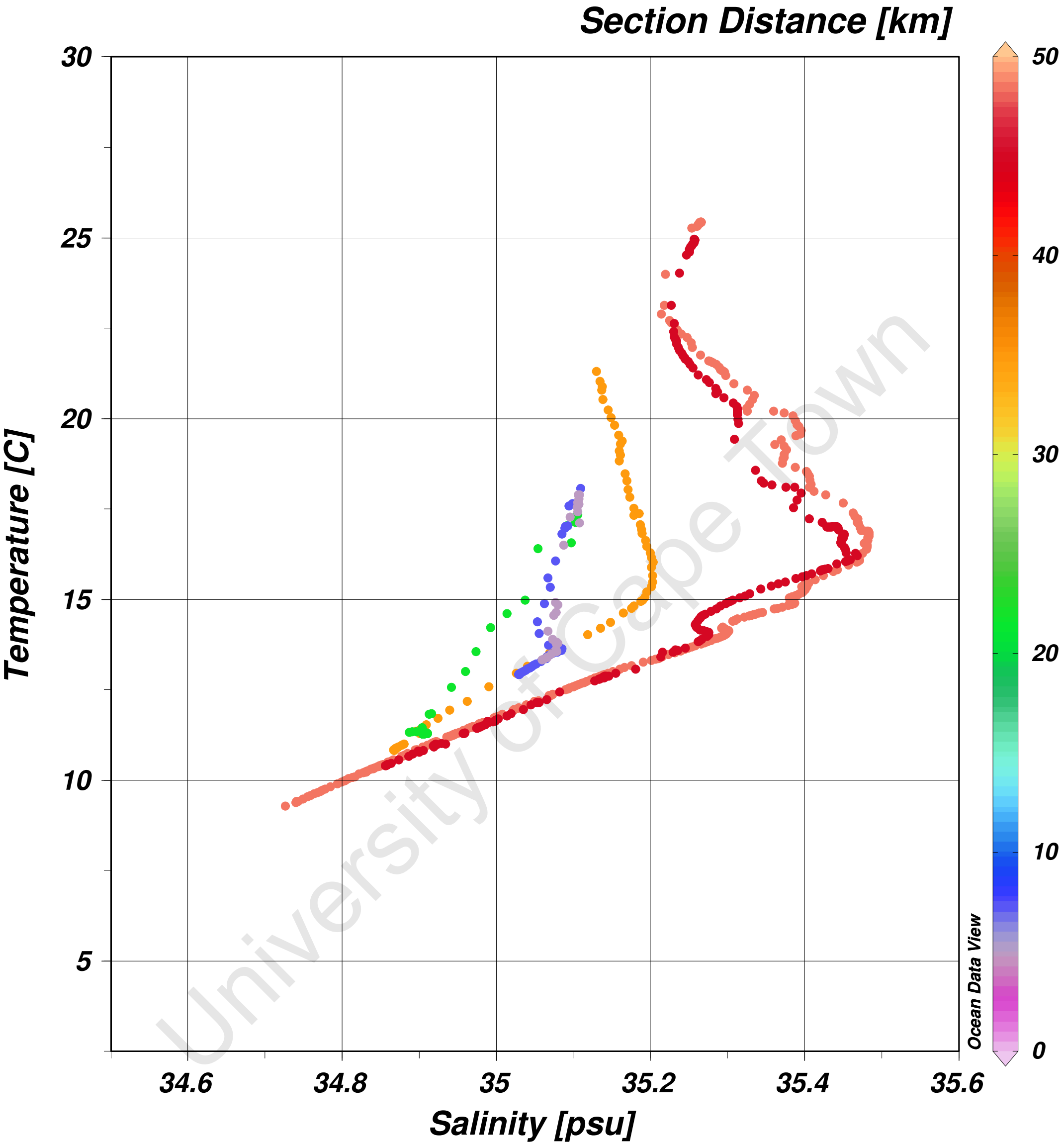

Fig. 5.9: Temperature - Salinity (coloured with distance from the shore) plot of the Port Alfred mooring line transect from FRS Algoa cruise 147, April 2006.

Summary

As could be expected from a semi-permanent upwelling cell, there is a large amount of variability in the water mass characteristics of sections taken off Port Alfred. However, in all cases examined, inshore waters have been fresher than those offshore (see figures 5.7, 5.8 and 5.9). It appears that sections in which the edge of the Agulhas is visible within 50 km of the coast feature a strong dome of colder, fresher water on the shelf. It should also be noted that much of the variability in this area, especially on the shelf, is sub-surface and as such will not always be represented in studies of satellite remote sensing data. A question that crops up on examination of these CTD sections is one of residence times - how permanent are the cold domes of water visible on the shelf? Are they driven by a constant process or simply the result of mesoscale features on the inshore edge of the current? In order to further assess the nature of the Port Alfred upwelling cell, a greater temporal resolution was needed. As much of the variability in this system is not visible in remotely sensed data, an in situ mooring array is ideal for examining the longer-term variability in this area.

5.2 Port Alfred mooring array

Bottom temperatures

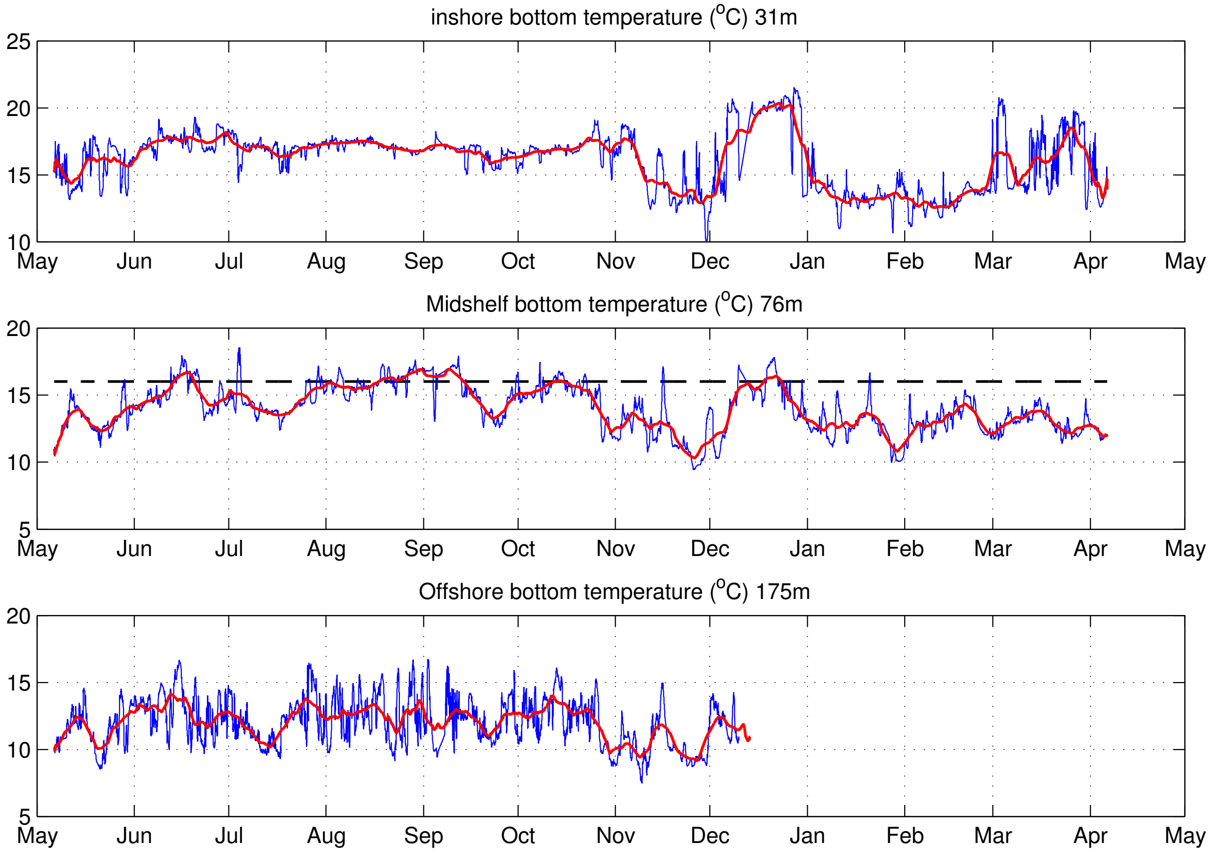

Fig. 5.10: Bottom temperatures for the 2005-2006 periods of the Port Alfred mooring sites. 7-day running means are plotted in red.

An examination of the bottom temperatures recorded at the three Port Alfred mooring sites over the period 2005 to 2006 (Figure5.10) reveals a large temperature range over both the inshore, mid-shelf and offshore regions. Immediately noticeable is the similarity in temperature range (see Table 1) between the offshore and mid-shelf mooring sites, despite the fact that they have a 100m depth difference, indicating the tilt of the isotherms observed in the previous section.

The longest sustained cold event takes place from January to March 2006 and is clearly visible in both the inshore and mid-shelf records with temperatures remaining below 15°C at both sites for a continuous period of almost 2 months. This event takes place at a period where the position of the Agulhas Current is fairly stable and close to the shore, with little mesoscale activity visible in satellite imagery of the period. (see Figure 5.18). This could be seen to represent a strong shelf-upwelling event as observed in the CTD section taken in April 2006 (see Figure 5.5). A shorter, more intense upwelling event is also observed during November 2005 with temperatures at all 3 sites dropping to their minimum values over this period (see Table 1). This short, severe event coincides with a large perturbation in the current, visible in Figure 5.18 as a maximum in current core distance from the coast with the current core being identified as 170 km offshore, indicative of a Natal Pulse. Thus it is possible that this event is mostly driven by this Natal Pulse event, unlike the January to March event that would appear to be too long in duration to be driven by mesoscale dynamics.

Temperatures (°C)	Inshore	Mid-shelf	Offshore
minimum	10.06	9.45	7.5
maximum	21.5	18.52	16.71
median	16.72	13.1	11.95
mean	16.01	14.03	12

Tab. 1: Basic statistics of the time series of bottom temperature for the period May 2005 to April 2006 at the Port Alfred mooring array.

The 7-day running mean (plotted in red) reveals a common pattern in variability at this timescale especially between the inshore and mid-shelf moorings. A spectral analysis of the these time series (Figures 5.11,5.12 and 5.13) reveals that both the inshore and mid-shelf sites show a peak in variability at periods of 60-90 days, with various secondary peaks in the 5-12 day period range. However, it should be noted that the offshore site does not exhibit the strong 60-90 mode of variability with far more activity occurring in the 5-8 day range and a secondary shallow peak at periods of 12-30 days.

In the middle panel of Figure 5.10 a dashed line has been plotted to represent the

16° C temperature threshold that was suggested by Lutjeharms (2006) as an indicator of active upwelling, i.e. South Indian Central Water on the shelf. It should be noted that temperatures remain below this threshold on an almost permanent basis.

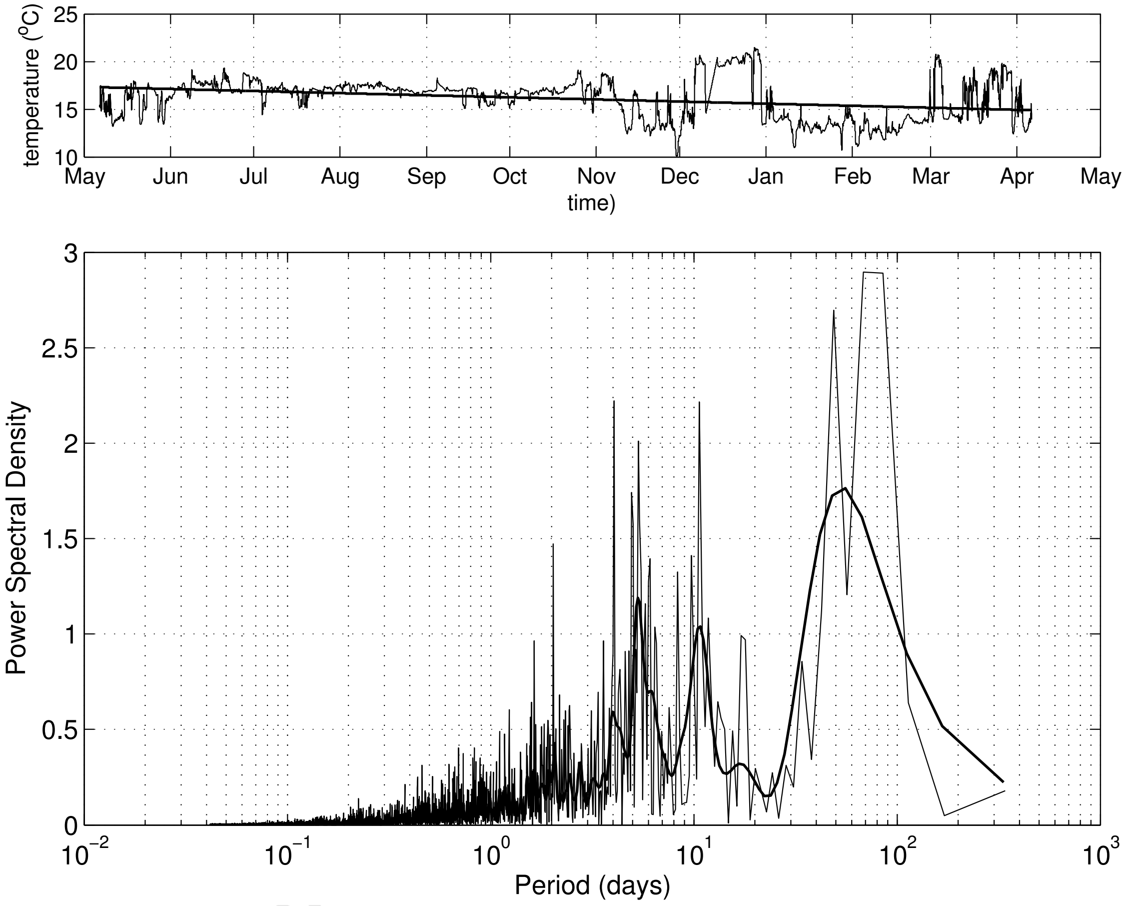

Fig. 5.11: Spectral analysis of inshore mooring temperature data from May 2005 to April 2006, showing the raw power spectrum overlaid with an averaged spectrum using the Welch method (in bold)

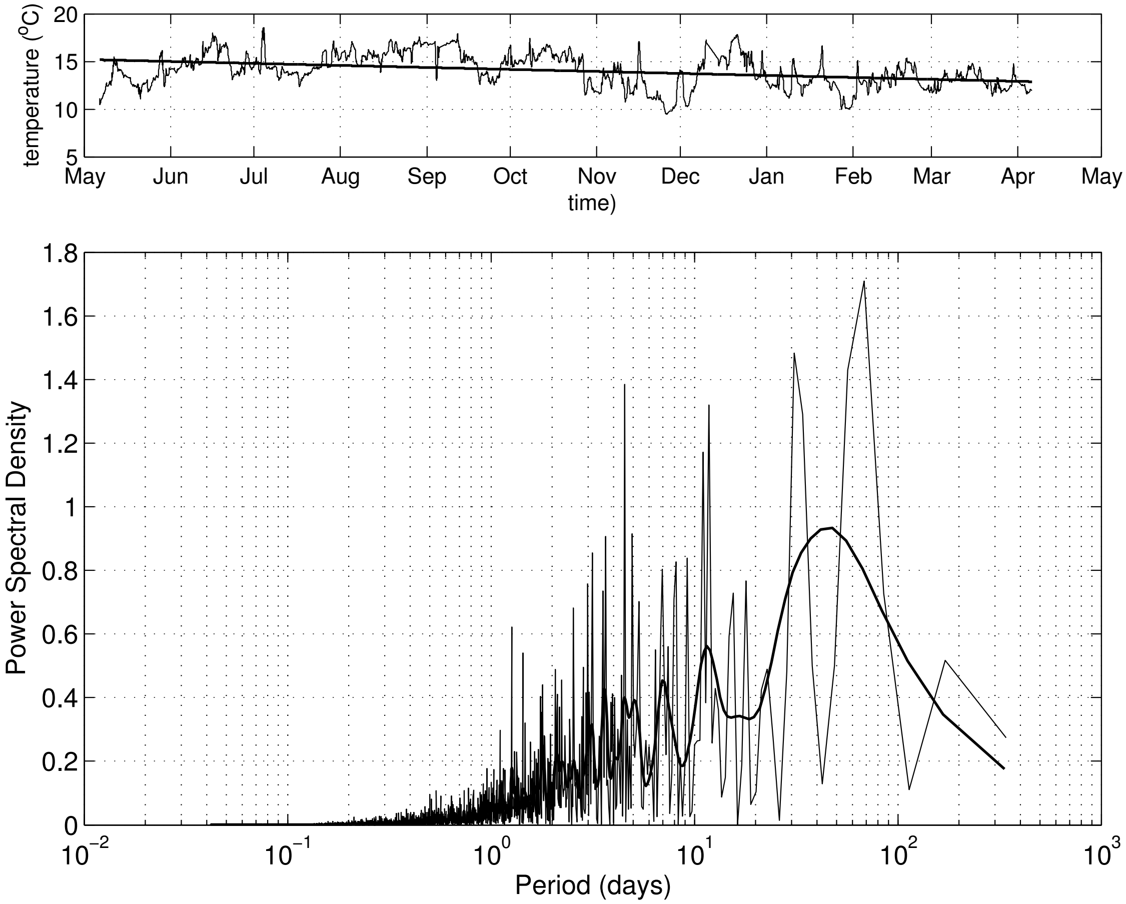

Fig. 5.12: Spectral analysis of mid-shelf mooring temperature data from May 2005 to April 2006, showing the raw power spectrum overlaid with an averaged spectrum using the Welch method (in bold)

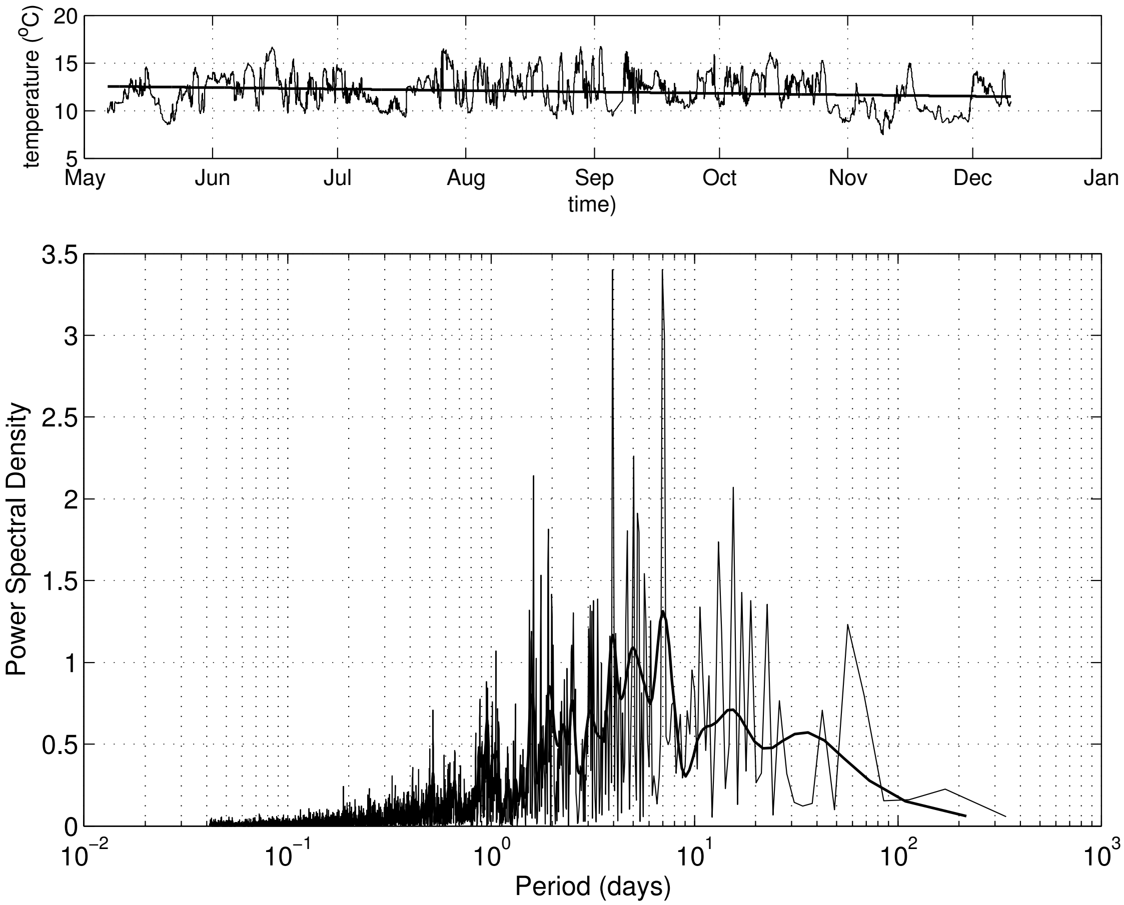

Fig. 5.13: Spectral analysis of offshore mooring temperature data from May to December 2005, showing the raw power spectrum overlaid with an averaged spectrum using the Welch method (in bold)

Ocean Currents

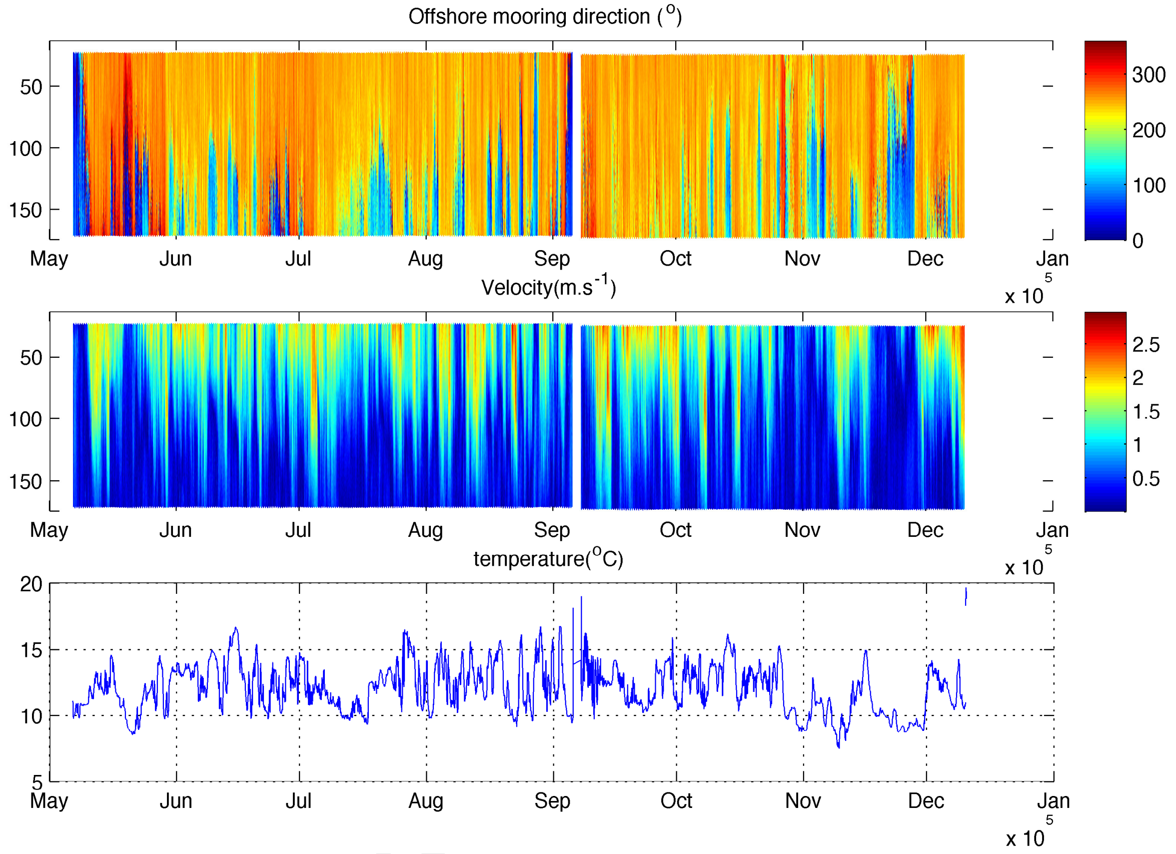

Fig. 5.14: Time series of ocean current magnitude and direction during 2005 for the full water column at the offshore mooring site, bottom temperatures for this site are also shown in the bottom panel.

Figure 5.14 shows an overview of data collected by the ADCP mounted at the offshore site in approximately 175m of water. As could be expected from a mooring sited on the edge of the Agulhas Current, the dominant direction of the flow is towards the South-West. Ocean current velocities have a large range, from a minimum of 0 to a recorded maximum of 2.975 m.s^{-1}. The mean velocity averaged over the water column for the offshore mooring was 0.76 m.s^{-1} , whilst the median direction was 247°.

Full water column current reversals are observed in May, September and November and correspond with periods of low ocean current velocities. It should be noted that the amount of shear in the current varies over the time series from completely barotropic as in much of September to the strong shear observed in July.

In contrast, little current shear was observed at the mid-shelf mooring site, an overview of which is presented in Figure 5.15. Here we see weaker current velocities with an average velocity of 0.33 $m.s^{-1}$ and a highest recorded velocity of 1.72 $m.s^{-1}$. In terms of mean direction, currents at the mid-shelf mooring are slightly more offshore in direction than those observed at the offshore mooring, with a median direction of 219°. The mid-shelf site also shows less current shear and a higher frequency of current reversal events when compared to the offshore site. However, it should be noted that during the period from January to March 2006 there are very few current reversal events compared to earlier in the time series.

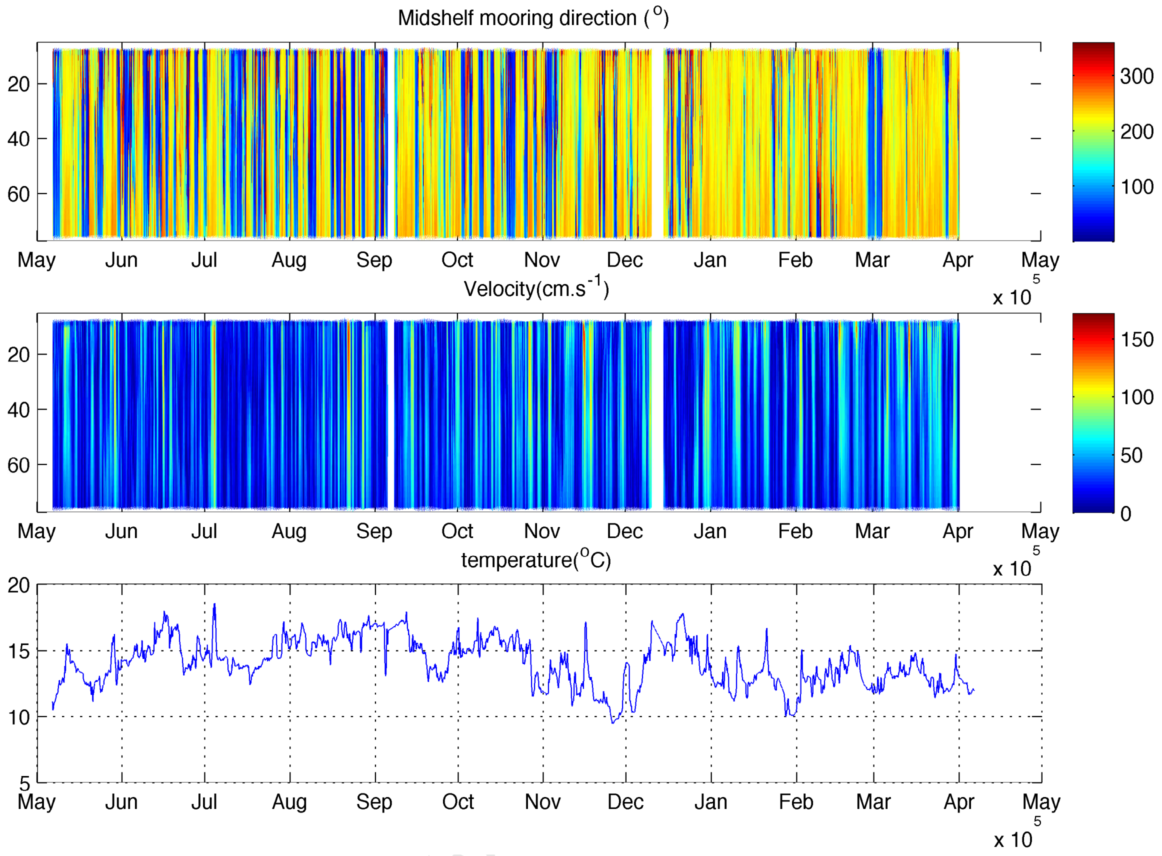

Fig. 5.15: Time series of ocean current magnitude and direction during 2005-2006 for the full water column at the mid-shelf mooring site, bottom temperatures for this site are also shown in the bottom panel.

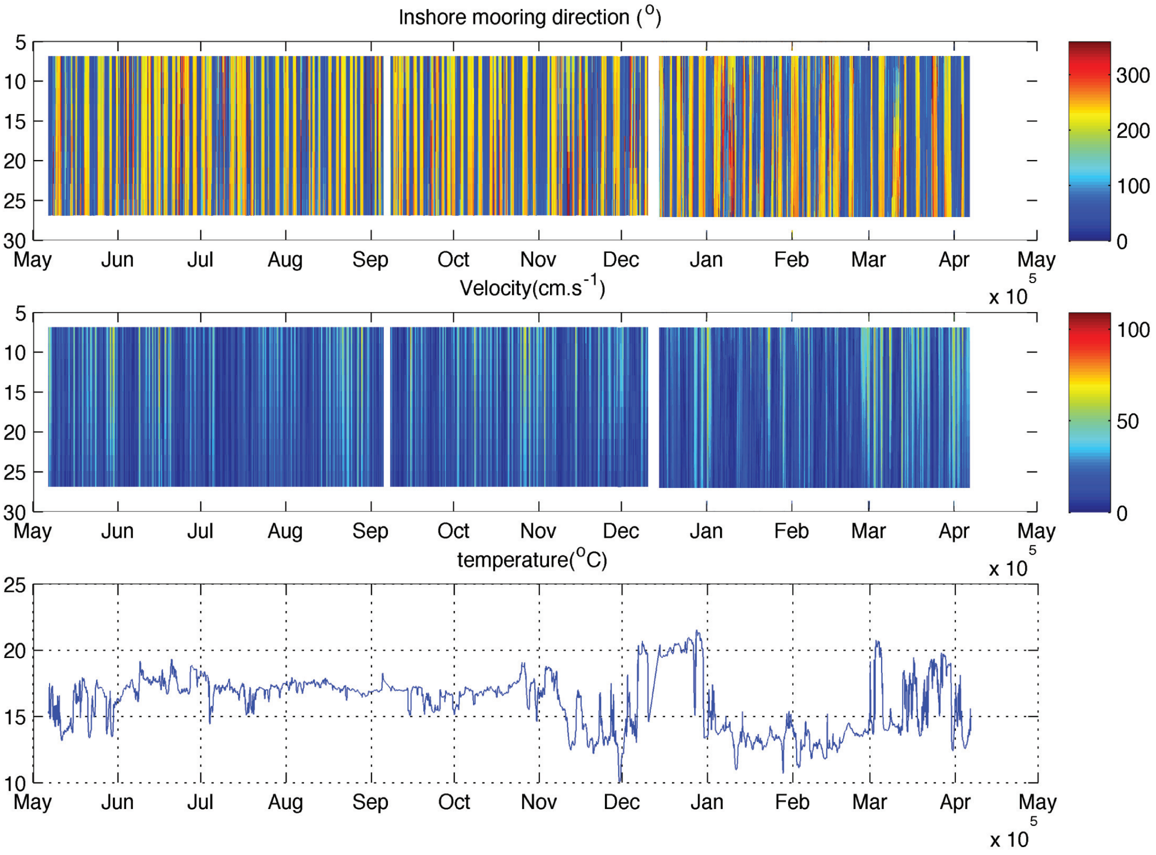

Fig. 5.16: Time series of ocean current magnitude and direction during 2005-2006 for the full water column at the inshore mooring site, bottom temperatures for this site are also shown in the bottom panel.

Close inshore, the ocean current dynamics differ from those at both the offshore and mid-shelf mooring sites. Here, instead of being dominated by the Agulhas Current itself, the flow is generally to the eastward with a median direction of 91.6º and current velocities are far weaker, with an average velocity of 0.17 m.s^{-1} and the highest recorded velocity being 1.09 m.s^{-1}. Little vertical shear is observed at these shallow depths, and frequent current reversals are observed. Interestingly, a spectral analysis of the inshore bottom temperatures (Figure 5.11) reveals very similar modes of variability to that observed at the mid-shelf mooring site (Figure 5.12), indicating that the temperatures at the inshore site are to some extent driven by the supply of water up the shelf from the mid-shelf site. However, due the proximity of the coastline, it can be assumed that some wind-driven upwelling must occur in this area and have an influence on the outcropping and therefore surface expression of this upwelling cell.

5.3 Wind Data

An analysis of wind data from the Port Alfred Airport station reveals that the predominant wind direction is from the South-west (downwelling favourable). However, it should be noted that the strongest wind events come from a North-easterly direction (upwelling favourable), but are short-lived, generally being only a day or two in duration. Examination of the dominant modes of variability using a spectral analysis shows most of the variability in alongshore, and therefore upwelling controlling, winds to be at periods of less than 8 days.

It has previously been suggested by Lutjeharms (2006) that the winds in the Port Alfred region act as a 'secondary pump' in the upwelling system, bring water that has been intruded up the shelf by shelf-slope upwelling to the surface via wind-driven upwelling. An examination of the upwelling event in January-March 2006 supports this idea, as the alongshore component of the winds during this period (01 Jan- 01 March 2006) has a mean alongshore wind component value of 0.0035 m.s^{-1}compared to the mean alongshore wind component for the entire time series (May 2005 to April 2006) of 1.28 m.s^{-1} . (Note positive alongshore wind is downwelling promoting, whilst negative is upwelling promoting). In contrast, immediately before the January to March cold period, in December 2005, there is an above average alongshore wind component of 2.17m.s^{-1} . Examination of the inshore bottom temperatures in the top plot of Figure 5.10 shows a corresponding warm period for December 2005 with temperatures above 20°C recorded over most of the month. However, it should be noted that this relationship between inshore bottom temperature and alongshore winds is not always valid, for example in March 2006 which has a similar wind regime to February 2006, but bottom temperatures of around 5°C warmer. This suggests that other factors apart from wind-driven upwelling are controlling the inshore temperatures. In order to begin to separate out these different factors an event scale approach is needed, where the effects of the current's position, the wind and mesoscale activity are considered.

Daily correlations of upwelling favourable winds with a decrease in bottom temperature produce and R value of 0.42 for the inshore mooring site, and an R value of 0.14 at the midshelf mooring site. Whilst not significant, these corelations suggest that the effect of wind events is limited to the inshore zone.

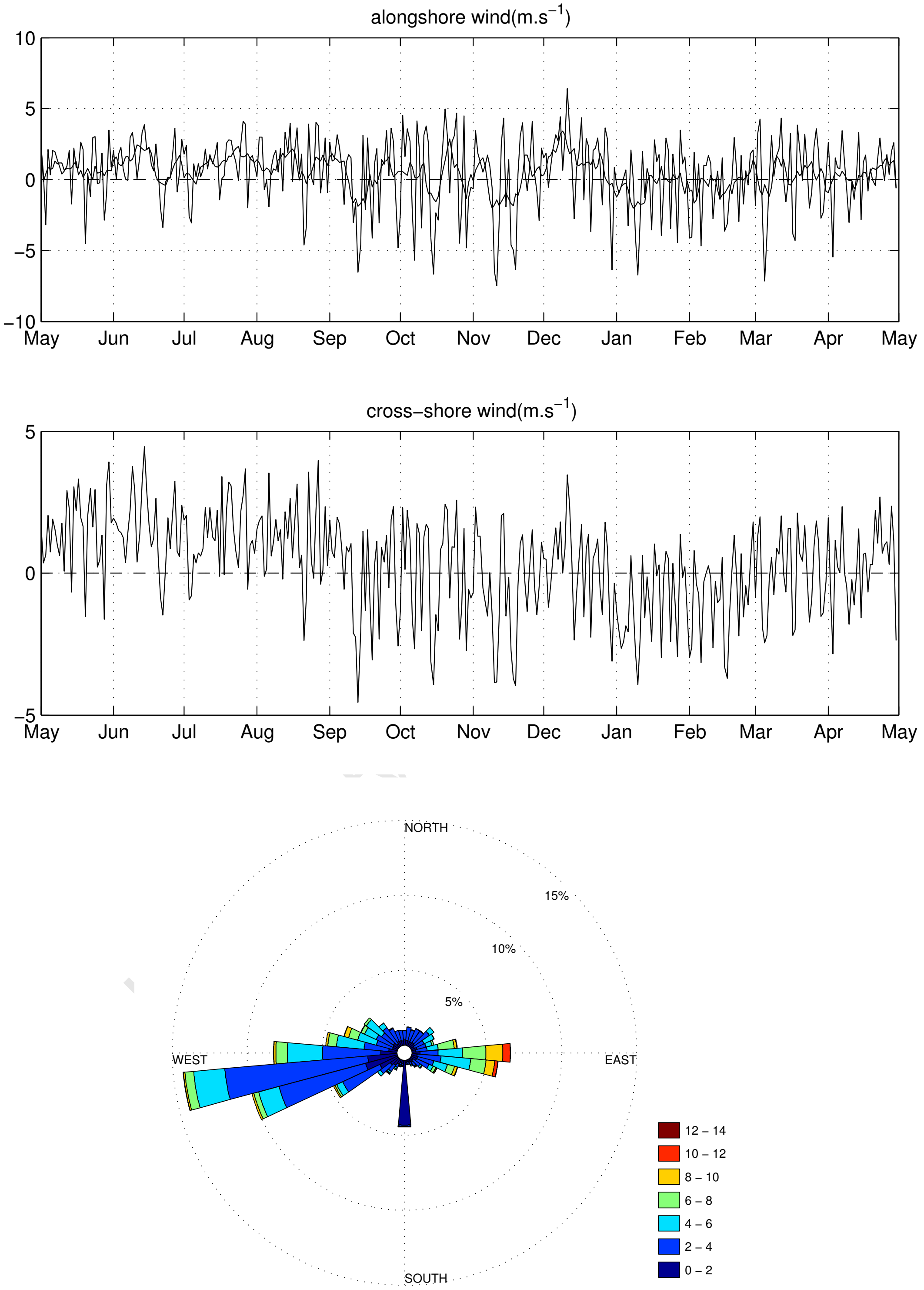

Fig. 5.17: Time series of along and cross-shore wind velocities taken at Port Alfred Airport for the 2005-2006 period. A wind-rose (units in m.s^{-1}) is shown in the bottom part of the Figure.

5.4 Case study of Mesoscale feature effects.

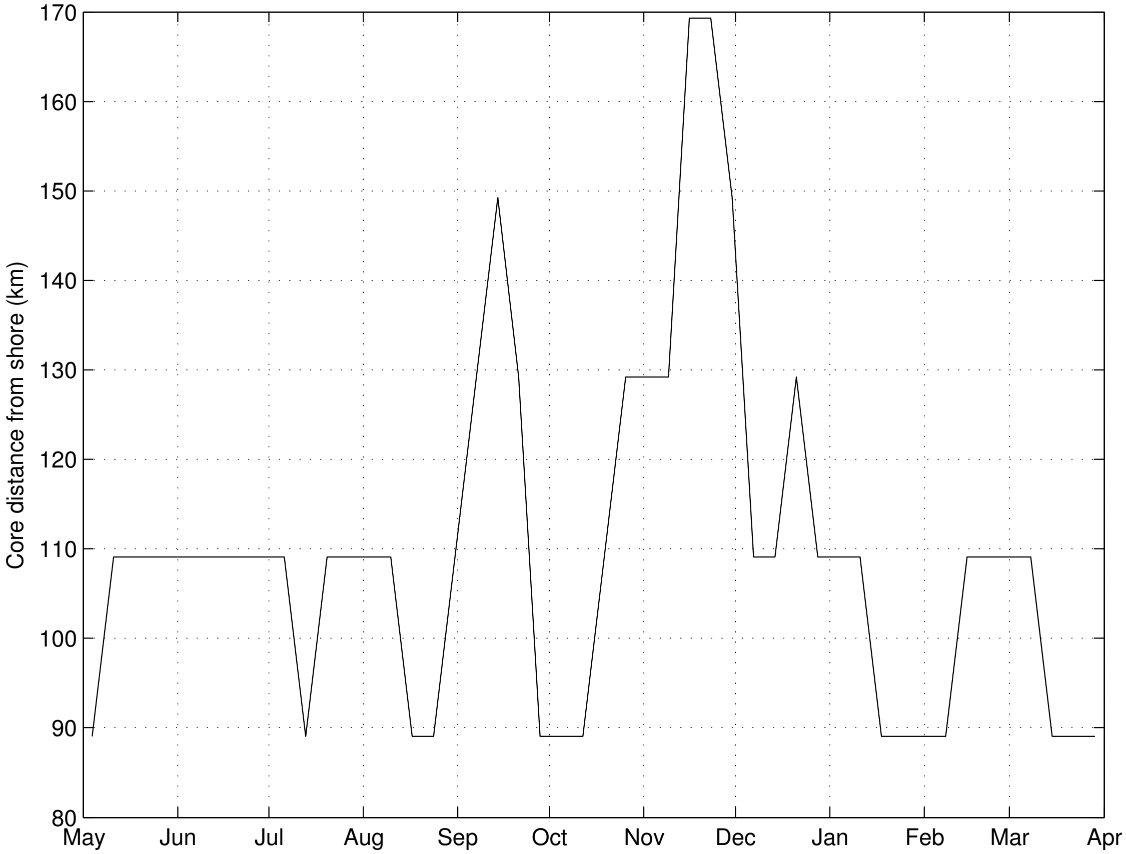

Fig. 5.18: A time series of the distance of the Agulhas Current core from the coast for the period May 2005 to April 2006, computed from Aviso altimetry data (Figure courtesy Marjolaine Krug)

Encroachment of the Agulhas Current onto the Port Alfred Shelf

Between the 10th and 20th of June 2005, the Agulhas Current encroached onto the shelf in the region of the Port Alfred mooring array. Embedded in this encroachment were two distinct warm plumes on the inshore edge of the current. Evidence of these plumes can be seen in the full water column ocean current record as current reversals in the bottom half of the water column during mid-June (see Figure 5.14). The MODIS daily SST for the period from the 10th to the 20th of June is shown in Figure 5.20. Its effects can be seen in the bottom temperatures shown in Figure 5.10 as a warm spike (above 15°C) in both the mid-shelf and offshore bottom temperature records. In order to explore the effects of this encroachment further, especially in terms of its influence on the bottom flow of cold water up the shelf slope, the cross and along shelf components of the offshore ADCP record have been plotted for the bottom 55m and top 60m of the water column at a 175m depth (see Figure 5.19). This is then compared to the bottom temperature taken at 175m. Note that positive along-shelf values show downstream flow, whilst positive along-shelf values show flow up the shelf.

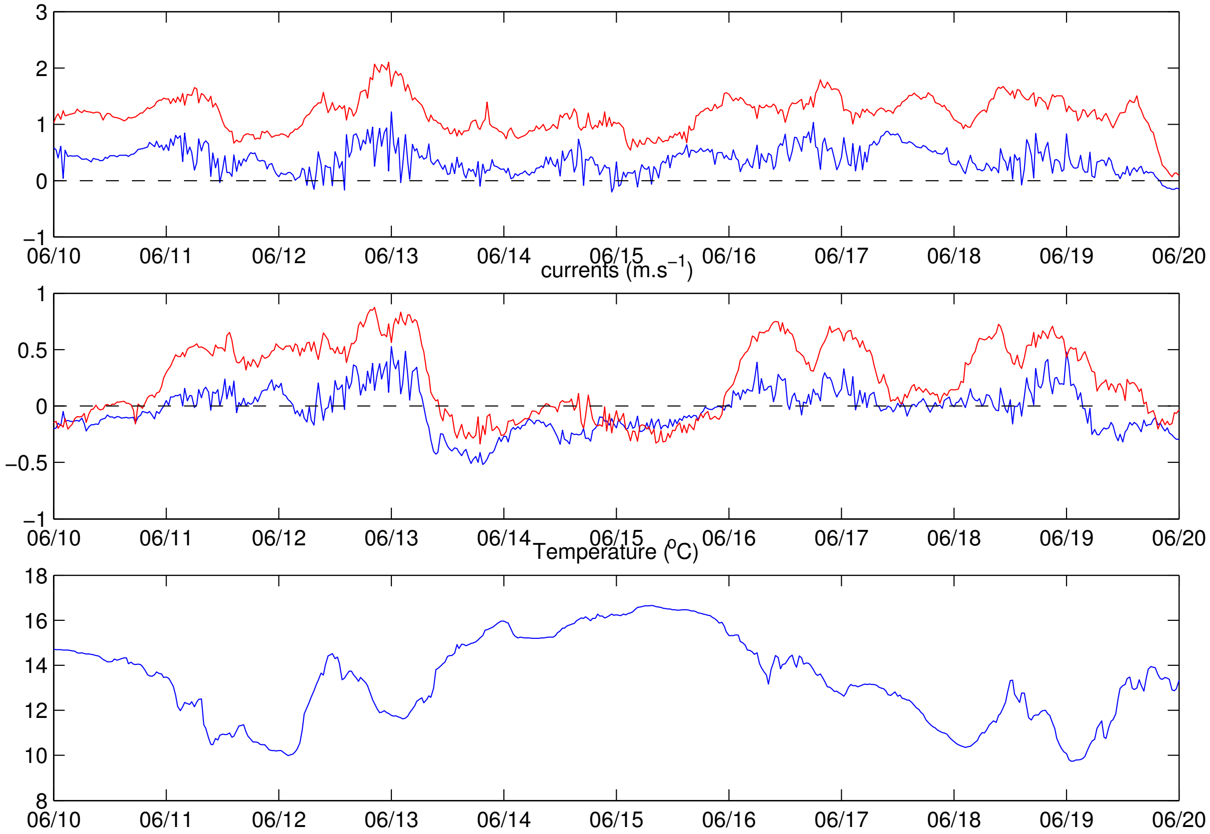

Fig. 5.19: Cross and along-shelf velocities for the bottom layer (175-120m depth) at the offshore mooring site during the passage of an elongated plume feature from the 10th to the 20th of June 2005. The red lines indicate along-shelf current (+ve is in the direction of the Agulhas Current) while the blue lines indicate cross shelf current (+ve is onto the shelf). The top panel shows the currents in the surface layer (0-60m) while the middle panel shows currents in the bottom layer (120-175m). The associated bottom temperatures are shown in the lower panel.

In Figure 5.19, the leading edge of the 2nd plume can be seen to pass over the mooring on the 12th and 13th of June. Associated with this is an increase in both cross and along-shelf currents and fluctuation in bottom temperature, with a minimum on the 12th being followed by a spike at midday and a drop on the morning on the 13th. The current itself then appears to effect the bottom layer as it encroaches closer to the coast, completely flooding the shelf on the 15th of June and causing an increase in temperature to almost 17° C, the maximum recorded in the study period. Bottom temperatures then dropped again to below 12°C as the warm surface water moved further offshore again on the 17th of June (see Figure 5.20). Of particular interest is the shear between the surface and bottom currents, with the current in the upper 60m remaining in a predominately along-shelf direction, whilst the current in the bottom layer (120-175m depth) show a distinct reversal between the 13th and 16th of June.

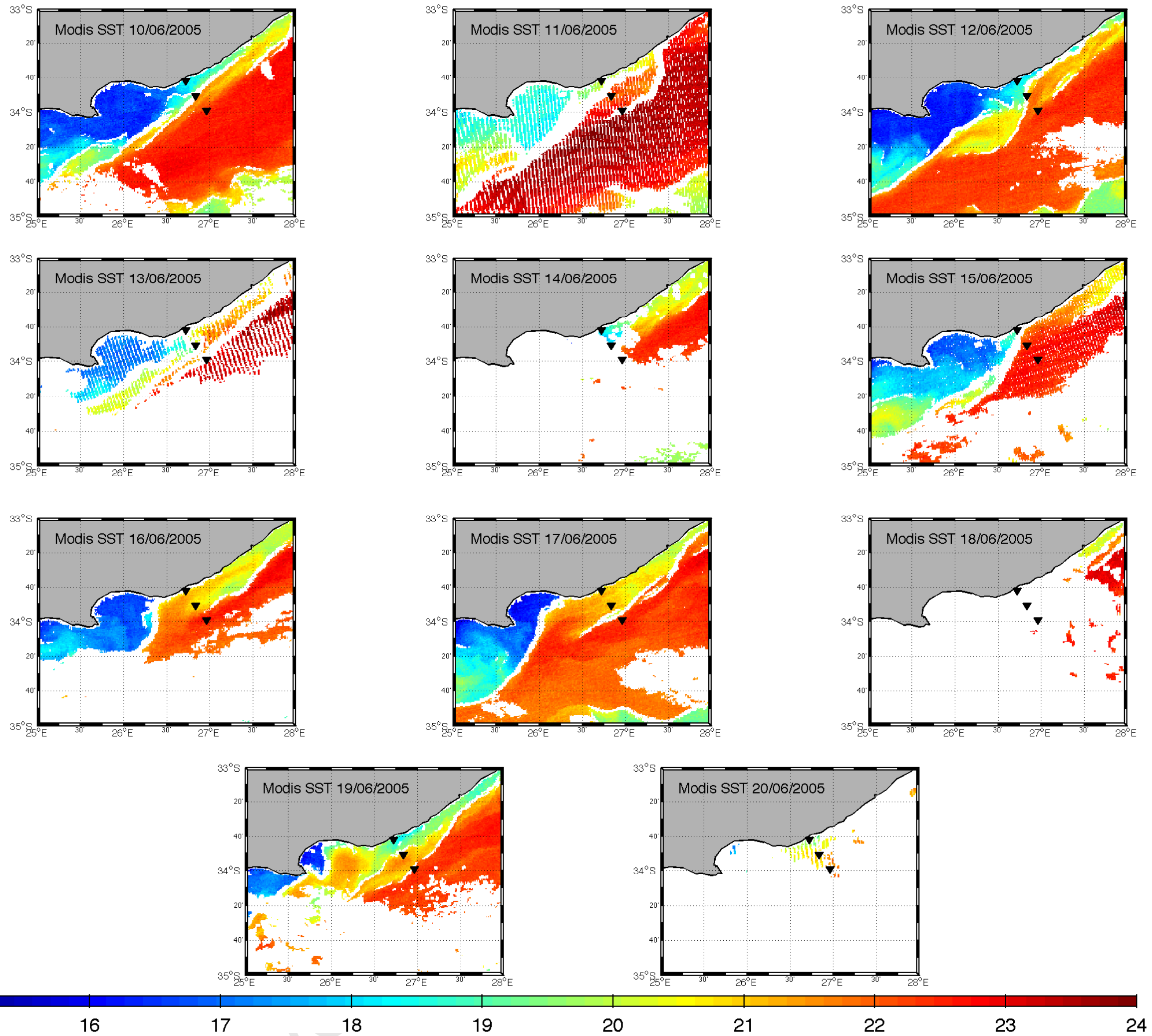

Fig. 5.20: Satellite image of sea surface temperature from MODIS an encroachment of the current on to the shelf in the Port Alfred area in the region of 34° S. ADCP mooring sites are marked by black triangles.

6 Discussion

The data presented above provides an insight into the frequency and extent of upwelling events in the Port Alfred cell over an 11-month period. Analysis of these parameters, in conjunction with satellite SST imagery allows a picture of the interactions between the various dynamics in the system to be developed.

6.1 Hydrographic Sections - relating Agulhas Current position to shelf-break upwelling

The three different CTD transects presented in this study highlight several important points. Firstly, they highlight the presence of cold bottom water over the shelf in all 3 sections included in the study. This is also in agreement with the sections published by Lutjeharms et al. (2000a). Secondly, the importance of the position of the Agulhas Current in relation to the shelf break is shown. This is particularly clear in the section taken in May 2005 (see Figure 5.1), this section can be taken as representative of an 'inactive' phase of upwelling in the Port Alfred cell, with a strongly stratified water column over the shelf region and relatively warm surface temperatures (greater than 19° C over the majority of the shelf). An examination of satellite SST from the 5th of May 2005 (Figure 5.2) shows the passage of a small meander resulting in the offshore movement of the inshore edge of the current. Of particular interest is that on the 5th of May, the meander was only just passing Port Alfred and thus the current had only recently taken up its offshore position. This recent change from an 'active' upwelling phase (with the current close inshore) to an 'inactive' upwelling phase (due to the meander) would explain why, while surface temperatures on the 5th of May were warm, bottom temperatures along the shelf remained cool (below 12° C). This idea of a change from an active to a passive upwelling phase just prior to the taking of the CTD section on the 5th of May is further supported by the low bottom temperatures and current reversals observed at the offshore and mid-shelf mooring sites (see figures 5.14 and 5.15). Thus it would appear that the small meander visible just east of Port Alfred at 34°, 27°E is responsible for flushing the shelf with warm surface water.

The CTD section taken on the 11th of September shows the Agulhas Current being situated directly at the shelf break, with the salinity maximum associated with the inshore edge of the current appearing to lie directly along the edge of the shelf. Of interest is, despite the current being close inshore, the water over the shelf is relatively warm (>15° C). There are two possible explanations for this. Firstly, examination of the satellite SST image for the 9th of September (the 10 and 11th September images could not be used due to cloud cover) shows that the current appears to be rather dispersed and weak following the passage of the large feature visible off Algoa Bay (see Figure 5.4). This agrees with the relatively cool surface temperatures of 22° C observed at the inshore edge of the current in Figure 5.3. However, it should be noted that this section is taken in early spring and thus the low temperatures could be due to seasonality rather than a lowering in the intensity of the current.

A second explanation for the warm water observed over the shelf on the 11th of September is due to the inshore edge of the current appearing to be in direct contact with the shelf break. It is possible that this could stop the upwelling of 12° C water up from its usual depth of 400m onto the shelf. This would appear to be supported by the theoretical work of Condie (1995) who showed, using a geostrophic adjustment model, that conditions are most favourable to shelf-slope upwelling before the Western Boundary current comes into contact with the shelf slope. Thus it would appear that on the 11th of September, the inshore edge of the current had effectively shut down transport in the BBL, stopping shelf-slope upwelling from taking place.

In contrast, on the 10th of April 2006, a very strong active upwelling situation can be seen, with large boluses of cold water (<12°C) being visible on the shelf in Figure 5.5. The satellite SST image from that day (Figure 5.6) shows the Agulhas Current to lie very close to the coast, however, the inshore edge of the current is not in contact with the shelf break, thus cold water is able to be transported up unto the shelf from 400m. This is confirmed by the presence of water colder than 12°C on the shelf slope at a depth of 200m.

6.2 Ocean Currents from the Port Alfred mooring array.

The most notable features of the offshore mooring ocean current record for the 2005 period are three full water-column current reversals. These take place in May, September and December 2005 and can be attributed to the passage of meander events over the mooring array. Reference to Figure 5.18 shows that the Agulhas Current was very far offshore in both September and December 2005, indicating that these current reversals were caused by the passage of Natal Pulses, while the May reversal can be attributed to the smaller meander discussed above and visible in Figure 5.2. However, an examination of the bottom temperature records in Figure 5.10 show that only the December Natal Pulse had a significant effect on bottom temperatures at the inshore mooring site. Unfortunately cloud cover the use of satellite imagery impossible so it is difficult to ascertain the exact nature of this pulse and what is responsible for the very warm period that followed.

The spectral analyses performed on the bottom temperature data highlight the difference in the frequency of the variability at the offshore site when compared to the inshore and mid-shelf sites. The most plausible explanation of this is that, due to the offshore mooring's location right on the edge of the Agulhas Current, it is more affected by small perturbations of the current itself than the inshore and mid-shelf sites which are only affected by large scale changes in the current. This may explain the reasons behind the inshore and mid-shelf sites showing more variability in the 30 to 80 day range compared to the offshore site where most of the variability occurs at periods of less than 12 days.

It is probable that much of the shorter time scale variability, i.e. that at periods under 12 days, is probably caused by a combination of coastal trapped waves, small mesoscale features such as the Durban Break-away Eddy as well as the strong North-Easterly wind events with these factors combining to result in the regular current reversals seen most clearly at the mid-shelf and inshore sites.

However, it is suggested that the effects of the wind may be considered to be a series of short high frequency upwelling episodes, due to the short duration of upwelling wind events. Thus wind events are likely to only affect the inshore regions on short time-scales and not be a major driver of the supply of nutrient-rich water to the region as a whole. This would be in agreement with the findings of Goschen et al. (2012), who found the wind to be a major driving mechanism of upwelling at the event scale in regions shallower than 80m off Port Alfred. This also helps to explain the difference in the time scales of variability between the offshore (176m depth) and midshelf (76m depth) and inshore (31m depth) stations, supporting the idea of this upwelling cell being driven by a hierarchy of processes.

6.3 Lessons from the case study of Agulhas encroachment

The case study of the encroachments of the current and the associated warm plumes (most likely triggered by flattened Durban Break-away Eddies) gives an insight into the complexity of processes taking place on the shelf during the passage of a mesoscale cyclonic feature past the mooring array off Port Alfred. Of particular interest was the strong relationship seen between the strength and direction of both the alongshore and offshore currents in the bottom layer and the bottom temperatures. The plumes show marked upwelling on its leading edge, similar to that observed by Campos et al. (2000) in cyclonic eddies on the shelf of the Brazil Current. However, in this example there is also a marked warm period, which coincides with the flooding of the shelf with warm surface water. (see satellite imagery in Figure 5.20). Thus it is possible that the 15°C to 17°C temperatures recorded at the offshore mooring site during the encroachment show that South Indian Subtropical Surface Water has moved onto the shelf and that transport in the BBL has been shut down, in a similar situation to that seen in the CTD section of Figure 5.8. The small fluctuations in bottom temperature on the 12th and 18th of July can be attributed to the effects of upwelling and downwelling driven by the small warm plumes visible in the satellite imagery. In the case study there are thus two scales of variability. The first of these, with a period of 6 days, is driven by the encroachment of the current onto the shelf, displacing the cold South Indian Central water, whilst the second is driven by the smaller mesoscale features in the form of two elongated warm plumes extending shoreward from the current itself. At the same time, it is seen that the encroachment of the current is seen to shut down shelf upwelling the in BBL, thus interrupting permanent shelf-slope upwelling driven by the minimum in shelf width just upstream of Port Alfred (see Gill and Schumann (1979); Oke and Middleton (2000); Palma and Matano (2009) or discussion in literature review above).

This case study has highlighted the importance of mesoscale activity in modulating upwelling activity in the Port Alfred Cell. Whilst it could be suggested that these same features affect the entire East Coast, the semi-permanent presence of cold, nutrient rich water on the shelf at Port Alfred, exacerbates the effect of these features. In an attempt to create a framework for identifying mesoscale activity off Port Alfred, daily sea surface temperature images from MODIS for the period 2005-2010 were studied. This allowed five general modes of activity in the Port Alfred Cell to be identified. Schematic diagrams of these modes are presented in Figure 6.1.

Mode 1 shows the passage of a Natal Pulse, which is associated with upwelling on its leading edge and in the cyclonic core.

Mode 2 shows the absence of mesoscale activity, with the dominant mode of upwelling thus being continuous processes such as Ekman veering in the BBL.

Mode 3 shows the passage of an elongated warm plume, as discussed in connection with the case study above.

Mode 4 shows a small meander event such as that seen in Figure 5.2, which has distinct upwelling and downwelling regions as discussed by Campos et al. (2000).

Mode 5 shows strong shelf-edge upwelling in the absence of mesoscale activity, which then outcrops at the surface due to a North-easterly wind.

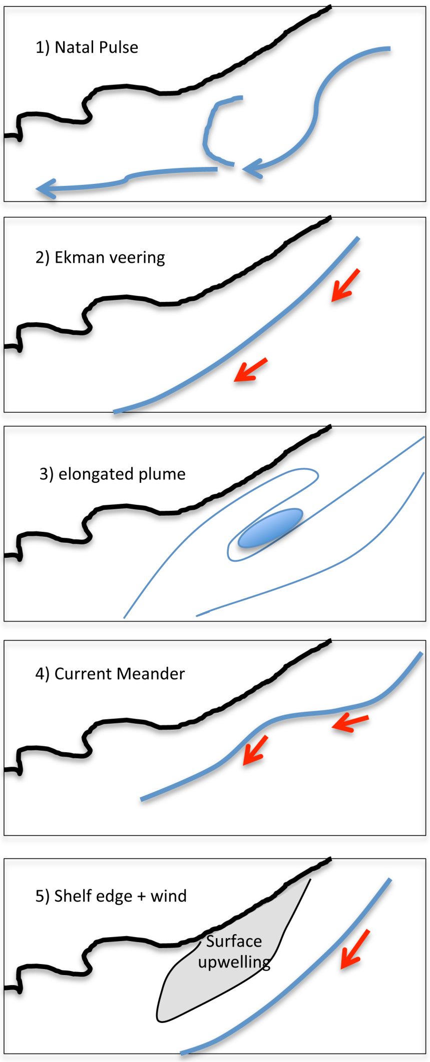

Fig. 6.1: Schematic illustration of the different mesoscale modes of the Agulhas Current in the Port Alfred region, produced from a visual analysis of satellite SST for the 2005-2006 period.

6.4 Possible Driving Mechanisms

There are several processes that could be responsible for the semi-permanent upwelling cell at Port Alfred. These can be broadly divided into two categories. Firstly there are the transient processes; these include upwelling on the leading edge of meanders and in the core of cyclonic features which are then entrained up onto the shelf, as well as wind-driven coastal upwelling. The second group of processes could be termed the continuous processes. These continuous processes involve the interaction of an inertial jet current with the bathymetry. From the current literature (Lutjeharms et al., 2000b; Lutjeharms, 2006) and the evidence presented above, it appears that changes in the structure of the current due to the conservation of potential vorticity, as put forward by Gill and Schumann (1979) is the most likely the most important continuous process, due to the fact that it is site-specific due to the particular shelf configuration at Port Alfred. Other continuous processes, such as Ekman veering in the bottom layer, whilst likely to be a contributed factor to the upwelling observed at Port Alfred, will occur all along the shelf and so fail to account for the site-specific nature of the upwelling at Port Alfred. This is in agreement with the findings of Lutjeharms et al. (2000b). However, the extension of the BBL shut down time is also controlled by the minimum in shelf-width which is site specific to Port Alfred and thus is also likely to be a crucial part of the mechanism which transports South Indian Central Water from the shelf slope onto the shelf itself. This mechanism being largely driven by the conservation of potential vorticity. It should be noted that these continuous processes can be interrupted by the encroachment of the Agulhas Current onto the shelf itself. In this study this shut-down has been observed in both a CTD section (see Figure 5.3) and a case study using ADCP moorings (see Figure 5.19).

An interesting result of the data presented above is the suggestion that mesoscale activity, such as the Natal Pulse and Break-away Durban Eddies, may in fact inhibit the functioning of the Port Alfred upwelling cell, due to their disturbance of the conditions ideal for the continuous processes discussed above. Thus, changes in the frequencies and size of mesoscale feature could have a significant effect on the large-scale nutrient dynamics of the region. However, at this stage this is pure conjecture and a dedicated, idealised numerical experiment would be needed to explore this idea further.

7 Conclusions

In order to assess the nature and driving mechanisms behind the semi-permanent upwelling cell observed at Port Alfred, 3 key questions were posed:

- **How often does shelf-edge upwelling occur?**

This study has described the variability of the semi-permanent upwelling cell centred around Port Alfred. Upwelling, defined as the presence of South Indian Central Water (i.e. temperatures of 16°C or lower) was observed to be present 85% of the time over the period May 2005 to April 2006. This highlights the importance of subsurface dynamics in this upwelling cell upwelling was reported to only be expressed at the surface 40% of the time (Lutjeharms et al., 2000b). The main temporal scales of variability were observed to be at 50-70 days - indicative of Natal Pulses and smaller meanders in the Agulhas Current, 4-6 day pulsing - likely driven by wind events and coastal trapped waves, and 8-12 days - reflecting the effects of mesoscale features inshore of the Agulhas Current such as Breakaway Durban Eddies and warm plumes associated with shear-edge features.

- **What are the main possible driving mechanisms of this upwelling?**

Upwelling at Port Alfred is maintained by continuous processes related to the bathymetry upstream of the upwelling cell. Mechanisms for this include conservation of potential vorticity - causing uplift of the interface as the shelf broadens from its minimum width, or an increase in shutdown time for transport in the bottom boundary layer - driven by acceleration of the current at the point of minimum shelf width. It is possible that both these processes drive the upwelling of water from below 400m up onto the shelf. Upwelling can also be driven by cyclonic features such as meanders and shear-edge eddies on the inshore margin of the current and the influence of coastal trapped waves. Although these mesoscale cyclonic features appear to make an important contribution to upwelling in the region, they do not explain the continuous and site-specific nature of the upwelling activity at Port Alfred.

Close inshore, in water less than 50m depth, coastal winds affect upwelling activity, but this upwelling is only effective if cold bottom water is already present on the shelf. Thus the wind, while contributing to variability, is not a primary driver of upwelling.

- **How do mesoscale, current-driven and other factors combine to control the variability of the Port Alfred upwelling cell?**

It thus appears that there are several tiers of variability that interact to produce the semi-permanent upwelling cell that had previously been described off Port Alfred. The continuous, topographically-driven upwelling is controlled by the position, depth and intensity of the current, especially the position of the inshore edge in relation to the shelf break. These continuous processes supply the upwelling cell with cold, nutrient-rich South Indian Central Water from depths below 440m, which then remains on the shelf in large boluses.

Mesoscale features modulate this upwelling on scales from tens of days (meanders and Natal Pulses), or less (shear-edge and break away eddies). Inshore, winds and coastal trapped waves drive current reversals at time scales of a few days, with wind events also seeming to have an important effect on the surface expression of the upwelling cell.

However, the inherent restrictions provided by the resolution of this dataset and the limited time available to conduct this study has left scope for a more detailed, quantitative examination of this upwelling cell.

7.1 Limitations

In a coastal study of this nature, resolution is always going to be a limiting factor. The 11 month mooring record (7 months in the case of the offshore mooring) does not enable the seasonal cycle, if existent, to be resolved. The lack of full water column temperature, as would be provided by temperature arrays, or CTD measurements, in the form of microcats, limits the tracking of water mass movement over time, as only bottom temperatures are available.

In terms of hydrographic measurements, these were taken when a ship was in the area to deploy, service or recover moorings. Resulting from this, moorings were not recording data when the CTD sections were taken, making direct comparisons between time series and synoptic measurements impractical.

In terms of the use of satellite remote sensing products, the use of more advanced satellite products for sea surface temperature and ocean colour with a higher temporal resolution would allow greater insight to be gained into both the inshore dynamics of the current and the surface expression of the upwelling cell. However, it care should be taken, as in the preliminary stages of this study, merged SST products were observed to interpolate over many of the coastal mesoscale features, rendering them invisible.

7.2 Future Directions

Future investigations into the nature and driving mechanisms of the Port Alfred upwelling cell could be taken in two directions. Due to the complexity of the system, a multi-disciplinary approach would be needed in order to provide a greater spatial and temporal resolution of data. Firstly, to test the theoretical basis of topographically controlled continuous upwelling, and to quantify its contribution, a theoretical study using a suite of dedicated, idealised numerical modeling experiments would be needed. This would allow dynamics and sensitivity of the proposed continuous mechanisms to be assessed, and the effects of interannual variability of the Agulhas Current to be explored. Secondly, an investigation into the identification and dynamics of the various mesoscale features found inshore of the current, using synoptic cruise data, mooring arrays and coastal altimetry would allow a better understanding of the links between the mesoscale dynamics of the Agulhas Current and biological activity in its shelf waters.

The eventual goal would be to accurately model the effects of both the continuous and mesoscale processes at Port Alfred and investigate the effects of this powerful nutrient pump on the greater Agulhas Bank ecosystem.

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