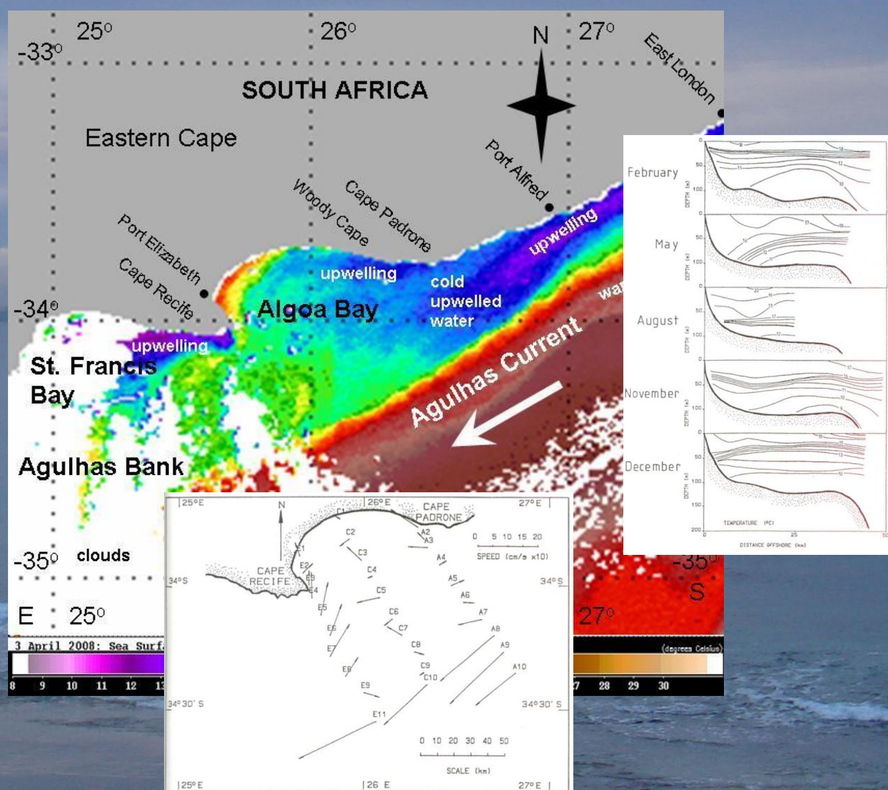
# The physical oceanographic processes of Algoa Bay, with emphasis on the western coastal region

**Wayne S. Goschen and Eckart H. Schumann**

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# The physical oceanographic processes of Algoa Bay, with emphasis on the western coastal region

A synopsis of the main results of physical oceanographic research undertaken in and around Algoa Bay up until 2010

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A SAEON internal publication, complied by the SAEON Egagasini Node for Offshore Marine Systems with contributions from the Institute for Maritime Technology and the SAEON Elwandle Node for Coastal-Inshore Systems

Sponsors:
South African Environmental Observation Network (SAEON)
Institute for Maritime Technology (IMT), on behalf of the South African Navy

This scientific study was co-funded by the South African Environmental Observation Network (SAEON) and the Institute for Maritime Technology (IMT), on behalf of the South African Navy.

IMT Document number: P0106-110000-730002.

For use by the Environmental Characterisation Domain.
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8 March 2011

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## Table of Contents

# 1 Introduction

Algoa Bay is the easternmost and largest of several log-spiral shaped embayments on the south Cape coast of South Africa (Figure 1). The coastal ocean off Algoa Bay is located in the transition zone between the Agulhas Current dominated region to the northeast and the wide Agulhas Bank shelf dynamics to the southwest. Within the bay, interactions between nearshore, coastal and deep-water oceanographic processes, weather systems and local bathymetry and shoreline contours result in a dynamical ocean. Figure 2 shows a typical satellite thermal image of the Eastern Cape which illustrates the large scale ocean dynamics of the region. These features are introduced below.

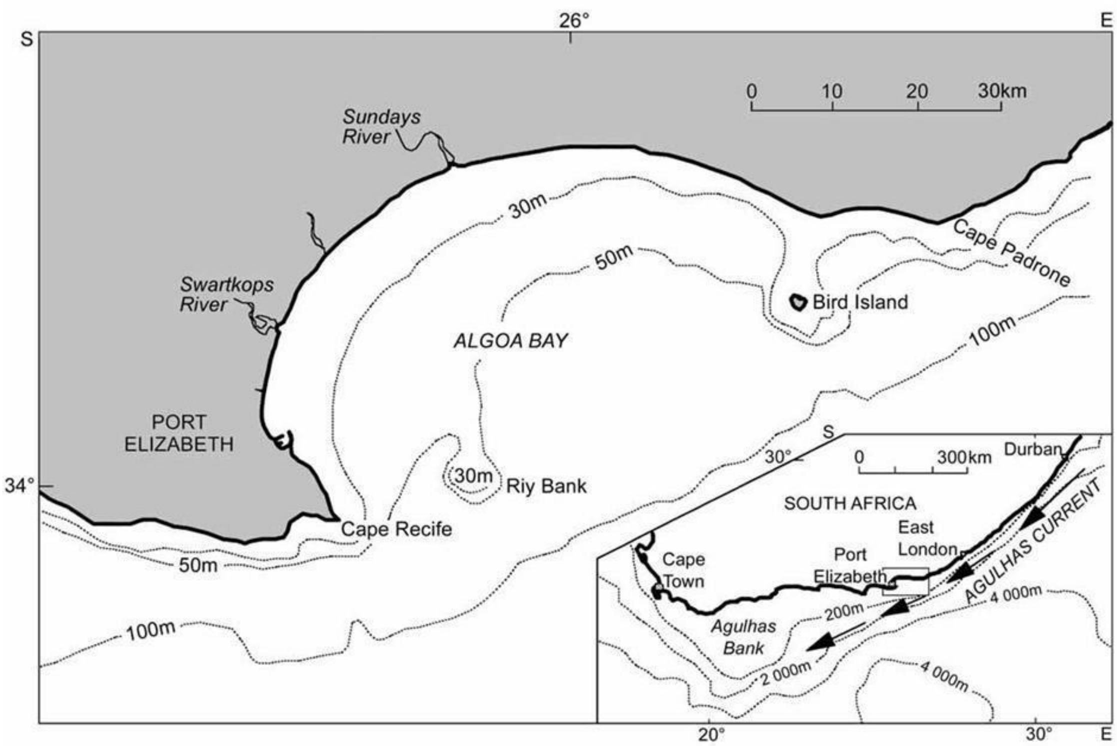


**Figure 1: Map of Algoa Bay, with the city of Port Elizabeth in the western sector. The inset map shows the position of Algoa Bay on the coast of South Africa. The general flow of the Agulhas Current is indicated. From Schumann et al. (2005).**

The Agulhas Current flows southwestwards along the continental shelf edge of the east coast of South Africa (about 50 km offshore Algoa Bay) and dominates large-scale ocean features in the region (Schumann, 1987, 1998). Refer to Lujteharms (2006) for a comprehensive treatise on the Agulhas Current. Over the continental shelf off Algoa Bay (depth 150 m - 200 m), wind-driven ocean dynamics become more important (Goschen and Schumann, 1988). However, large episodic meanders in the Agulhas Current ("Natal Pulses") are known to influence the dynamics of the shelf waters from time to time as they propagate southwestward past Algoa Bay (Goschen and Schumann, 1990; Roberts, 2010). In this region shear-edge eddies and plumes on the inshore edge of the Agulhas Current also frequently penetrate over the shelf (Lutjeharms and Ruijter, 1996) and may be driven into Algoa Bay by southwesterly winds (Schumann et al., 1988). There is evidence of entrainment of shelf water by the Agulhas Current, sometimes causing predominantly southwestward flows in the deeper reaches of Algoa Bay (Schumann et al., 2005).

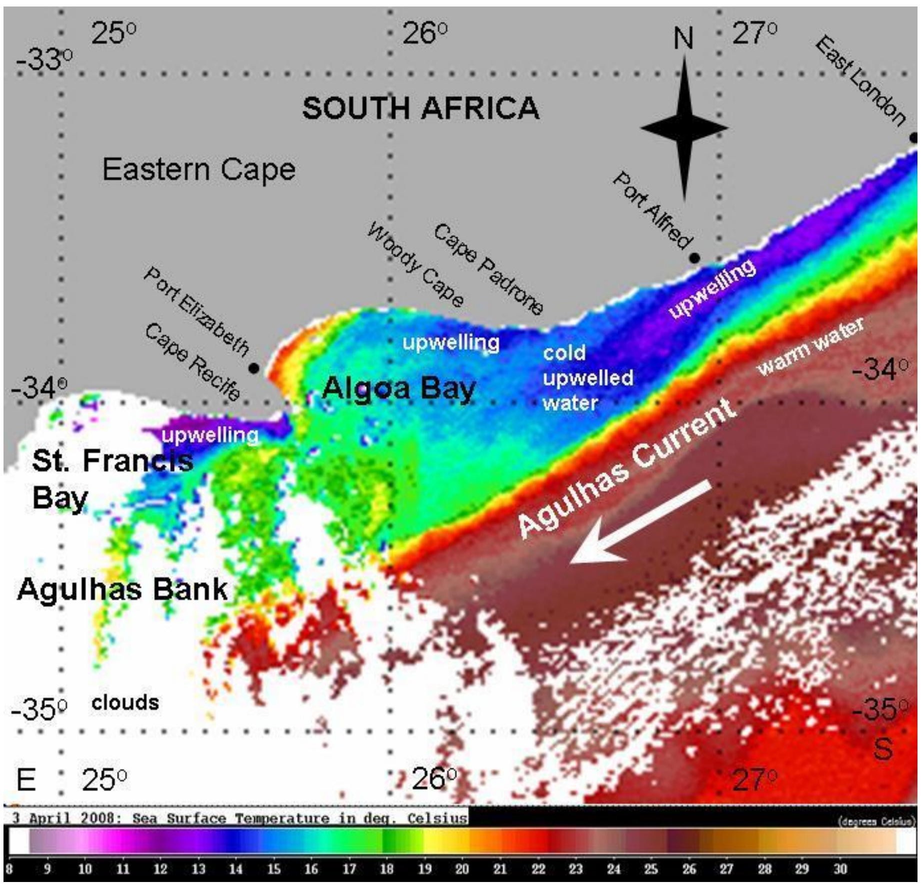


**Figure 2: A satellite thermal image showing some of the surface dynamics of the ocean off the Eastern Cape. Upwelling of colder water, shown in blue, is evident along the coastline from the northern area of Algoa Bay to Port Alfred and East London, as well as off the southern shoreline of Cape Recife. The Agulhas Current is clearly visible further offshore as a red/brown colour, with its inshore edge at the continental shelf break. The shallower waters in the southwestern sector of Algoa Bay are relatively warm compared to the surrounding upwelled water. The grey area is land and the white patches are cloud cover. (Courtesy of UCT Marine Remote Sensing Unit).**

The dynamics of the Agulhas Current ensures that isotherms slope upwards at the continental slope, on its inshore boundary. This colder, deeper water can then be brought onto the shelf by a combination of Ekman veering in the bottom boundary layer (Schumann, 1987), the widening shelf and associated dynamical processes described by Gill and Schumann (1979). The cold water upwells sporadically at the coast, at times accentuated by local north-easterly winds. Such upwelling has been observed as far north as Port Edward, but commonly occurs south of Mbashe (Schumann, 1987). Lutjeharms et al. (2000) have proposed the existence of an upwelling cell near Port Alfred, but it is probably just part of an increasing frequency of upwelling southwestward. Such cold water then also rounds Cape Padrone and penetrates into Algoa Bay (Figure 2).

Along the south coast upwelling occurs preferentially at the prominent capes, driven by easterly-component winds, and then progresses westwards (Schumann et al., 1982; Beckley, 1983, 1988; Schumann et al., 1988). Goschen and Schumann (1995) have shown that this cold, upwelled water can be brought eastwards into Algoa Bay by subsequent westerly winds. Because of the seasonal nature of the winds, such upwelling occurs predominantly in summer.

Within the shallower reaches of Algoa Bay, wind-driven, tidal, geostrophic and inertial currents play a large role in the water circulation, while in the nearshore zone wind and wave action are known to cause the northward transport of sediment. Warm water filaments originating in the upper layers of the Agulhas Current also sometimes penetrate into the shallow, nearshore zone of Algoa Bay (Goschen and Schumann, 1990, 1994; Roberts, 2010).

This report will concentrate specifically on the physical oceanography of Algoa Bay and over the adjacent continental shelf and the processes that drive the dynamics.

# 2 Bathymetry

Bremner (1991a) provides a detailed description of the bathymetry of Algoa Bay (Figure 3). Algoa Bay is the easternmost, and largest, of several crenulated embayments found on the Cape southeast coast (Bremner, 1991b). It's almost perfect clockwise logarithmic spiral shape faces into the southwest Indian Ocean. In general, the sea floor slopes very gently towards the south-southeast at about 0.15° and has a maximum depth of about 70 m. Locally, numerous islands, depressions, ridges and scarps reverse this gradient.

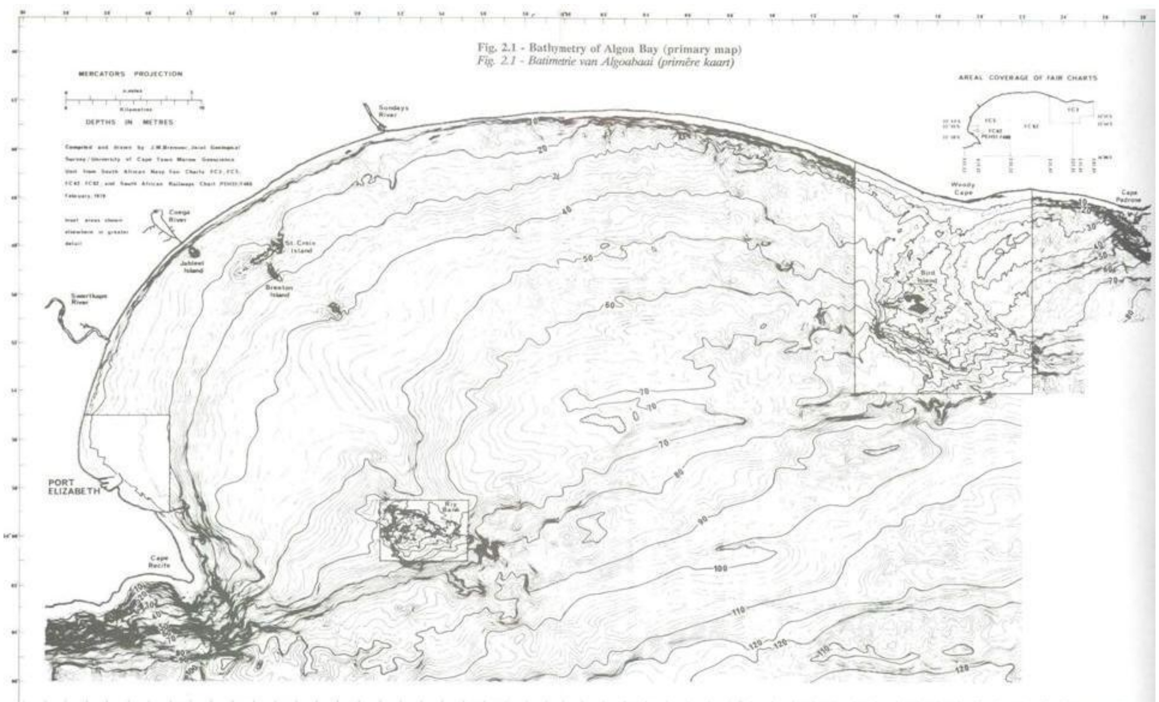


**Figure 3: Bathymetry of Algoa Bay. From Bremner (1991a).**

The most rugged bathymetry in Algoa Bay exists over the exposed bedrock (Table Mountain Group sandstones protruding through Cretaceous and Cenozoic sediments) off Cape Recife, Riy Bank and Bird Island. These three areas, together with Cape Padrone, constitute the mouth of the bay. They are joined by a discontinuous subdued ridge named the Recife Bird Ridge, which in places is a relatively steep sea-ward dipping scarp that tends in an east-northeasterly direction. The ridge is considered to be the dividing line between Algoa Bay and the adjacent continental shelf. The shelf break off Algoa Bay is situated about 50 km south of Cape Recife at a depth of about 150 m.

In the bay there are other exposed rocky areas: St. Croix Island, Brenton Island and Jaheel Island, found in the northwest quadrant of the bay near the mouth of the Coega River. They are small, isolated outcrops of Table Mountain Group, generally surrounded by a smooth sea floor of Quaternary sand.

The bathymetry of the approaches to Port Elizabeth harbour is shown in Figure 4 (Bremner, 1991a). It is evident that the construction of harbour infrastructure has distorted the continuity of the nearshore isobaths. This is due to the accretion of nearshore sediment on the south side and the erosion on the north side Lord et al. (1985). One consequence of this is the exposure of a small rocky outcrop to the north that rises to 2 m below Mean Low Wet Springs (MLWS), as well as other irregularities. In addition, the dredging of the artificial approach channel to about 16m depth has further distorted the isobaths. To the southeast is a roughly circular bank rising to about 8m below MLWS which is known to exert considerable influence on the nearshore sedimentation pattern (Bremner, 1991b). The nearshore drops off steeply to about the 10 m depth but then flattens out to a gentler gradient.

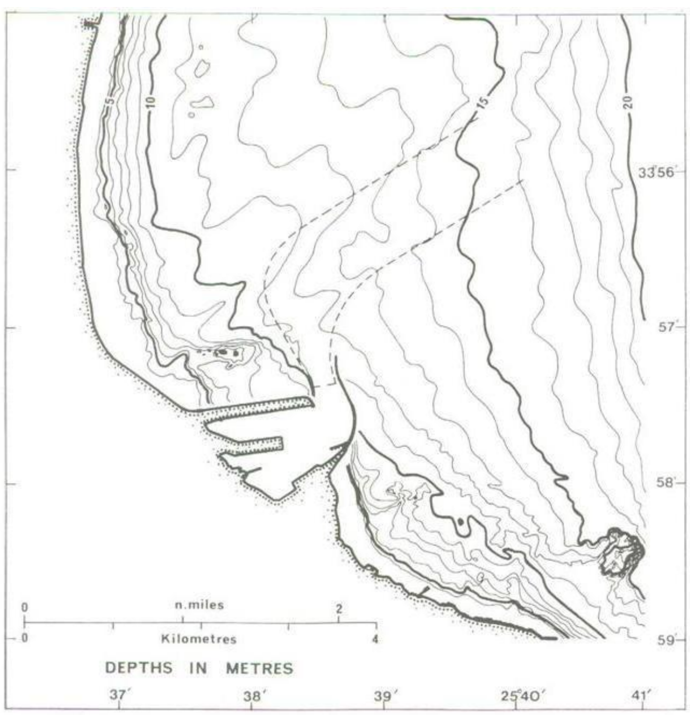


**Figure 4: Bathymetry of the approaches to Port Elizabeth harbour. From Bremner (1991a).**

# 3 Weather and wind

## *3.1 The weather of South Africa*

The position of South Africa in the subtropics ensures that its climate and weather are affected by both the general easterly circulation in the tropics and the westerly circulation in the temperate latitudes. The semi-permanent high pressure cells of the southern hemisphere, namely the South Atlantic Ocean High (SAOH) in the west and the South Indian Ocean High (SIOH) dominate the atmospheric circulation (Preston-Whyte and Tyson, 1988). Both cells show a latitudinal seasonal movement of about 5 to 6° with the result that in summer fronts ridge eastward south of the continent, while in winter a high pressure region is established over the subcontinent and the fronts pass over the land.

The small scale disturbances that control individual weather systems, and have periods of a few days, owe their origins to these features of the general circulation. The major systems that influence the coastal weather are cold fronts, the coastal lows (Gill, 1977) and associated berg winds. Cut-off lows, bud-off highs and land/sea breezes also influence the coastal weather (Hunter, 1982, 1987).

The large scale weather systems propagate from west to east in a path that is dictated by the land topography, and Figure 5 illustrates a typical sequence of weather systems that influence the surface weather patterns over southern Africa. Hunter (1987) documented the passage of coastal lows, while Schumann (1989) confirmed that the major axes of the wind systems are oriented approximately parallel to the general trend of the coastline in response to the interaction with the land/sea interface. Schumann and Martin (1991) also recorded the anti-clockwise propagation of air pressure and wind systems, showing that variability in the east occurred on shorter time scales than the western Cape; this was confirmed by Schumann (1999). The westerly winds are common during all seasons although a shift towards the southerly direction tends to occur in winter.

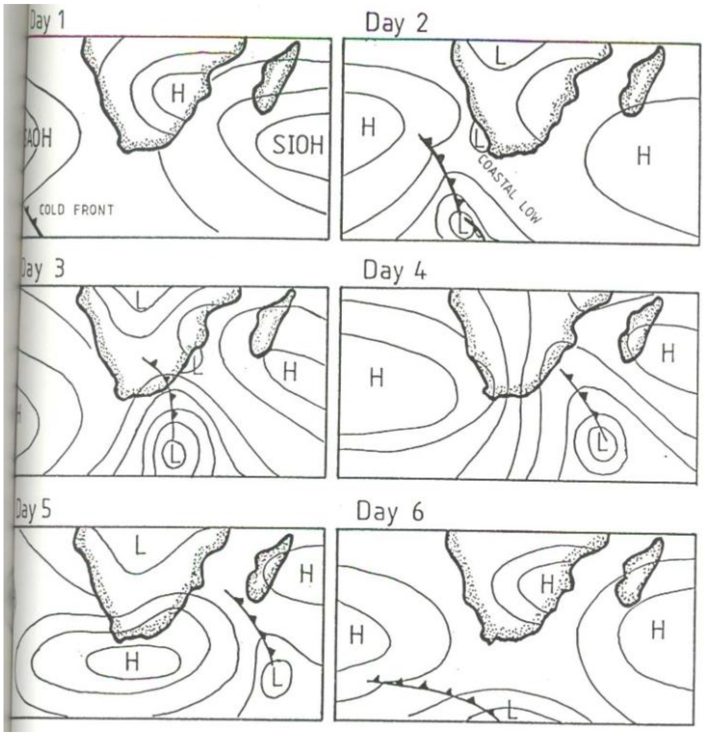


**Figure 5: A schematic illustration showing a typical sequence of weather systems over a six-day period that influences the surface weather patterns over southern Africa (after Preston-Whyte and Tyson 1988). The South Atlantic Ocean High (SAOH), the South Indian Ocean High (SIOH), a cold front and the coastal low are illustrated.**

## *3.2 The winds of Algoa Bay*

The landward boundary of Algoa Bay rises relatively gradually into the interior; there is little prominent topography in the coastal zone. Figure 6 shows the major land contours. Nevertheless, both Illenberger (1986) and Hunter (1982,1987) do not put much reliability on the ability of the wind data from Port Elizabeth (PE) Airport to represent the total wind field over Algoa Bay. Apart from the change in wind stress across the land/sea boundary, Schumann et al. (1991) found the wind to vary across Algoa Bay (Figure 6 and Figure 7). They also found that prevailing wind directions in Algoa Bay are parallel to the large-scale orientation of the coastline, namely west-southwesterly and east-northeasterly. These prevailing wind directions were also found by Schumann and Martin (1991), who analysed data collected from PE Airport over a 38 year period. The wind systems pass through Algoa Bay at periods of 2.6 days and 7 days (Schumann et al., 1991). Figure 8 shows the auto spectra of the major axis of wind and Figure 9 the coherency and phase.

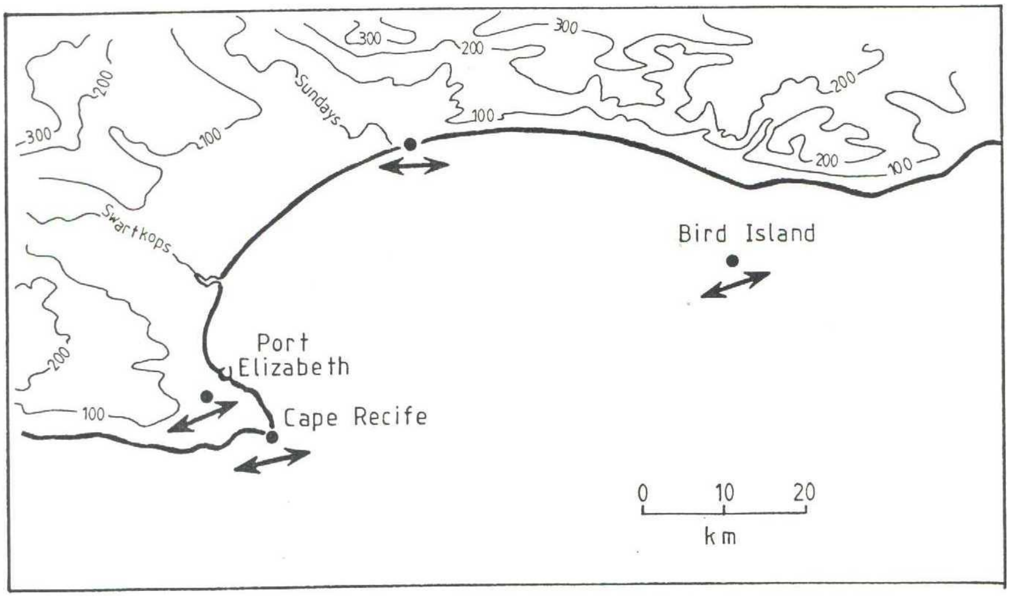


**Figure 6: A map showing the orientation of the major axes of wind parallel to the coastline at the four weather stations at Cape Recife, Port Elizabeth, Sundays River and Bird Island. Land contours are in meters. From Schumann et al. (1991).**

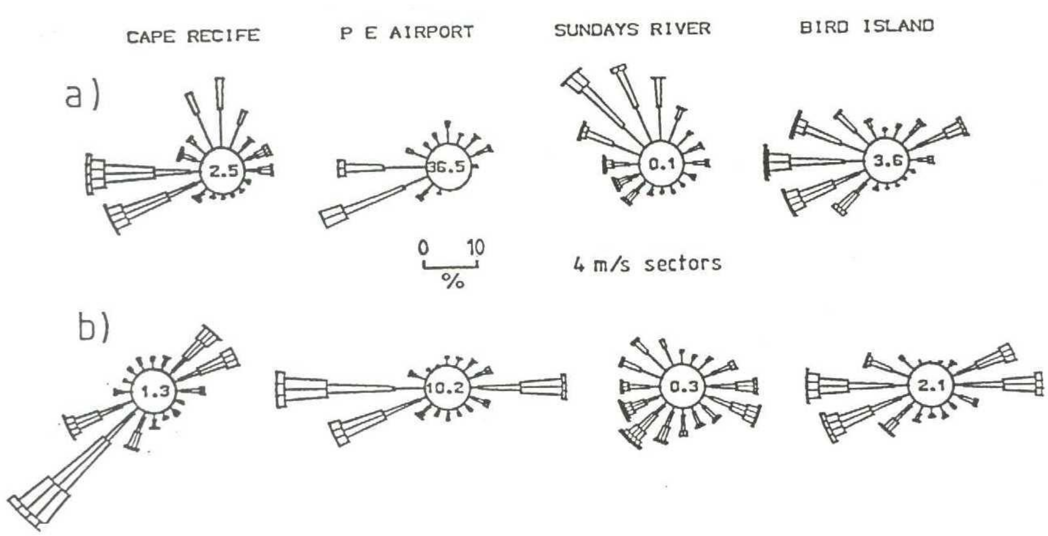


**Figure 7: Wind roses from hourly measurements made at Cape Recife, PE Airport, Sundays River and Bird Island during (a) May, June and July and 1987 (b) September, October and November 1988 by Schumann et al. (1991). The length of the radius in any direction gives the percentage occurrence on a given scale while the width gives the speed in 4 m/s bins. Values in the inner circle designate the percentage of winds less than 1 m/s (calms). From Schumann et al. (1991).**

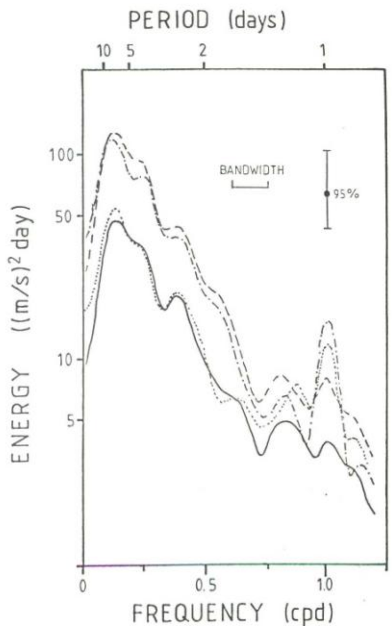


Figure 8: Autospectra of the major axes of wind measured at the four weather stations in Algoa Bay. Port Elizabeth Airport is shown by a solid line, Sundays River by a dotted line, Cape Recife by a dashed line and Bird Island by a line of dashed with two dots. The dominant peaks occur at about 7 and 2.6 days and are related to large-scale weather systems, while the diurnal land/sea breeze is also distinctly evident. After Schumann et al. (1991).

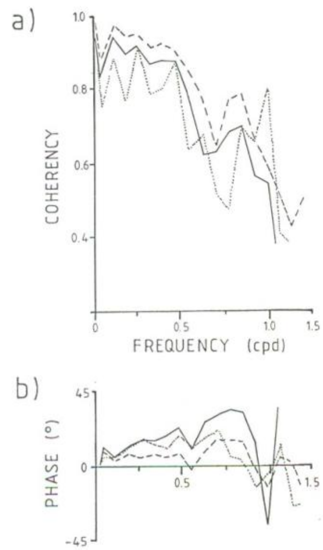


Figure 9: Coherency (a) and Phase (b) spectra for the major axes of wind. Bird Island is the independent variable while Cape Recife (dashed line), Port Elizabeth Airport (solid line) and Sundays River (dotted line) are the dependent variables. A positive phase indicates that the Bird Island station lags behind the other corresponding station. After Schumann et al. (1991).

## *3.3 Annual wind variability over Algoa Bay*

Schuman and Martin (1991) found that the westerly-component of wind dominated in speed and frequency throughout the year, while the easterly-component of wind varies considerably between seasons (Figure 10). Both northeasterly and southwesterly winds reached a maximum in speed and frequency during October and November and a minimum during May, June and July. The maximum average wind speed was 4 m/s for NE winds and 4.7 m/s for southwesterly winds during October.

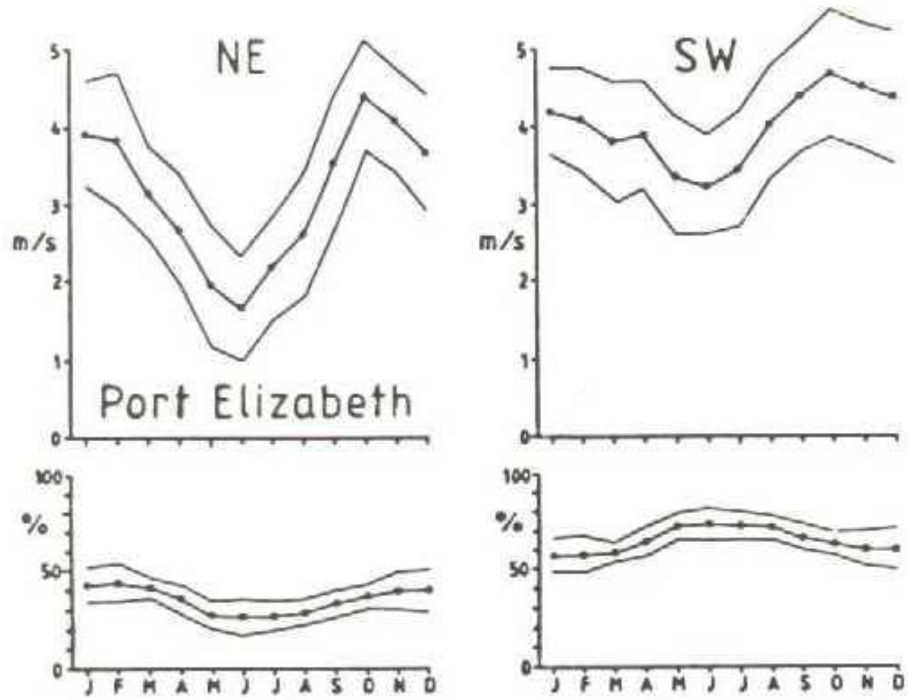


**Figure 10: Monthly variation of the mean major wind speed components at Port Elizabeth Airport. Northeasterly (NE) winds are on the left and southwesterly wind (SW) on the right. Standard deviations about the mean are indicated by the envelope lines. The bottom plot depicts the percentage occurrence of the two wind components through the year. From Schumann and Martin (1991).**

## *3.4 Interannual wind variability over Algoa Bay*

An analysis of over 38 years of wind data from PE Airport showed that there was a net change of -19$^{o}$ in wind direction from 1950 to 1982 (Schumann, 1992). See Figure 11. This -0.6$^{o}$ per year meant that the winds tended to blow from a more southerly direction year after year. Between 1982 and 1983 the wind direction changed back by more that 30$^{o}$ i.e. a large change towards a more northerly direction. The change back in wind direction appears to be linked to a very strong El Niño Southern Oscillation event in 1982/1983. However, there appeared to be no appreciable change in wind speed.

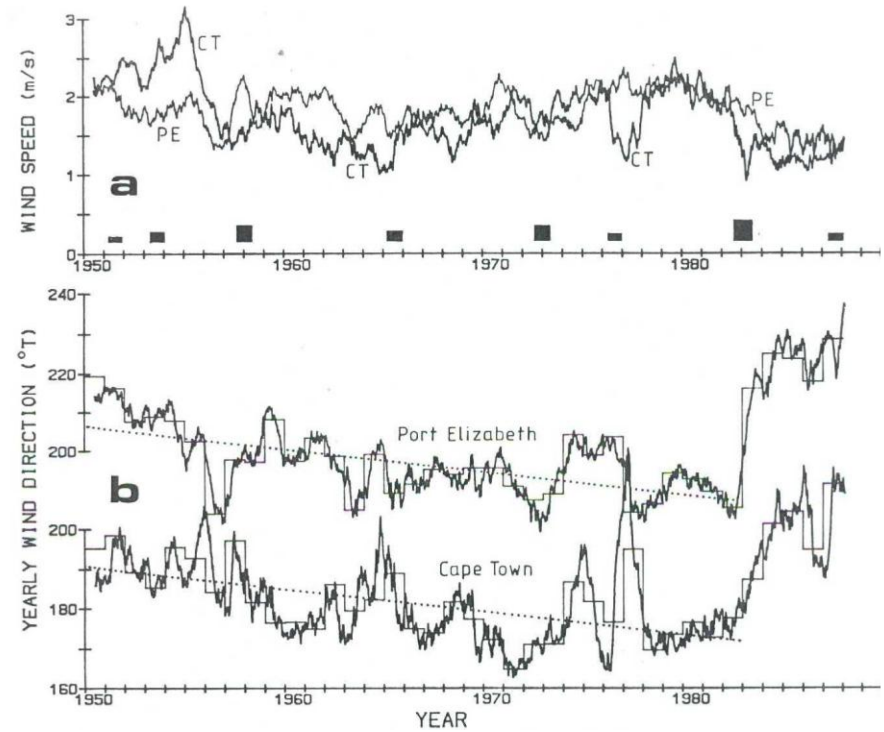


**Figure 11: Time series of (a) yearly mean wind speed and (b) wind direction at Cape Town and Port Elizabeth. The latter site has a slightly thinner line in the speed record. Evident is the sudden change in wind speed and direction at both sites after 1982. After Schumann (1992).**

## *3.5 The radiation budget of Algoa Bay*

Goschen (1991) analyzed the radiation budget over Algoa Bay. He found the incoming radiation to vary from about 350 W/m$^2$ during summer to about 140 W/m$^2$ during winter, while atmospheric radiation (317 W/m$^2$) and longwave radiation (90 W/m$^2$) were fairly constant throughout the year. During summer there was a net gain in heat by the atmosphere, while during winter there is a net loss of heat (Figure 12). Local air and sea temperatures were correlated with solar radiation over daily and annual cycles (Figure 13). These vertical heat fluxes were found to contribute to the sea temperature variability within the bay. Diurnal fluctuations in both air and sea temperatures are caused largely by solar radiation, but the subtidal variability are caused by both changes in atmospheric conditions and by the influx of water of a different temperature into Algoa Bay.

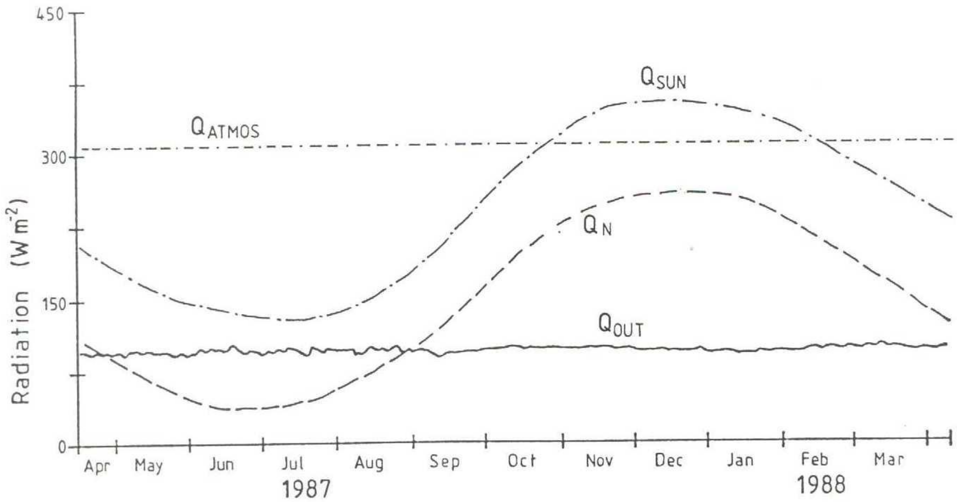


**Figure 12: The annual cycle of total radiation ($Q_N$), net radiation ($Q_{OUT}$), atmospheric radiation ($Q_{ATMOS}$) and incoming solar radiation ($Q_{SUN}$) over Algoa Bay between April 1987 and April 1988. After Goschen (1991).**

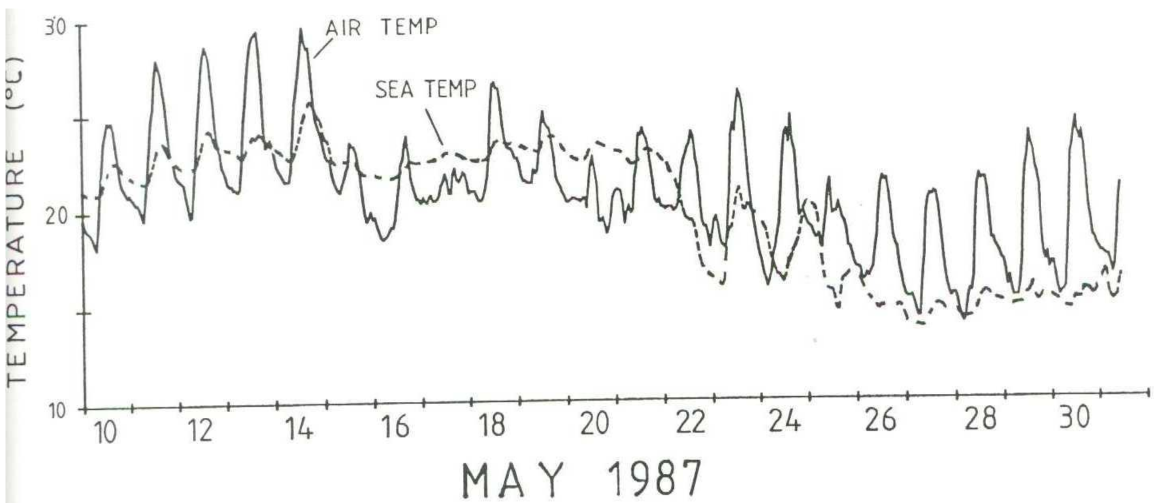


**Figure 13: A time series plot showing a close correlation between air and sea temperate during May 1987. The same close correlation was found over annual periods. After Goschen (1991).**

# 4 Tides, tidal currents and inertial currents

Table 1 lists the dominant semidiurnal and diurnal tidal constituents. The resultant tides around the South African coast are dominantly semidiurnal, with the tidal range generally falling into the microtidal category. In this classification (e.g. Carter, 1988), the spring tidal range is less than 2 m, a value which is rarely exceeded around South Africa.

## 4.1 Tidal and inertial currents around South Africa

Inertial currents occur as a result of the rotation of the Earth, and the relative position of an observer on such a rotating reference frame. In the southern hemisphere a parcel of water put into motion with no additional forces will move in a horizontal circle in an anticlockwise sense. The period of rotation is given by the inertial period $T_i$, where

$$T_i = 11.97/(\sin ø) \text{ hours}$$

where ø is the latitude (Pond and Pickard, 1983). This varies from 11.97 hours at the poles, 16.93 hours at $45^O$ latitude and infinity at the equator; in Algoa Bay it is 21.40 hours (0.0467 cycles/hr).

An early study of tidal and inertial currents around the coast of South Africa was undertaken by Schumann and Perrins (1982). They deployed current meter arrays near the shelf edge off the West Coast, on the Agulhas Bank south of Mossel Bay and offshore Port Edward on the Kwa-Zulu Natal coast. Analysis of the data was done using standard spectral analysis techniques described in Jenkins and Watts (1968) and empirical orthogonal mode (eom) analysis developed by Kundu et al. (1975) and extended by Wang and Mooers (1977).

Schumann and Perrins (1982) found that all sites exhibited energy peaks at the semi-diurnal and diurnal/inertial frequencies, as well as in the lower frequencies (Figure 14). However, the influence of the fast flowing Agulhas Current on the east coast and the more sedate Benguela Current on the west coast meant that there were large differences in the energies of these currents.

**Table 1: The main diurnal and semi-diurnal tidal constituents. The amplitude is given relative to the dominant $M_2$ tidal constituent From Carter (1988).**

| | Tidal Symbol | Description | Period (hours) | Frequency (cycles/hr) | Relative Amplitude |
|---|---|---|---|---|---|
| Diurnal | $O_1$ | Principal lunar | 25.82 | 0.0387 | 41.5 |
| | $P_1$ | Principal solar | 24.07 | 0.0415 | 19.3 |
| | $K_1$ | Lunisolar declinational | 23.93 | 0.0418 | 58.4 |
| | | | | | |
| Semi-diurnal | $N_2$ | Elliptical to $M_2$ | 12.66 | 0.07900 | 19.1 |
| | $M_2$ | Principal lunar | 12.42 | 0.0805 | 100.0 |
| | $S_2$ | Principal solar | 12.00 | 0.0833 | 46.6 |
| | $K_2$ | Lunisolar declinational | 11.97 | 0.0835 | 12.7 |

On the wide Agulhas Bank the tidal and inertial energy peaks were very sharp and had higher spectral energy in comparison to the lower frequencies. The anti-clockwise spectrum dominated the clockwise spectrum, meaning that the current fluctuations were not linearly polarized. On the west coast the anti-clockwise spectrum also dominated, but most of the current fluctuations at the tidal and inertial frequencies contribute a major portion to the energy. In contrast, on the narrow shelf of the east coast, fluctuations of longer period associated with the Agulhas Current dominated the energy spectrum, and the tidal and inertial currents are relatively unimportant.  Here, the clockwise and anticlockwise spectra are more aligned. Modal analysis (eom) indicated that the tides are primarily barotropic and the inertial fluctuations mainly baroclinic. As expected from Kelvin wave propagation, there were indications that tidal currents propagate from west to east around South Africa (Figure 15).

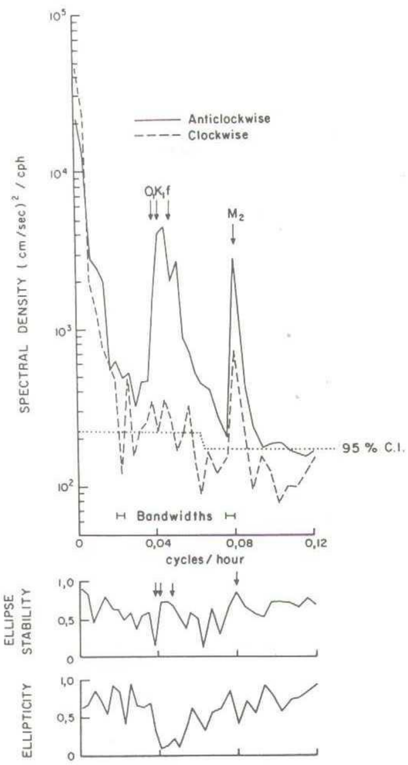


Figure 14: Clockwise and anticlockwise spectra and ellipse stability and ellipticity for the measurements taken at the topmost meter (depth 38 m) at a site south of Mossel Bay on the outer Agulhas Bank. From Schumann and Perrins (1982).

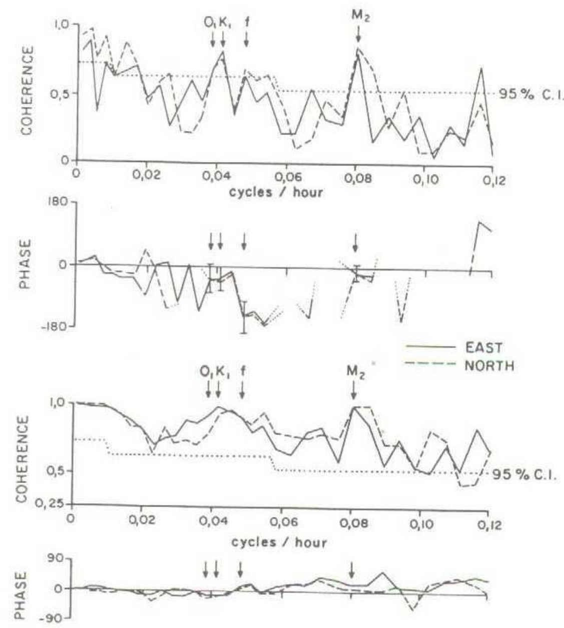


Figure 15: Coherence and phase between the east and north current components at the same site south of Mossel Bay. From Schumann and Perrins (1982).

## 4.2 Tides in Algoa Bay

Algoa Bay is located on the far eastern Agulhas Bank, approximately midway between the south and east sites of Schumann and Perrins (1982). Although the shelf width off Algoa Bay is approximately 50 km, ocean circulation and structures in the bay are partly, and frequently, influenced by the Agulhas Current (Goschen and Schumann, 1990, 1994; Schumann et al., 2005). Thus, it is expected that the current fluctuations in the semi-diurnal and diurnal/inertial frequencies in Algoa Bay will be a compromise between the two sites. This was shown to be the case by Schumann et al. (2005), in an analysis of 6 current meters deployed in the shallower reaches (< 30 m) of Algoa Bay at sporadic intervals between 1989 and 1995. The mooring sites are shown in Figure 16. They found a strong energy peak at the $M_2$ semi-diurnal period at all sites (Figure

17). Inertial currents were also present at all sites, although to a lesser degree in the shallower and sheltered areas of the bay. Substantial current fluctuations occurred at longer periods, especially in the deeper regions of the bay, which were attributed to Agulhas Current influences.

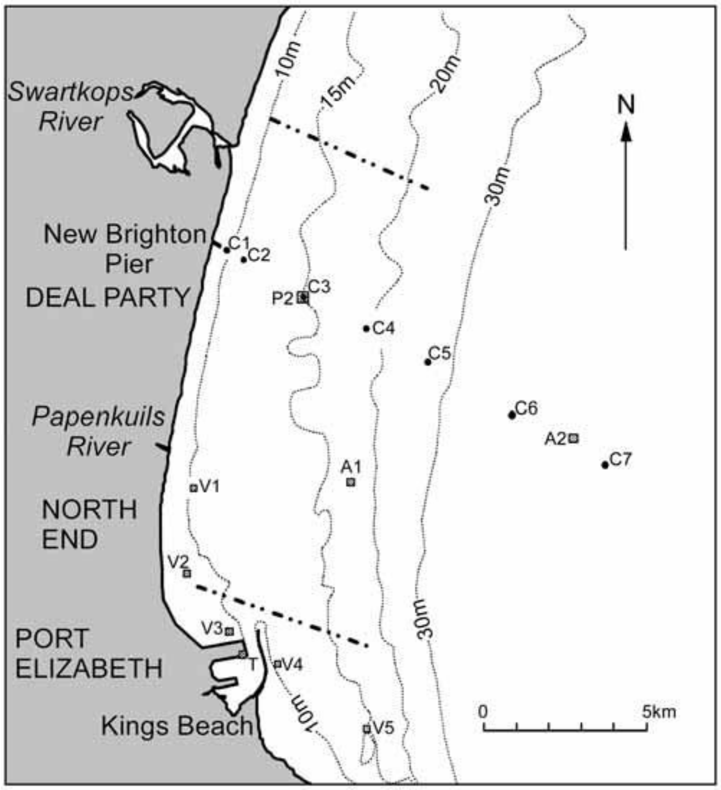


**Figure 16: Current and sea temperature mooring and profiling stations in the western sector of Algoa Bay used by Schumann et al. (2005). The current/temperature moorings are labeled V1 to V5, A1 and A2, and P2. The line off New Brighton Pier is labeled C1 to C7. From Schumann et al. (2005).**

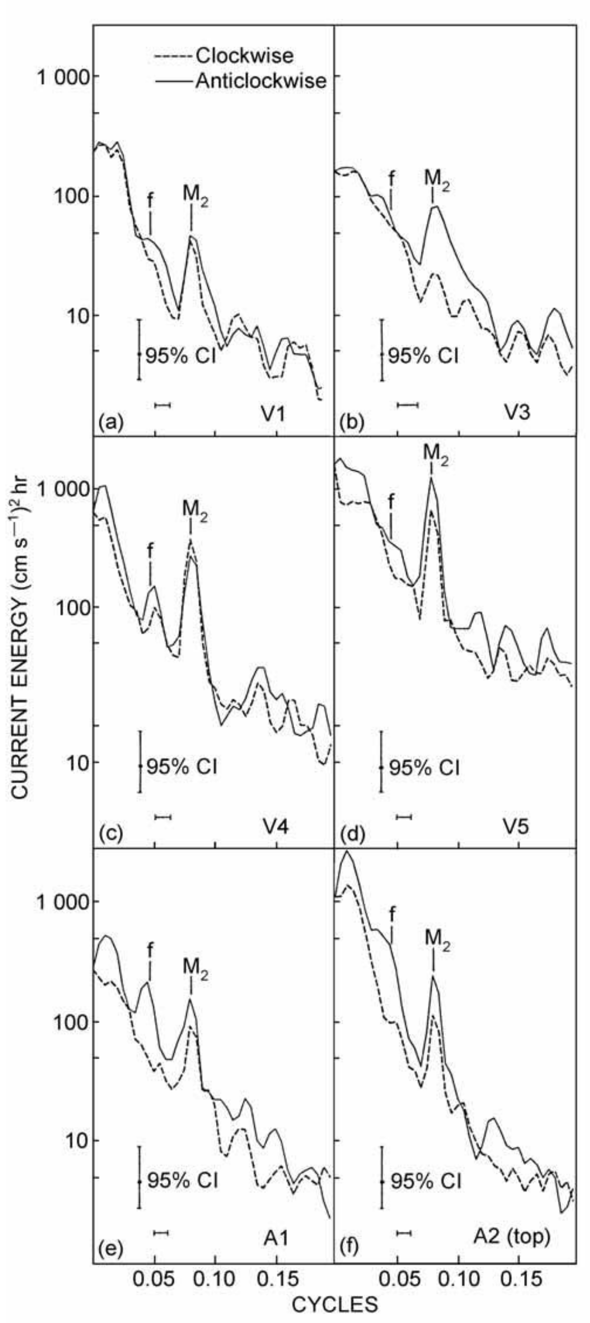


**Figure 17: Clockwise and anticlockwise rotary spectra from moorings deployed at the sites depicted in Figure 16: (a) from the deployment at position V1, (b) from the second deployment at V3, (c) from V4, (d) from V5 and (e) and (f) from A1 and the shallower meter at A2 respectively. The $M_2$ tidal peak, as well as the inertial period (f = 21.4h) for the latitude of Port Elizabeth (34°S), are shown. From Schumann et al. (2005).**

# 5 Sea temperature

## *5.1 Introduction*

Temperature structures over the wider region of the Agulhas Bank are well documented by Schumann and Beekman (1984) and Swart and Largier (1987). In Algoa Bay and over the adjacent continental shelf the vertical and horizontal temperature structures were investigated by Goschen and Schumann (1988). They based their results on one extensive cruise and the results may only be representative of that particular cruise period. Some shelf water column structure was described by Goschen and Schumann (1990), but this was interpreted from the point of view of an Agulhas Current intrusion. Prior to that temperature measurements had been made in connection with the summer upwelling centres of Woody Cape and Cape Recife (Schumann et al., 1982; Beckley, 1983, 1988; Schumann et al., 1988), but these in situ physical measurements were scattered around Algoa Bay at isolated positions and had record lengths of less than a year. Schumann et al. (2005) obtained results from moored current meters water and a line off New Brighton Pier (Figure 16), both to a depth of less than 40 m. Apart from these specific studies, over the years many Sea Fisheries and Marine and Coastal Management (MCM) cruises traversed a line off Algoa Bay (e.g. Boyd et al., 1992) but the results were (and are still) never analysed with the intention of furthering the knowledge on the dynamics of Algoa Bay, but rather formed part of a larger study to support large scale fisheries management.

## *5.2 Agulhas Bank*

The vertical temperature structure over the Agulhas Bank varies with season. A strong thermocline develops in the summer with temperature changes of 10 °C over a depth of 20 m being fairly common (Schumann and Beekman, 1984). Schumann and Beekman (1984) also showed that the thermocline is well defined close towards the coastline, but decreases further out. Swart and Largier (1987) investigated the structure of the thermocline over the Agulhas Bank in some detail.

Schumann and Beekman (1984) suggest two reasons for the formation of an intense thermocline during summer and its dissolution during winter. Firstly, the surface waters are heated directly by the solar radiation to a much greater extent during summer months than during winter. If there is no mechanism to induce mixing, the heated upper layers will lead to the formation of intense thermoclines. Secondly, while westerly wind conditions occur in all seasons, extreme westerly winds are most likely to occur in winter. Under unstable conditions (sea surface temperature greater than air temperature) the effective stress exerted by a given wind is considerably increased (Gill, 1982). This is most probably the case in winter and suggests that, with westerly winds, the resulting vertical mixing can break down the thermocline established in summer. Pugh (1982) confirmed the effects of wind while studying the seasonal change in thermal structure on the Agulhas Bank. The far eastern Agulhas Bank (offshore Algoa Bay) was investigated by Goschen (1988, 1991) who found that the thermocline was also present all year round, although its intensity varied (Figure 18). During summer the mixed layer was between 20 m and 30 m depth while during winter it was about 60 m depth (Figure 19).

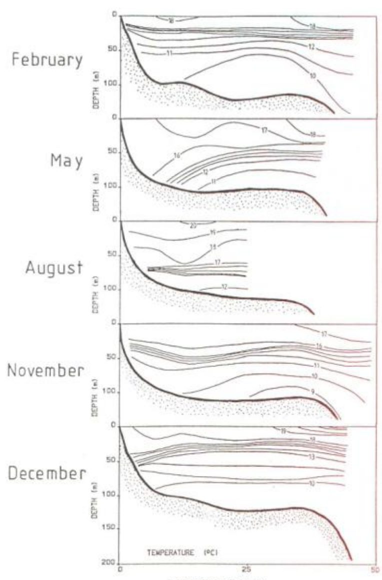


**Figure 18: Seasonal variation in the sea temperature structure measured off Cape Recife during five cruises. The sections during both winter (actually autumn and spring) and summer show a thermocline present over the shelf of the far eastern Agulhas Bank, although its intensity varied. From Goschen (1991).**

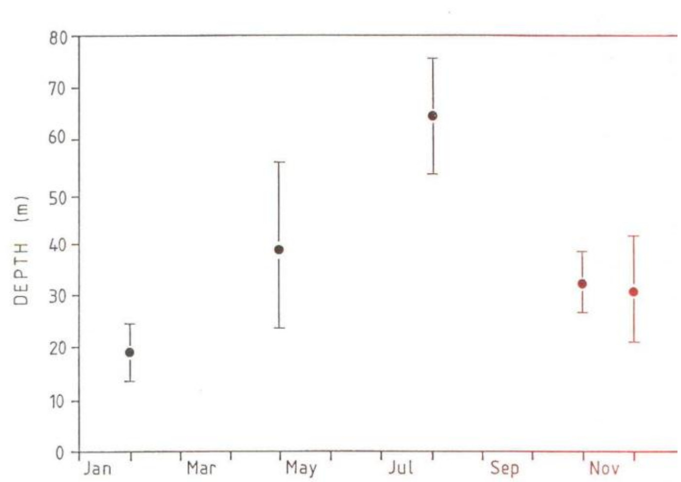


**Figure 19: The variation in depth of the surface-mixed layer over an annual period. The values were calculated by averaging the depth of the mixed-layer observed at each station during a five cruise study period. Standard deviation bars are shown. The mixed layer was shallow during summer (20m – 30m) and deeper during winter (60 m). From Goschen (1991).**

## *5.3 Algoa Bay*

Beckley (1983) showed the existence of the seasonal varying thermocline around the area of Cape Recife. The thermoclines are enhanced by cold water upwelling over the shelf edge which forms a cold base layer, while the intrusive plumes of the warmer surface waters of the Agulhas Current replenishes the surface layers (Swart and Largier, 1987). Intense thermoclines are established in summer in the deeper sections of the bay, with more isothermal conditions in winter (Schumann, et al., 2005). Figure 20 shows the variation of the thermocline over a six month period in the western sector of Algoa Bay. During summer in Algoa Bay Schumann, et al. (2005) found the thermocline to be deeper than about 15 m with fairly intense gradients of up to 3 °C/m

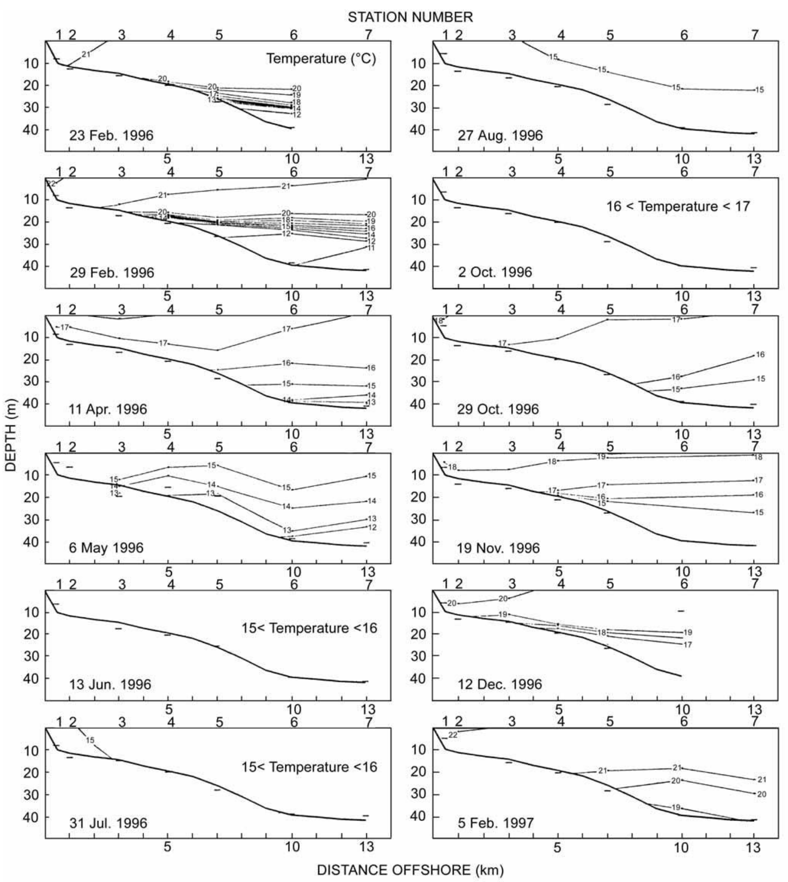


**Figure 20: Temperature sections from a line off New Brighton Pier (about 10 km north of Port Elizabeth harbour, Figure 16) during 12 cruises between February 1996 and February 1997. Clearly shown is the development of a strong thermocline in summer and its dissolution in winter. From Schumann et al. (2005).**

## *5.4 Spatial variability across Algoa Bay*

Goschen (1991) found seasonal differences in sea temperatures across Algoa Bay (west to east) and suggested that the main mechanism is due to the seasonal changes in the frequency and intensity of upwelling associated with the capes. The surface and sub-surface temperature structures vary seasonally across Algoa Bay in response to the seasonal changes of the “upwelling centres” from one side of the bay to the other. The summer upwelling events reduce the mean daily surface temperatures in the northeastern region of Algoa Bay (Woody Cape/Cape Padrone) while during winter the predominantly southwesterly winds lower the mean temperatures in the southwestern section of Algoa Bay because of replacement flow of cooler bottom waters when the surface waters are driven offshore. Consequently the surface waters of the southwestern regions of Algoa Bay are warmer in summer and colder in winter than the northeastern side. Locally, these changes are ultimately dependent on seasonal changes in the dominant wind field

# 6 Salinity

The rivers flowing into Algoa Bay input minor amounts of fresh water, as do the freshwater outfalls such as the New Brighton Pier outfall pipeline. Roberts (1990) and Schumann et al. (2005) found that the freshwater influence was constrained in the upper few meters of the water column and usually dispersed within 2 km of the outfall, and were usually short-lived. Schumann et al. (2005) intercepted a 120 mm downfall event in the catchments of the Swartkops River and found it did not have much effect on the salinity of Algoa Bay and the effect was short lived. From that they also surmised that even a major flood would have a restricted and transient influence. In the western sector of Algoa Bay the seawater salinity values generally stay around the oceanic average of about 35.2 and there was limited variability in the bay (Schumann, 1998).

# 7 Nutrients

Goschen and Schumann (1988) took measurements of silicates and nitrates in the Algoa Bay area during a phys-chemical cruise undertaken in 1986, and found good correlation with the temperature structures. The surface structures of both silicates and nitrates around Cape Recife revealed relatively high concentrations (nitrates are shown in Figure 21), which would correspond to the coastal wind-driven upwelling associated with the cape (see Chapter 9). Off the Cape Padrone area there were high concentrations over the outer shelf and shelf edge, which is likely to have originated in upwelling along the Agulhas Current inshore edge (see Chapter 10). The isoclines shoal upwards along the inner edge of the Agulhas Current from the abyss onto the continental shelf. Similar structures and range of values were found by Lutjeharms et al. (2000) off Port Alfred and further north.

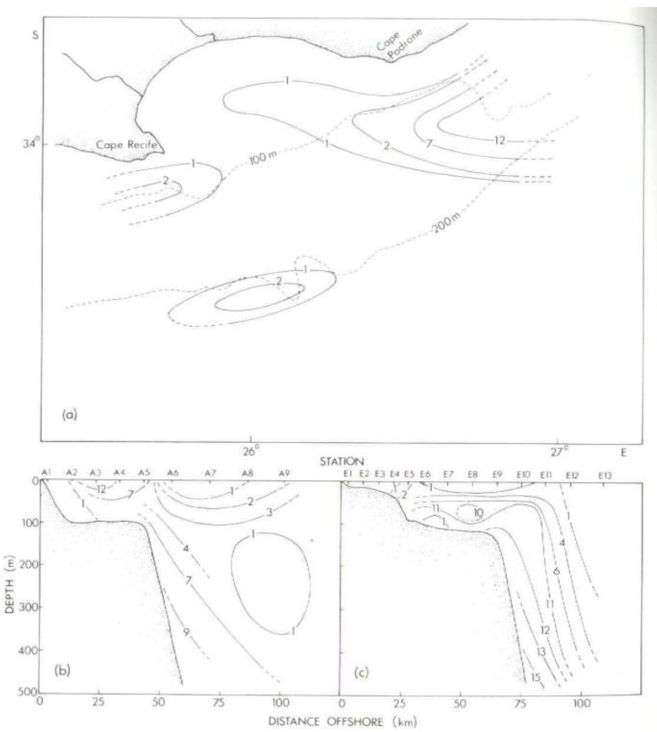


**Figure 21: Distribution of nitrate in µmol/l (a) at the surface, (b) a line off Cape Padrone and (c) a line off Cape Recife. Note how high concentrations of nitrates are found over the continental shelf near the shelf break and around Cape Recife, in areas known for wind driven and shelf edge upwelling. The isoclines slope upwards from the abyss at the shelf edge. From Goschen and Schumann (1988).**

# 8 Ocean Currents

## *8.1 Algoa Bay surface currents*

An early study by Tripp (1977), in an analysis of ships drift data between Bird Island and Port Elizabeth, came to the conclusion that eastward component currents were almost always in a downwind direction, whereas this was not always true for westward currents. Harris (1978) analysed results obtained both by drift cards and tracked floats released in Algoa Bay and ships drift data obtained by Tripp (1977). His results also showed the surface flow to be generally in the direction of the wind, parallel to the coastline. Exceptions occurred, as was found by Tripp (1977), during a southwesterly or south-easterly wind when the current pattern was then either northward-eastward or south-westward. However, north-eastward currents were about twice as frequent as south-westward currents, signifying a definite net surface drift towards the northeast. Lutjeharms et al. (1986), using surface drift cards, confirmed the dominance of longshore surface currents. They also pointed out the influence of wind on surface currents in Algoa Bay, in contrast to the dominance of the Agulhas Currents to the north of Algoa Bay. They found speeds of between 0.2 m/s and 0.4 m/s. However, drift cards float in the upper centimetre or so of the ocean and thus come under the direct influence of the wind; they do not necessary give an indication of currents over the whole water column.

## *8.2 Currents in Algoa Bay and over the continental shelf*

Current structures in Algoa Bay, and extending into the Agulhas Current, were later investigated by Goschen and Schumann (1988). Their results were based on vertical profiles taken during a single cruise, from which the Eulerian nature of the measurements allowed little interpretation of the components that made up the observed motion. It was known, however, that wind stresses are the major forcing mechanisms of water movement in the coastal region (Winant, 1980; Gill, 1982) and this was the conclusion reached by Goschen and Schumann (1988). They also found predominantly barotropic motion in a downwind direction that was influenced by coastline shape and other topographic irregularities. However, the cruise took place during predominantly southwesterly winds and the conclusions could only apply to that wind regime. The number of cruises analysed was extended to five by Goschen (1991), but unfortunately southwesterly winds prevailed during all the cruises (except for one northeasterly blow at the beginning of one cruise), but in all cases the conclusions supported those found by Goschen and Schumann (1988). However, from a current meter mooring in about 40 m depth, Schumann et al. (2005) found a dominant south-westward flow, which indicated that the Agulhas Current could be important in entraining water from the central areas of Algoa Bay.

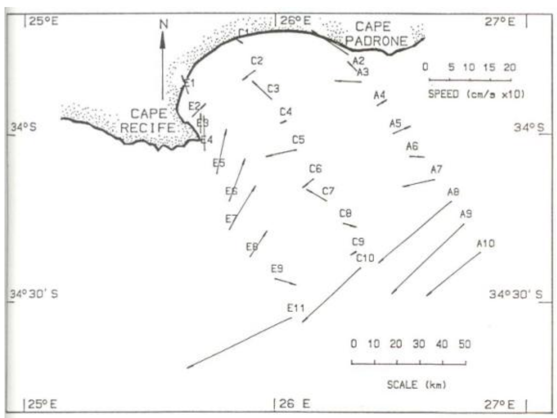


**Figure 22: Surface currents (10 m) measured during a cruise undertaken in February 1989. The lines were completed in order A, C and E. Transect C was sampled during an easterly-component wind and the surface currents were predominantly westwards, while transect E was sampled immediately after a westerly-component wind and the currents were predominantly northeastward. From Goschen (1991).**

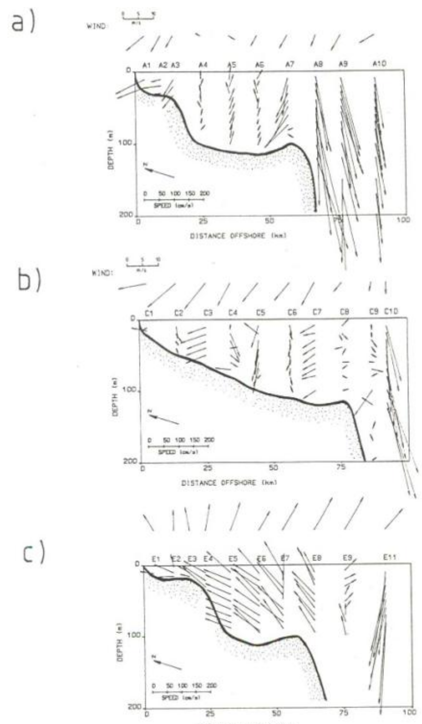


**Figure 23: Vertical structure of currents in and offshore of Algoa Bay measured along (a) line A, (b) line C and (c) line E. The currents over the shelf were generally barotropic, while the flow of the Agulhas Current is evident seaward of the shelf edge. The current and wind are oriented relative to the north arrow in the bottom left hand corned of each transect, so that a flow perpendicular to the orientation of the sampling line will point up- or downwards relative to the page. From Goschen (1991).**

## 8.3 Shallow water currents north of PE harbour

Roberts (1990) undertook a study to investigate the nearshore circulation patterns in the western sector of Algoa Bay in order to understand the dispersion of effluent and contaminated water from the Papenkuils Canal and the Fishwater Flats Water Reclamation Works outfall at the New Brighton Pier. His results were based on the interpretation of hydrodynamics information obtained from past studies, satellite imagery, drogue and dye studies under the dominant wind conditions. It must be noted that his in situ measurements were only made in the nearshore region off the Papenkuils Canal. Nevertheless, he came to the following conclusions for different wind regimes:

**Southwesterly wind**

During the dominant southwesterly wind, in general the surface waters of Algoa Bay, from breaker zone to the outer confines of the bay, flow downwind in a northeasterly direction (Figure 24). In the vicinity of the Papenkuils Canal the flow through the water column is almost parallel to the shoreline. Surface currents reach speed of between 0.1 m/s and 0.15 m/s down to depths of about 4 m. This surface velocity increases with distance offshore, reaching velocities of up to 0.5 m/s further out in the bay.

**Northeasterly wind**

The northeasterly winds increase in strength and duration during the summer months. The surface flow pattern set up by the northeasterly wind results in complex patterns, as is shown in Figure 25. In the deep reaches of Algoa bay, away from the influence of the PE harbour structure the currents are dominantly southwards. However, along the shoreline swift longshore currents (0.3 m/s to 0.5 m/s), caused by onshore surface drift and shoaling waves are obstructed by PE harbour, and form cyclonic eddies on both the north and south sides, the eddy to the north being smaller than the one to the south.


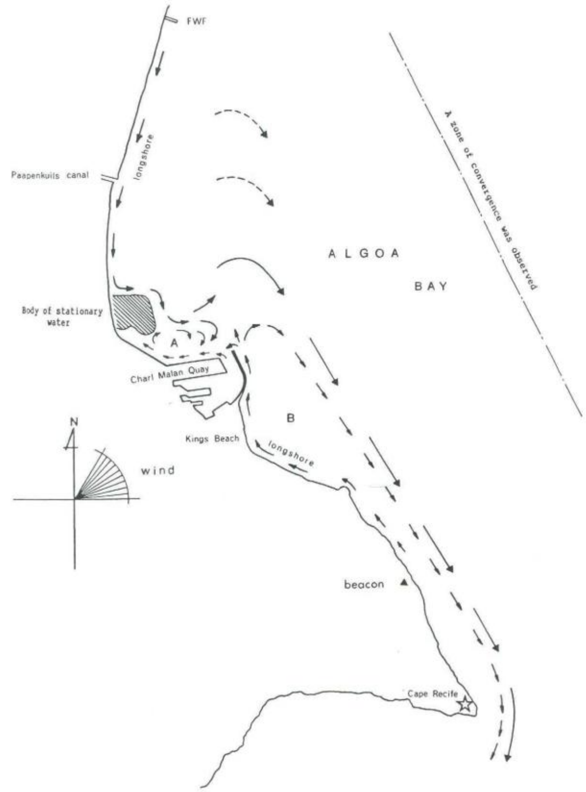


**Figure 24: A conceptual model of the surface flow in the western bight of Algoa Bay during southwesterly winds. From Roberts (1990).**

**Figure 25: The nearshore surface circulation associated with the northeasterly wind. The circulation pattern was inferred from sediment trails in aerial photographs. From Roberts (1990).**

## Northwesterly wind

The northwesterly wind is a land breeze that blows mainly during the night and seldom exceeds 7 m/s. It is predominant over the low lying coastal areas, such as the Swartkops valley. These winds generate a large number of slack water with surface velocities between 0.05 m/s and 0.07 m/s and result in complex dynamics by the interaction with residual flow. The residual flow is confined to the bottom layers (> 2 m) while the wind responsive surface layers (top 0.5 m) generally flows towards the south. See Figure 26.

## Southeasterly winds

Southeasterly winds usually occur in winter and are light breezes (< 7 m/s), and as such only influence the top 2 m of the nearshore water column. Its main effect is to create north going surface currents with strong onshore components, but with weak velocities (< 0.05 m/s). These currents could reverse the southward flow in the upper layers off Papenkuils caused by the northwesterly winds (Figure 26).

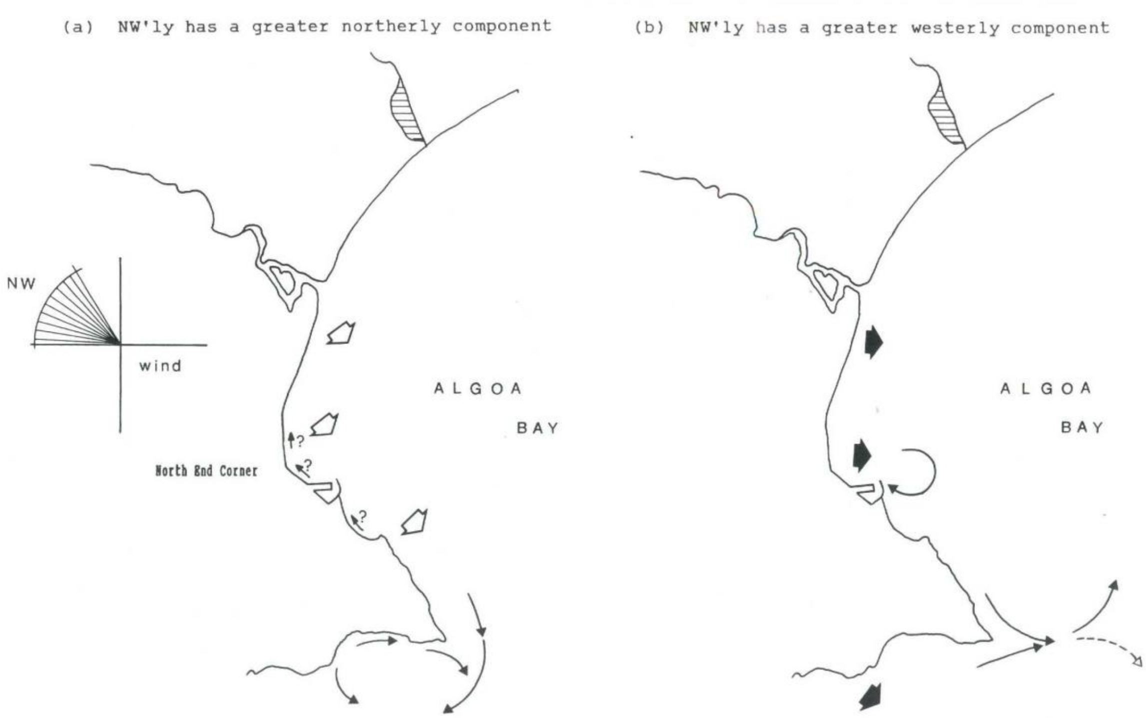


**Figure 26: Surmised circulation pattern during (a) northwesterly wind with a greater northerly component and (b) northwesterly wind with a greater westerly component. Derived from satellite imagery, there appears that two nearshore circulation patterns exist. From Roberts (1990).**

## *8.4 Currents in the western sector of Algoa Bay and around PE harbour*

More recently ocean variability in the western sector of Algoa Bay was investigated by Schumann et al. (2005) with data gathered over several projects between 1989 and 1998 (Figure 16). They used measurements from moored vector averaging current meters (VACM), arrays of underwater temperature recorders (UTR) and conductivity/temperature/depth (CTD) profiles taken at boat stations along several lines. Although the study extended over a period of 10 years, seldom did measurements correspond over the same time period long enough for comparisons to be made. Thus they concentrated on describing the general mechanisms forcing the ocean circulation and structures in that section of Algoa. They found that marked variability occurred over spatial scales of kilometers and over time scales of days. Average current speeds close to the coast were generally low, increasing further offshore, although they found substantial variability. Schumann et al. (2005) measured currents close to the coast to be between 4 cm/s and 8 cm/s, and even at depths of about 40 m the average speeds were < 10 cm/s. However, speeds in excess of 20 cm/s are not uncommon and, though calms were common at the inshore sites, virtually no calm periods occurred at the deeper stations, indicating substantial variability at a range of scales. The currents around the harbour were aligned with the shoreline orientation but further out there were dominant southwesterly flows (Figure 27).

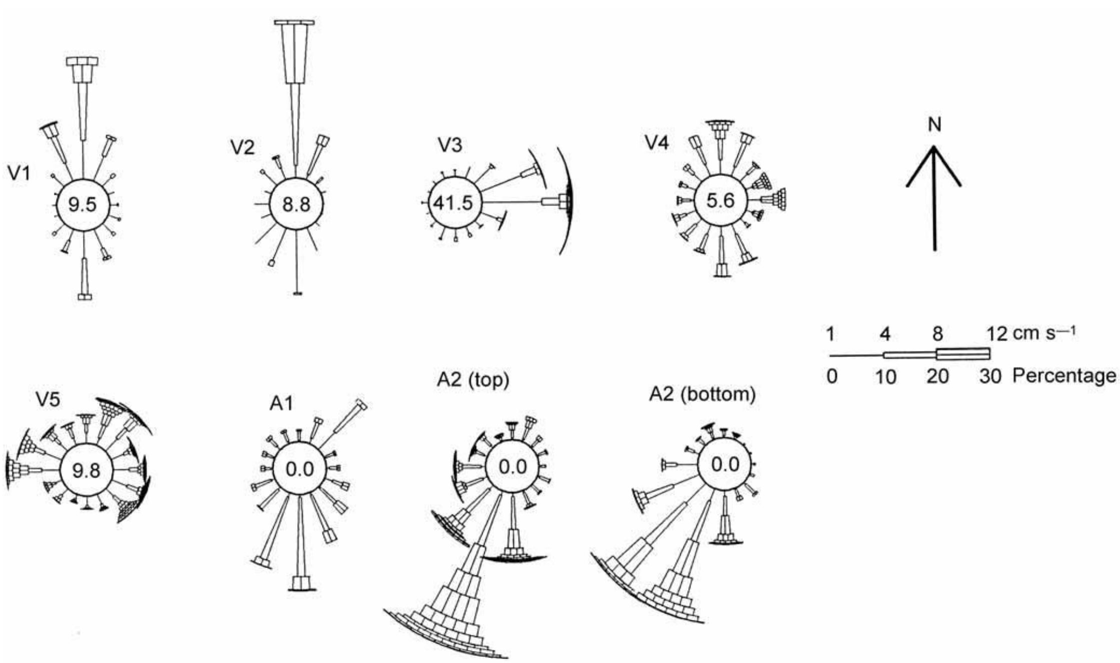


**Figure 27: Current roses from the moorings deployed at the sites depicted in Figure 16. Percentage occurrence is given by the length of the line, with speed on the given scale. Direction is in the oceanographic sense. Percentage calms is given in the centre circles. From Schumann et al. (2005).**

Schuman et al. (2005) found that there was little visual and statistical correlation between wind and currents at the inner sites of V1 and V4 around PE harbour (moorings depicted in Figure 16). Wind forcing thus appeared to play a minor role in the generation of these currents. Moreover, there was little correlation between sea-level and currents, leading them to conclude that coastal trapped waves were not important in the generation of currents in Algoa Bay (Figure 28).

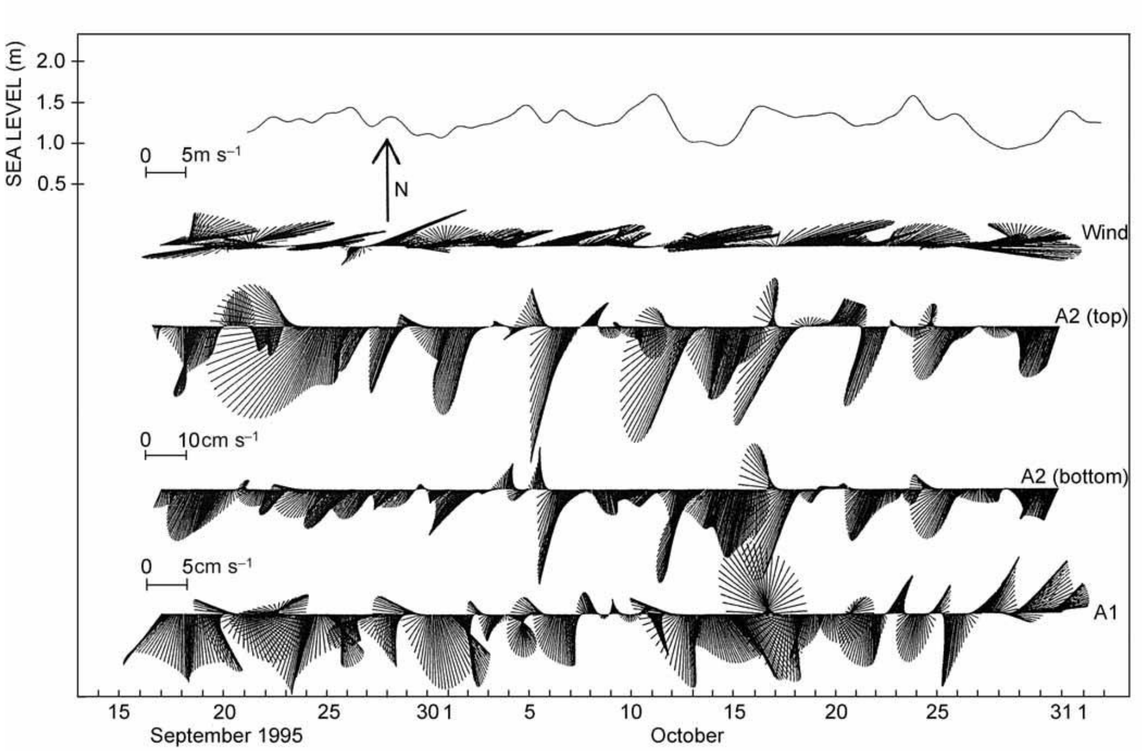


**Figure 28: Time-series of sea level from Port Elizabeth Harbour, wind vectors from Port Elizabeth Airport and current vectors from the mooring sites V1 and V4.**

The data from the same five VACM moorings used by Schumann et al. (2005) have recently been re-analyzed in a study to look at cases (three) where deployments from at least two moorings correspond in time. Initial conclusions are that wind does play a role (although undetermined) in driving shallow-water currents around PE harbour. During one period there is evidence that a large meander in the Agulhas Current overrode local wind driven effects. The study confirmed that, generally, the nearshore currents tended to follow the local bathymetry and orientation of shoreline and harbour walls, and that oscillation of wind along its major axis correlated fairly well with longshore currents, while cross-shore currents were out of phase with wind, although this was not always the case. Sea temperatures recorded at all moorings during all three studies were very well correlated, which implied that the water moved in unison around PE harbour, although not always evident from the current data. Off the North Sea Wall of PE harbour the currents were predominantly eastwards, aligned with the sea wall that is at almost right angles to the local shoreline (Figure 29, Figure 30). However, currents to the north of PE harbour either flowed northwards or southwards; this gives evidence for convergent/divergent flow and the possible formation of an anti-cyclonic eddy to the north of PE harbour under certain circumstances. This was much the same as the circulation patterns described by Roberts (1990). The evidence for an eddy is further supported by the generally lower sea temperatures off the North Sea Wall.

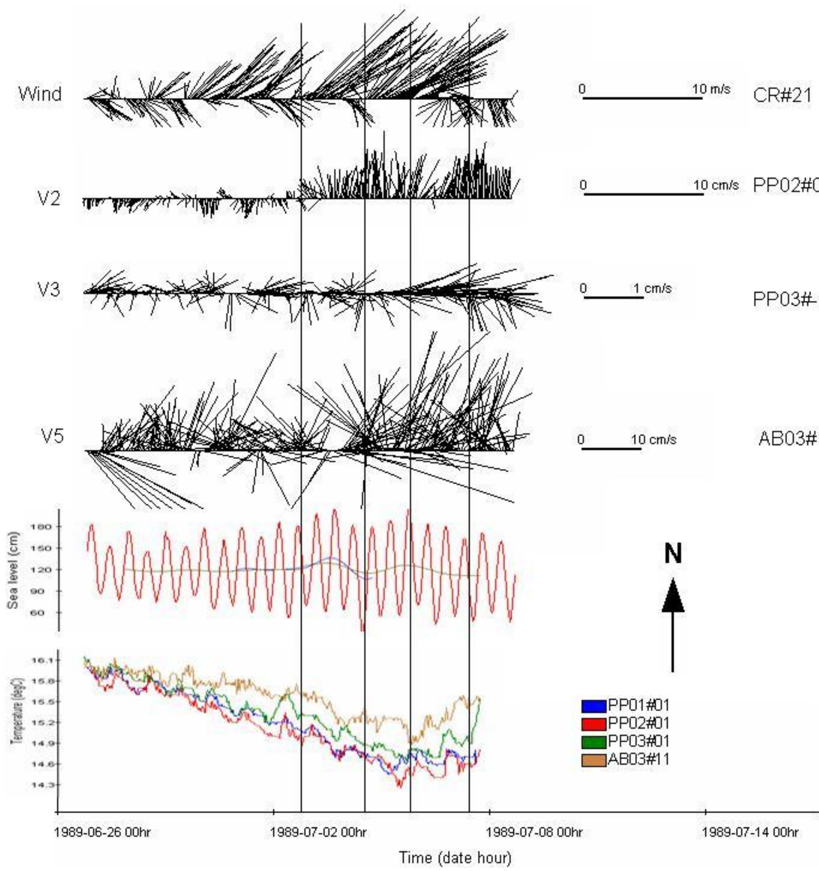


**Figure 29: Hourly winds, currents, sea level and sea temperatures from a study undertaken during August 1989. Wind was measured at a weather station on the point of Cape Recife and hourly currents during deployments V2, V3 and V5 (see Figure 16). Great variability is shown in the currents, but generally an increase in wind increased the current speeds and aligned the currents to the wind direction and local shoreline orientation.**

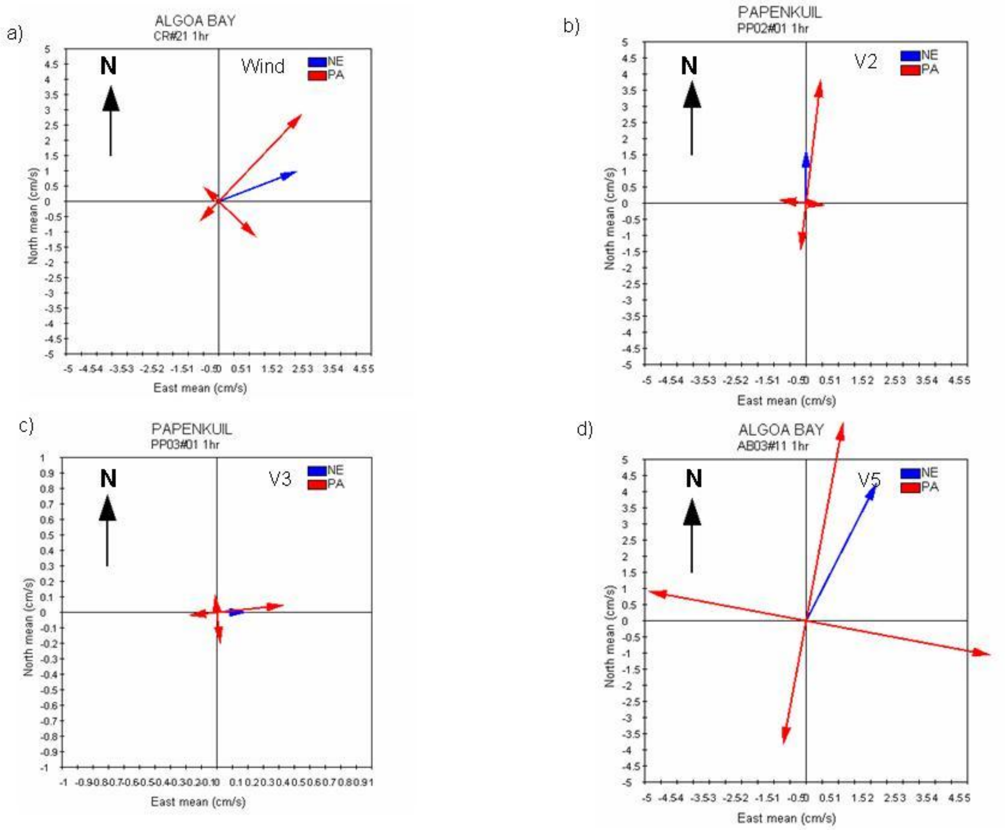


**Figure 30: Major and minor axes of wind (a) and currents at V2 (b), V3 (c) and V5 (d) from a case study shown on Figure 29. With a southwesterly wind the currents off North End were northwards, the currents of the North Sea Wall were eastward and the offshore mooring showed variable currents. This is a situation of divergence in the area immediately north of PE harbour.**

## *8.5 Currents in the shallow eastern sector of Algoa Bay*

Roberts (2010) deployed an ADCP (acoustic Doppler current profiler) over an 8 month period and did boat-based ADCP surveys in the nearshore region (5 - 25m depth) off the Alexandria Dune Fields, between Sundays River and Woody Cape. He found predominantly longshore currents with either an eastward or a westward flow through the water column. At times a baroclinic structure was present, with surface currents moving in the opposite direction to bottom currents. Average velocities were 17.6 cm/s for surface currents and 10.8 cm/s for bottom currents, with the frequency of eastward flow almost equal to westward flow (56% vs 47% respectively). Roberts (2010) found good correlation between wind and currents, which indicated wind to be the primary force of currents in the nearshore eastern Algoa Bay region (Figure 31). This was in contrast to the weak correlation between wind and currents found by Schuman et al. (2005) in the western sector of Algoa Bay.

Roberts (2010) also found that currents and sea temperatures were influence by a warm-water plume from the Agulhas Current that entered Algoa Bay, and that water temperatures decreased with the influx of cold upwelled water originating from the Port Alfred area. Rip currents, as described by Talbot and Bates (1987a, b), were also given as contributors to the variability of currents.

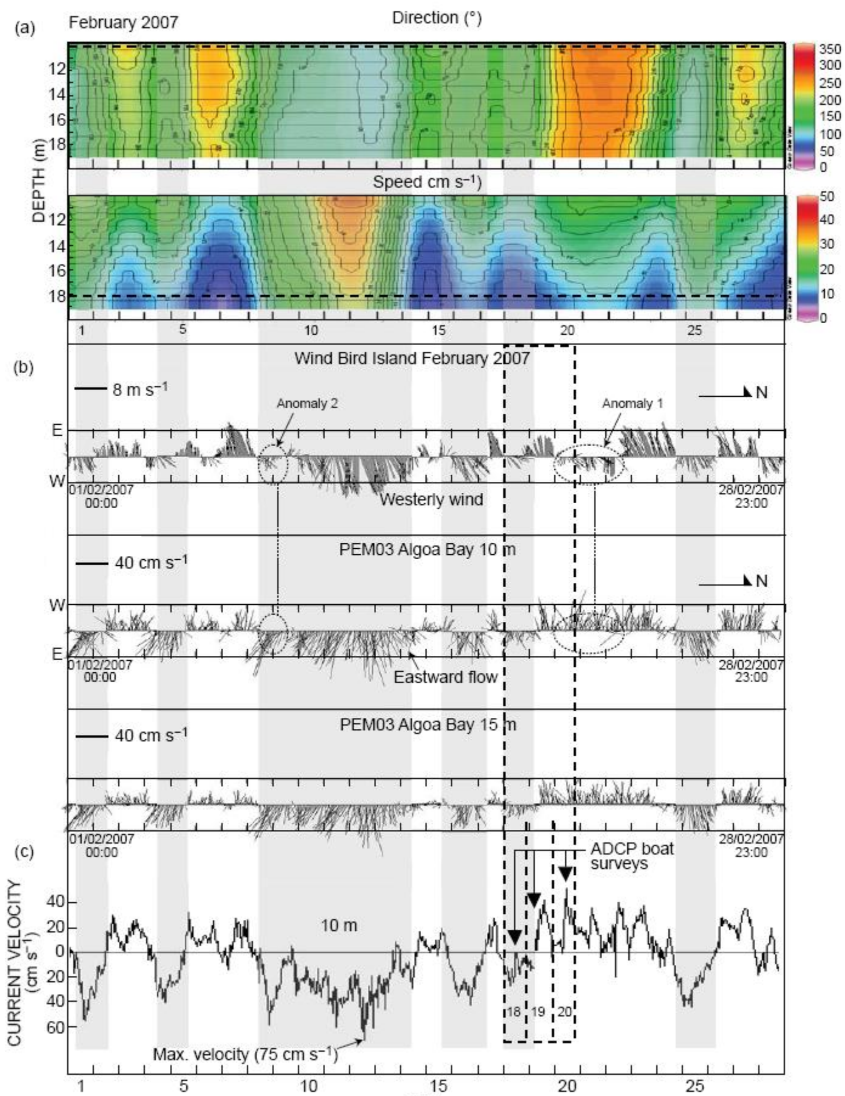


**Figure 31: ADCP mooring data collected at a nearshore site between Sundays River and Woody Cape (21 m depth) in February 2007: (a) direction and velocity plotted as a function of depth, (b) flow data for the 10 m and 15 m depths correlated with wind and (c) longshore velocity for the 10 m layer. From Roberts (2010).**

### *8.6 Coastal Trapped Waves*

Coastal trapped waves (CTWs) are a class of waves which depend on vorticity considerations, and propagate in the southern hemisphere with the coast on the left in the direction of propagation. The crest is aligned perpendicularly to the coastline, with the amplitude decreasing offshore (see e.g. Gill, 1982). The tides propagate as Kelvin waves, with the most important at the semidiurnal and diurnal periods (see Chapter 4). On the other hand, shelf waves depend on vorticity changes over a sloping bathymetry, and are generally generated by wind at periods of days.

Shelf waves with substantial amplitudes (> 0.5 m), and typical periods of 4 to 8 days have been shown to exist on the west and south coasts of South Africa (de Cuevas et al., 1986; Jury et al., 1990). Schumann and Brink (1990) showed that the reason for the substantial amplitudes lay in the fact that atmospheric coastal lows travel along the coast approximately in resonance with the waves.

These shelf waves have a marked influence on coastal currents, and Figure 32 shows the effect of such waves off East London. The southwestwards flow of the Agulhas Current is clearly evident most of the time, but when the peak of a CTW passes through it is enough to reverse the currents from around 100 cm/s southwestwards to 100 cm/s northeastwards; these reversals don’t last more than about one day.

Since these waves were followed from Cape Town through Knysna to Port Elizabeth and East London, it was surprising not to find such dynamic current changes in Algoa Bay (Schumann et al., 2005). However, a theoretical analysis by Brink (2006) incorporating finite-amplitude bottom friction showed that maximum current variability should occur at the shelf break and slope, decreasing towards the coast. This would explain the limited current variability at the Bay shoreline, but it does mean a greater CTW impact further offshore.

Recent analysis of data from an ADCP deployed in 30 m water off the east side of Bird Island (as part of the SAEON Algoa Bay Long-term Monitoring and Research Programme, ABLTMR) confirmed that CTWs do propagate past Algoa Bay (Figure 33). Moreover, results from sea pressure sensors deployed at several sites in Algoa Bay show evidence of CTWs within the Bay itself. The data is being analysed at present.

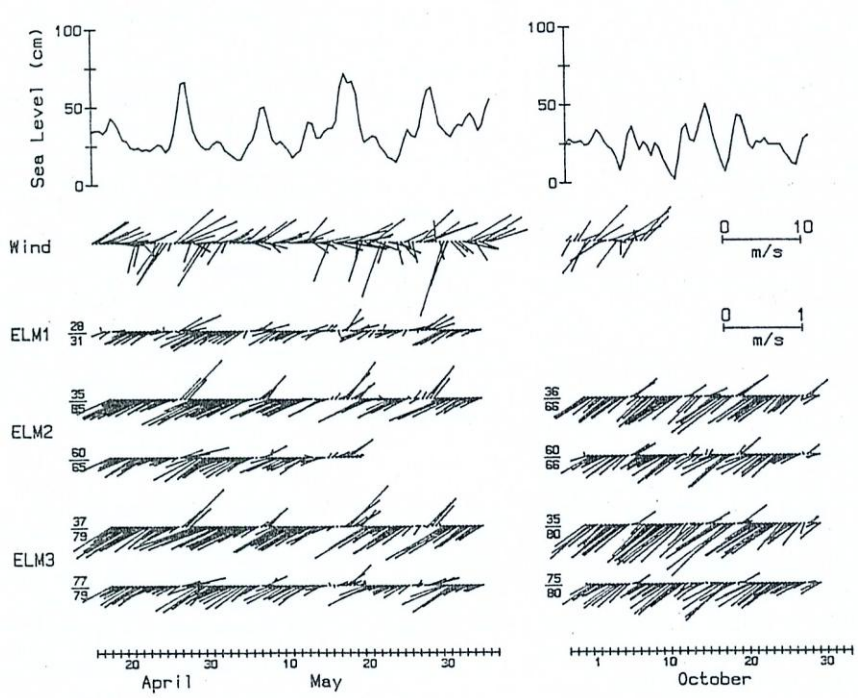


**Figure 32: Filtered, 12-hourly time series of sea level, wind and currents made off East London during 2 periods in 1984. The orientation of the vectors is such that north is to the top of the page. The three mooring sites are labeled, while the numbers on the left give the depth of the water over the total water depth. From Schuman and Brink (1990).**

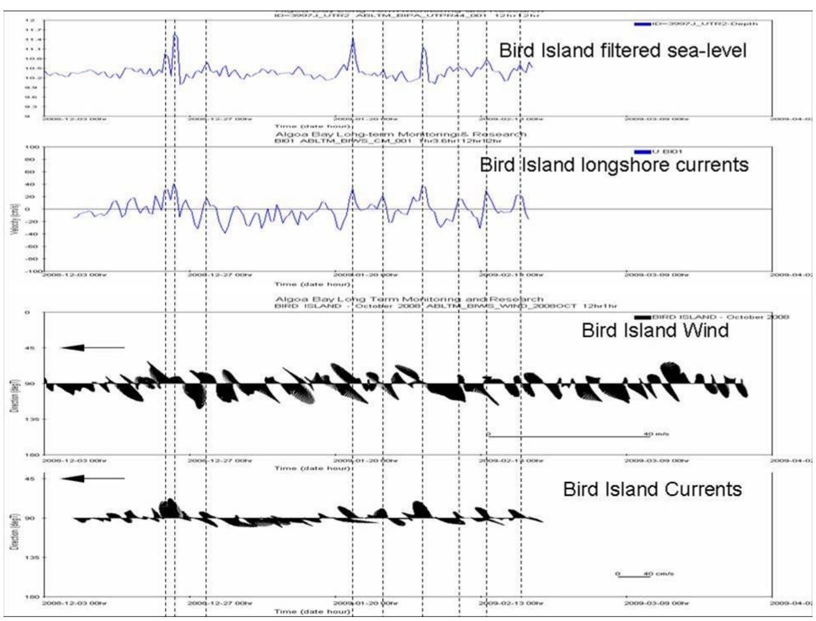


**Figure 33: The top two plots show sea level (compensated for atmospheric pressure) and longshore currents measured at Bird Island. The bottom figures show stick-vectors for wind and currents at Bird Island. Notice how a rise in sea level is accompanied by an increase in strength of the longshore component (approx. northeast) of current during a strong southwesterly wind (From the ABLTMR Programme).**

# 9 Coastal upwelling

## 9.1 The upwelling process

Coastal upwelling is the term given to the process that transports cold water from the deeper bottom layers to the shallower waters that lie adjacent to the coastline. The fundamental process in wind-induced coastal upwelling is well established, although in reality the situation is much more complex, especially in the shallow log-spiral bays such as Algoa Bay. Prominent capes (with bays) disturb the linearity of a coastline and, in addition to upwelling, have complicated dynamics associated with them. For example, Arthur (1965) showed how changes in relative and planetary vorticity contribute to upwelling in the lee of cape and to downwelling on the upstream side.

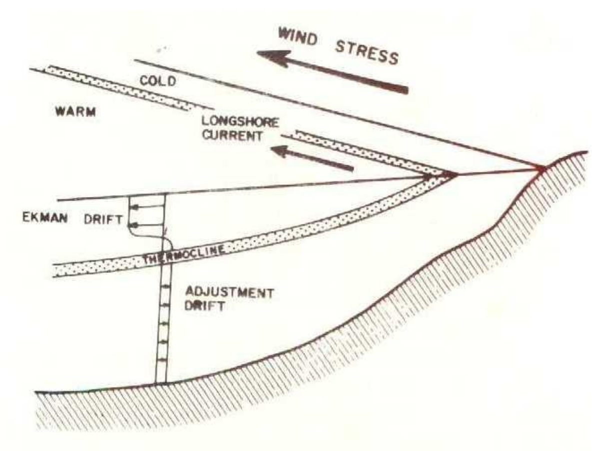


**Figure 34: A diagrammatic representation of processes which operate during upwelling. The Ekman drift in the upper layers, caused by the wind stress at the water surface, is compensated for by the adjustment drift in the deeper layers; this causes colder water to upwell at the coast and pressure gradients to form. From Schumann et al. (1992).**

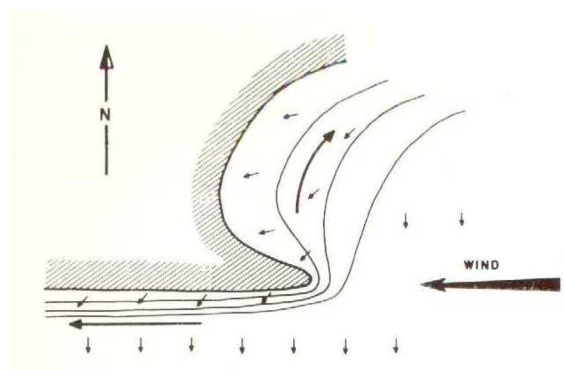


**Figure 35: Proposed processes operating at a cape like Cape Recife to produce upwelling. The surface wind induces an Ekman drift (small arrows) in the surface layers, while the resulting pressure gradients generate along-shore currents in the water columns (long arrows). From Schumann et al. (1992).**

Schumann et al. (1982) describe a mechanism for upwelling (such as along the southern Cape coast), shown in Figure 34. An easterly wind drives an offshore

Ekman transport in the surface layers off the southern shores of the capes. This is accompanied by the rise in the thermocline and the development of a coastal jet. Onshore transport below the surface layer compensates for the surface Ekman transport. Along the bay-side of the capes the response is opposite (and less in magnitude) due to the shortness in length of the capes on the northeastern side, the shallowness of the bays, and the onshore direction of the easterly component wind. In these areas the thermocline falls during an easterly-component wind with onshore flow in the surface layers, offshore flow in the bottom layers and accompanied by a coastal jet (Figure 35).

## *9.2 Observations off the capes of South Africa*

In South Africa extensive studies of upwelling have been carried out in the Benguela region (Shannon et al., 2006). Within the southern Benguela region upwelling around prominent headlands have been studied, in particular the Cape Peninsula (Nelson, 1985; Jury, 1985, 1988; Jury et al., 1985a, b), Cape Columbine, Cape Hangklip and Danger Point (Boyd et al., 1985; Jury, 1988). The coastline orientates towards the north in this region and upwelling is forced by south-easterly winds. At these capes upwelling tongues develop and grow in the downwind direction, while remaining anchored at the coast. Bathymetric, orographic and meteorological conditions, as well as coastal trapped waves and tides particular to the region, can influence the extent and strength of the upwelling (Taunton-Clark, 1985). Coastal trapped waves, tidal and inertial currents have been found to play important roles in the upwelling processes elsewhere (e.g. Hagan, 1981; Johnson, 1981).

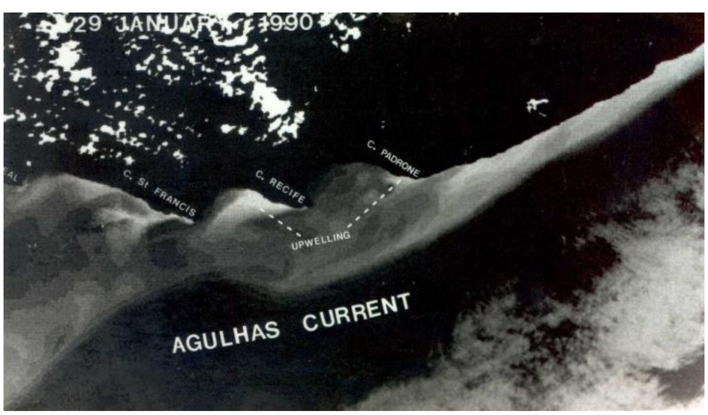


**Figure 36: A NOAA-11 satellite image taken on 29 January 1990, showing the typical surface structure of upwelling off the capes of the south coast of South Africa. Cold water is shown as a lighter shade of grey.**

Upwelling off headlands and in coastal embayments away from eastern boundary upwelling systems is of smaller scale and have been less studied (Schumann, 1999). Off the south coast of South Africa the capes have been identified as locations where upwelling is initiated by winds with an easterly component (Schumann et al., 1982, 1988; Beckley, 1983; Walker, 1986). Figure 36 shows a satellite thermal image during a typical upwelling event. The cold upwelled water then moves westward with the resulting coastal currents. Upwelling off the capes of the southern Cape is predominantly a summer occurrence (Figure 37), mostly because winds with an easterly component are more prevalent in summer than in winter (Schumann and Martin, 1991). In addition, the temperature difference at the upwelling front is accentuated by the intense and shallow thermoclines that are established in summer over the inner Agulhas Bank (Schumann and Beekman, 1984). These thermoclines are broken down in winter which further decreases the effects of the upwelling.

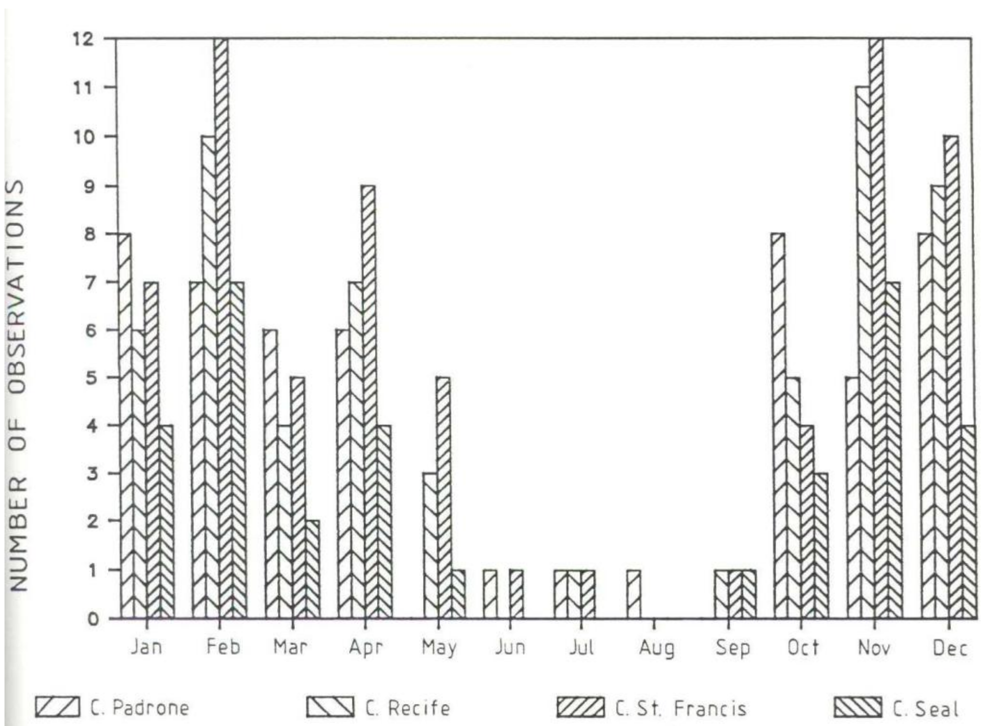


**Figure 37: A histogram of the total number of upwelling observations recorded by satellite images at Cape Padrone, Cape Recife, Cape St. Francis and Cape Seal between 1985 and 1990. From Goschen (1991).**

### 9.3 Algoa Bay

Algoa Bay is enclosed by prominent headlands and the orientation of the wind stresses in relation to the shoreline varies around the headlands. Since the local ocean response to wind forcing is largely determined by the orientation of the coastline to wind stress (Brink, 1983; Bye, 1986), this will lead to different ocean dynamics around the headland. In addition, the northeastern side of the capes have a gently sloping bottom compared to the southern sides and the shallower reaches of the bay are generally well mixed. The response on either side of the capes to wind forcing will therefore be different. Indeed, the results of Schumann et al. (1988) suggest that the causes of upwelling at the capes enclosing Algoa Bay on the east and west side, Woody Cape/Cape Padrone and Cape Recife, respectively, have their origins in different mechanisms: upwelling along the southern shoreline of Cape Recife is mainly wind driven, while that at Cape Padrone is influenced by both the wind and the Agulhas Current.

Further detailed investigations off Cape Recife and Algoa Bay were further carried out by Goschen and Schumann (1995). During a cruise in February 1989 an upwelling event was intercepted, illustrated in *Figure 38* to Figure 41.

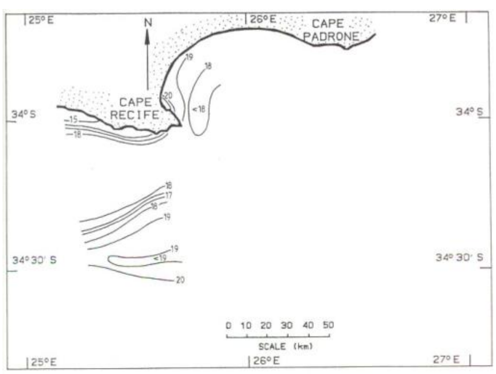


***Figure 38: Surface temperature structure (2 m) measured during the first leg of cruise undertaken in February 1989. An upwelling event was intercepted on the south side of Cape Recife while warm water was in the shallow waters on the north side. From Goschen and Schumann (1995).***

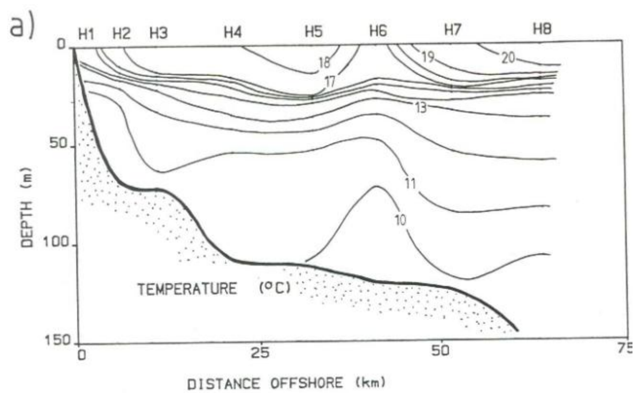


***Figure 39: The vertical temperature section off the south side of Cape Recife during an upwelling event intercepted during the first leg of cruise undertaken in February 1989. From Goschen and Schumann (1995).***

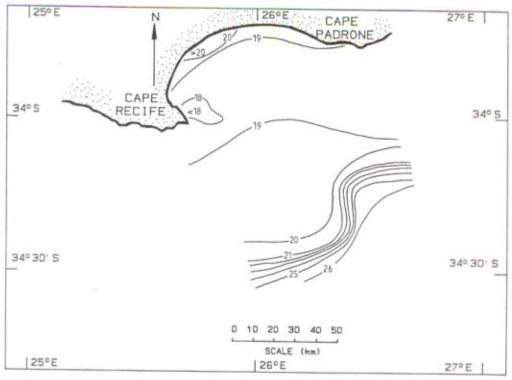


**Figure 40: Surface temperature structure (2 m) measured during the second leg of cruise undertaken in February 1989. The wind had switched to southwesterly and upwelling conditions relax. Cooler water is evident of the north side of Cape Recife. From Goschen and Schumann (1995).**

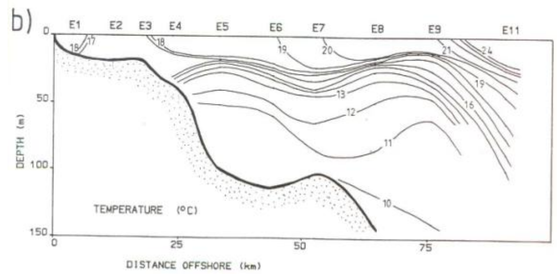


**Figure 41: The vertical temperature section off the north side of Cape Recife during an upwelling event intercepted during the second leg of cruise undertaken in February 1989. From Goschen and Schumann (1995).**

Both Beckley (1988) and Schumann et al. (1988) describe upwelling along the Algoa Bay side of Cape Recife on relaxation of an easterly-component wind. Upwelling events on both sides of Cape Recife are illustrated with wind in Figure 42 and Figure 43. They suggest that cold water moves across the floor of Algoa Bay from Woody Cape/Cape Padrone; satellite observations in the bays and detailed measurements around Cape Recife have confirmed this. Goschen and Schumann (1995) describe a different scenario for Algoa Bay when the wind reverses direction to westerly component, or the easterly component relaxes. In this case the thermocline drops (downwelling) and this causes an increase in sea temperatures off the southern shores of the capes and upwelling off the bay-side of the capes, where wind mixing reduces the mean water temperatures. The currents in the surface and bottom layers reverse direction. This conceptual model is supported by the results of Djurfelt (1989), who found similar reversals in temperature across a small bay off the west coast of Chile (in response to wind forcing).

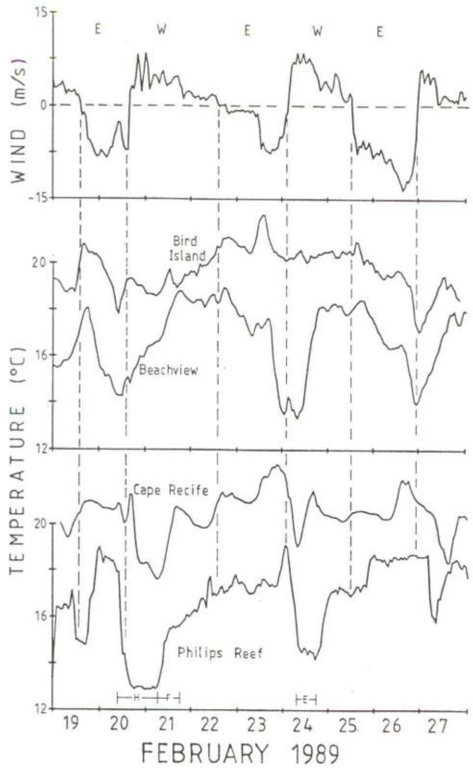


**Figure 42: The top plot shows hourly values of the principal axis winds measured at the Bird Island weather station. Winds with a westerly component (W) are given a positive wind speed and easterlies (E) negative values. The bottom plots are of hourly sea temperature values at Bird Island, Beachview, Cape Recife and Philips Reef (north side of Cape Recife, close to PE harbour) during the February 1989 cruise. From Goschen and Schumann (1995).**

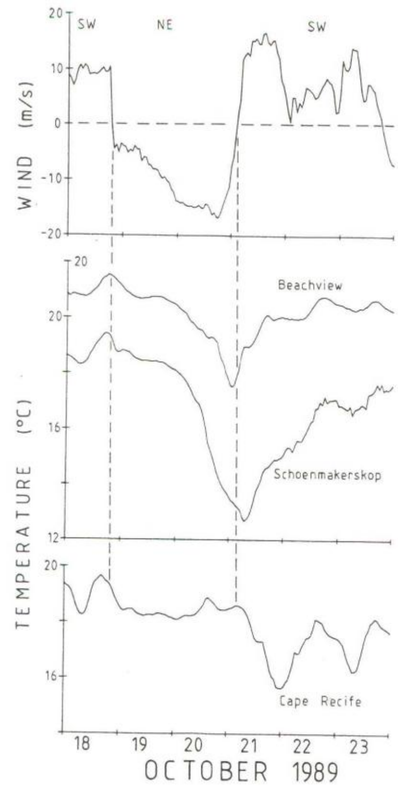


**Figure 43: The top plot shows hourly values of the principal axis winds measured at the Cape Recife weather station. Winds with a westerly component (W) are given a positive wind speed and easterlies (E) negative values. The bottom plots are of hourly sea temperature values at Beachview and Schoenmakerskop on the south side of Cape Recife and Cape Recife point. From Goschen and Schumann (1995).**

# 10 Agulhas Current influences

## *10.1 Introduction*

The dominant ocean-scale feature off the east coast of South Africa is the Agulhas Current, a western boundary current comparable in flow and transport to the Gulf Stream (Pearce, 1977; Schumann, 1998). This chapter deals specifically with the variability of the Agulhas Current off the southeastern coast of South Africa, in the vicinity of Algoa Bay, and its influence on the temperature structures and circulation in Algoa Bay and over the adjacent continental shelf. An exhaustive description of the Agulhas Current along its whole length has been published by Lutjeharms (2006) which, as excellent source of in-depth information on the Agulhas Current, should be consulted if more detailed knowledge is required. The phenomena and their relevance to Algoa Bay are briefly discussed below

## *10.2 Agulhas Current influences on Algoa Bay*

Pearce (1977) divides the surface characteristics of the Agulhas Current into three regions: the marked inshore boundary, the current core and the more diffuse eastern boundary. This structure, although presented for the conditions off Natal, is taken to apply to the whole southeast coast (Schumann, 1987) and is certainly valid off Algoa Bay.

**The Core**

The Agulhas Current core is characterised by a high speed central stream flowing at more than 1 m/s. The mean peak speed is about 1.4 m/s with a maximum observed speed between 2.6 m/s (Gründlingh, 1977, 1978; Goschen and Schumann, 1988) and 2.7 m/s (Schumann and Brink, 1990). On a typical offshore section the highest surface temperatures of the Agulhas Current are normally located at the position of the maximum current speeds (Pearce, 1977; Gründlingh, 1983). The surface temperature drops by approximately 3 °C over 1200 km along the South African east coastline, as indicated by the results of Christensen (1980). From transects off the Eastern Cape Province, Schumann and Beekman (1984) reported seasonal variations in surface temperatures of the Agulhas Current, from about 26 °C during summer to about 22 °C during winter.

### Inshore boundary

The inshore boundary of the Agulhas Current is a region of intensive cyclonic shear caused by the interaction of the rapidly moving Agulhas Current with the relatively stationary shelf waters and shelf wall boundary; it is also a fundamental dynamic requirement of such western boundary currents. Warm, subtropical surface waters are transported southwards, and the inshore current boundary is associated with a strong horizontal (perpendicular to the current direction) surface thermal gradient of about 0.13 °C/km off Natal (averaged over a station width of 10 km: Pearce 1977) and about 0.27 °C/km off Algoa Bay (Goschen and Schumann, 1988), with a maximum of greater than 1 °C/km reported by Pearce (1977). The eastern boundary is a poorly defined region of anticyclonic shear, with velocity and temperature gradients much less intense than in the cyclonic region. Figure 44 shows the average position of Agulhas inshore water, the Current inshore boundary and the core of the Agulhas Current in the Algoa Bay region over a 3 year period.

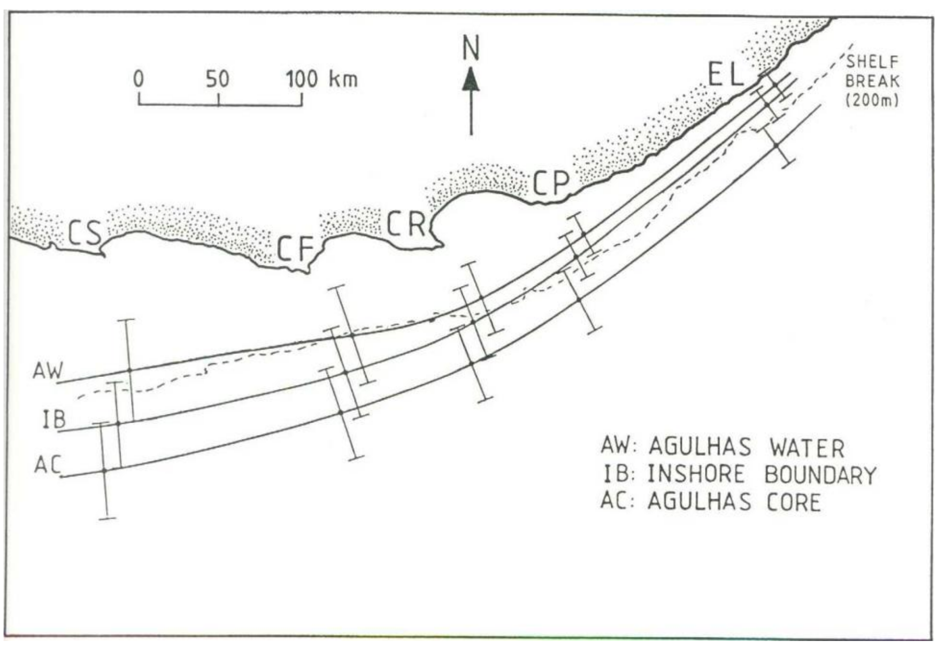


**Figure 44: Average distance (over a three year study) of the Agulhas Current thermal core (AC), its inshore thermal boundary (IB) and related inshore water (AW) over the shelf offshore East London (EL), Cape Padrone (CP), Cape Recife (CR), Cape St. Francis (CF) and Cape Seal (CS). The bars represent the standard deviations. From Goschen and Schumann (1990).**

The presence of the Agulhas Current along the coastline just offshore of the shelf break has a varying influence on the shelf waters depending on the shelf width and the coastline shape (Lutjeharms, 1981; Schumann, 1982). The variability in the position of the Agulhas Current is exhibited by border phenomena (e.g. plumes), meanders and the so-called “Natal Pulse” (Gründlingh, 1979; Lutjeharms and Roberts, 1988; Lutjeharms et al., 1989). These are described below.

**Meanders, frontal eddies and plumes**

As the Agulhas Current separates from the coast in the vicinity of Algoa Bay its core may begin to oscillate laterally (Lutjeharms and van Ballegooyen, 1984). Often cyclonic frontal eddies are situated in the trough of the meanders, where the northern front has moved offshore. The eddies then travel downstream in conjunction with the meanders (Lutjeharms, 1981b; Gründlingh, 1983b). Initially these are small with strongly defined boundaries; as they move downstream their lateral amplitudes are reported to increase on nearly all occasions (Lutjeharms et al., 1989), in a similar fashion to the Gulf Stream as it is freed from the constraint of the shelf north of Cape Hatteras (Fofonoff, 1981). Harris et al. (1978) and Lutjeharms (1981b) estimated that the average velocities of the eddies lie within the range of 10-20 km/day. Eddies between the Agulhas Current and the coast also form in the Natal Bight and propagate downstream in the lee of the offshore meander (Lutjeharms, 1981b; Gründlingh, 1983b; Gründlingh and Pearce, 1990). The eddies generally have dimensions of between 10 km and 20 km (Gründlingh, 1983b).

Plumes, similar to Gulf Stream frontal features (Bane et al., 1981; Lee et al., 1981; Lee et al., 1985; Pietrafesa et al., 1985) are formed when the leading edge of the meanders fold backwards around the eddies. These plumes may extend over the shelf area, with a cold core near the shelf break (Swart and Largier, 1987; Schumann and van Heerden, 1988). On occasion the plumes disperse over the Agulhas Bank and could have an important influence on the circulation patterns and water masses on the Agulhas Bank, such as thermocline formation and maintenance (Swart and Largier, 1987). Upstream of Port Elizabeth these features are not as strongly evident, although undulations in the landward thermal front of the Current do occur and are possibly the initial stage of the frontal eddies.

These phenomena are known to influence water structures and circulation in Algoa Bay. For example, during August 1988, warm water from a plume originating in an Agulhas Current meander, and cold water nested in the offshore deflection of the meander, penetrated over the adjacent continental shelf and into Algoa Bay (Goschen and Schumann, 1994). The event occurred during a strong to gale force westerly wind, which could have driven the water into the bay, while the meander initially caused the surface waters to move onto the shelf. A similar event was documented a few years earlier by Goschen and Schuman (1990), and is shown in Figure 45 and Figure 46.

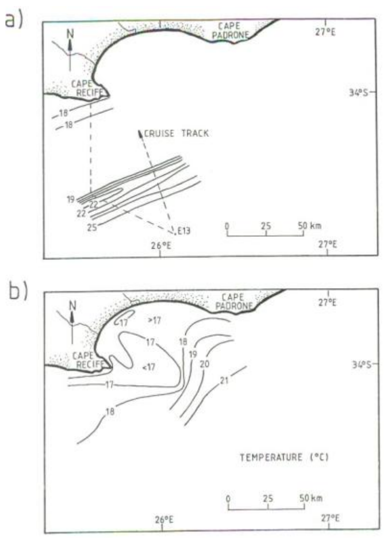


Figure 45: Surface temperatures (2m) measured (a) before a storm that occurred during a cruise on 5 May 1987 and (b) after the storm. Before the storm the sharp horizontal thermal gradient and the high temperatures further offshore show the Agulhas Current to lie in its “average” position offshore Cape Recife. After the storm, warm Agulhas Current surface water penetrated into the eastern region of Algoa Bay. From Goschen and Schumann (1990).

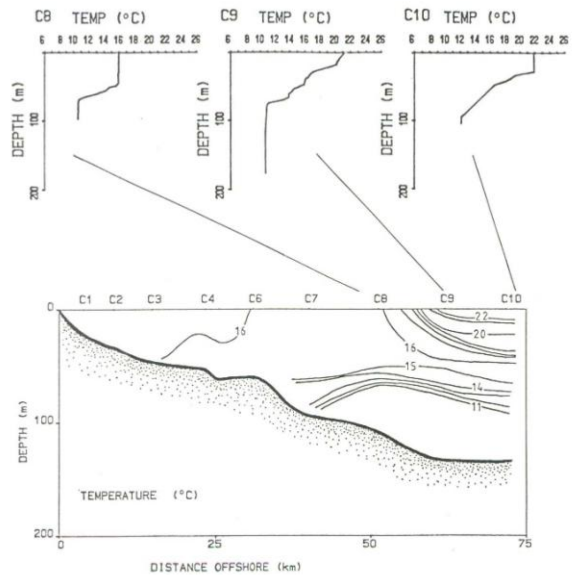


Figure 46: The vertical temperature structure measured along a transect through the middle of Algoa Bay in an offshore direction. It shows the penetration of an Agulhas Current plume over the shelf and into Algoa Bay at a depth of 20 m to 30 m. From Goschen and Schumann (1990).

## Natal Pulses

Distinct from the smaller frontal features are the large episodic meanders in the Agulhas Currrent, with amplitudes of 200 km to 300 km, advecting southwards along the whole east coast at phase speeds of about 21 cm/s and called the "Natal Pulse" (Harris et al., 1978; Lutjeharms, 1981a, 1981b; Lutjeharms and Roberts, 1988). Gründlingh (1979) and Lutjeharms (1981a) have reported that the Current core may be seen to follow a convoluted path around a huge mass of cold inshore water. Natal Pulses are possibly generated off the Natal Bight in the lee of Richards Bay (more recent results show that they are primarily formed by

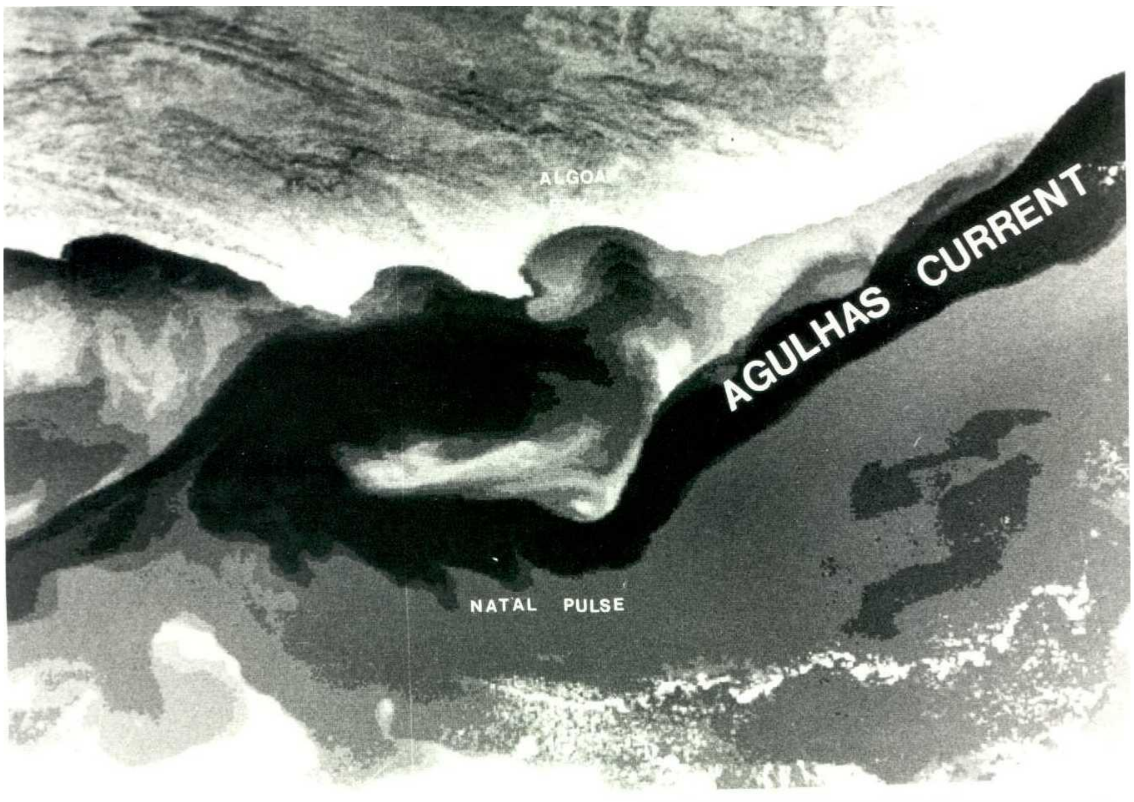


**Figure 47: A NOAA-10 satellite image taken on 4 August 1988 showing example of a Natal Pulse and the extensive influence it can have on the shelf waters offshore the southeast South African costal waters. Dark shades off grey signify relatively warm water and light shades of grey signify relatively colder water. On this occasion Agulhas Current surface water was advected over the shelf and into both Algoa Bay and St. Francis Bay. From Goschen (1991).**

westward propagating eddies from off Madagascar joining the source of the Agulhas Current ) and always move downstream while simultaneously growing in size (Lutjeharms and Roberts, 1988). Schumann et al. (1988) investigated a sudden upwelling of cold water along the Cape south coast of South Africa while a Natal Pulse was propagating through the area, They found upwelling generated in the bottom boundary layer of the Agulhas Current played an important role in the drop of sea temperature in Algoa Bay. Roberts (2010) also recognised that a sudden increase in temperature in the nearshore region of northern Algoa Bay occurred at the same time as Natal Pulse.

### Shelf edge upwelling

Upwelling occurs along the Agulhas Current inshore edge which can bring cold water to the surface under favourable conditions (Schumann and van Heerden, 1988; Lutjeharms et al., 2000). See Figure 48. It is caused through a process of Ekman veering in the bottom boundary layers (Gill and Schumann, 1974; 1979). Currents often drive this cold South Indian Central Water closer inshore and into Algoa Bay and along the coastline north and south of Port Alfred. It can contribute substantially to the temperature variability of the local water (Beckley, 1988; Schumann et al., 1988).

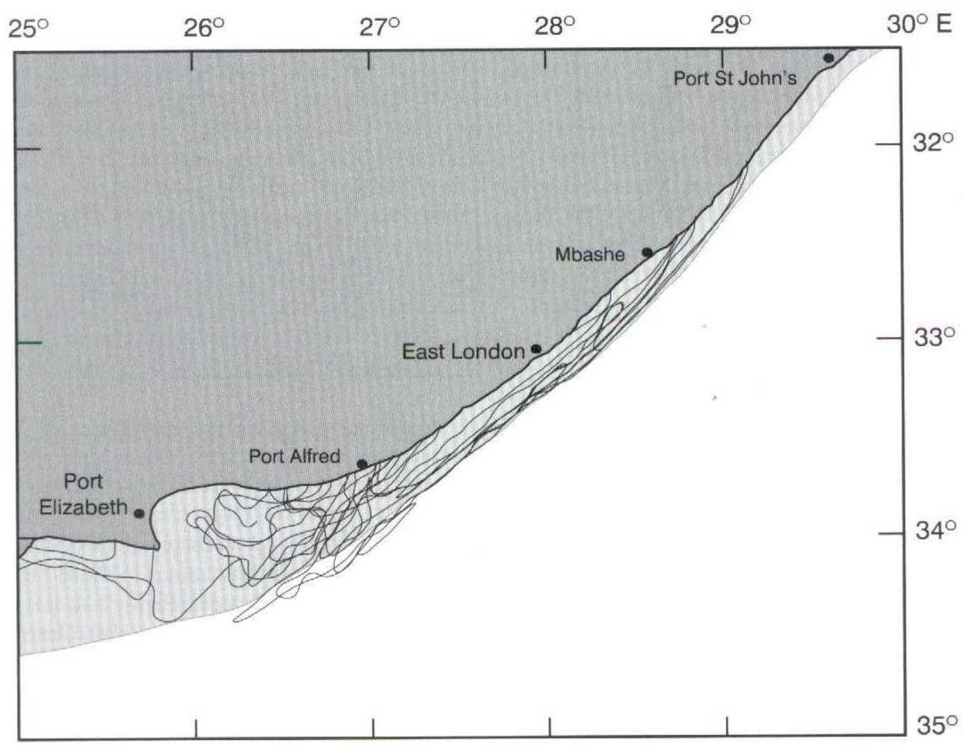


**Figure 48: An ensemble of outlines of cold upwelled water inshore of the Agulhas Current for the period January to May 1991. Satellite imagery in the thermal infrared was used for this portrayal. The 17 °C isotherm was used as an indicator of the edge of upwelling at the sea surface for each case. From Lutjeharms et al. (2000)**

**.**

# 11 Sediment structures and dynamics

## *11.1 Introduction*

The south coast of South Africa consists of a number of crenulated, half-heart or log-spiral bays, defined by the resistant quartzites of the Cape Supergroup which outcrop at Cape Recife and other headlands to the west. These serve to form a protected and safer lee area from the predominant south-westerly winds, as well as from ocean waves originating in the Southern Ocean. This afforded protection was one of the major factors in determining where Port Elizabeth was established (see Figure 49).

Nonetheless, it is important to recognise that there are few natural harbours along the South African coast, and that the original anchorage in Algoa Bay did not provide protection from the easterly gales which occur on occasion. This meant that substantial harbour structures had to be built extending offshore into Algoa Bay to provide the required safe anchorage under all wind and wave conditions.

However, the construction of the Port Elizabeth harbour has not been without its associated problems. In particular, the breakwater has caused an interruption in the longshore transport of sediment, which has led to the formation of a substantial beach area on the southern side of the harbour, and destructive erosion on the northern side over a period of more than seventy years; it is a problem which is still ongoing.

More recently, the Port of Ngqura has been built at the mouth of the Coega River, some 20 km to the north of Port Elizabeth – the situation is depicted in Figure 49. The same sedimentation problems have been experienced, and the installed sand bypass system experienced a number of problems before being commissioned.

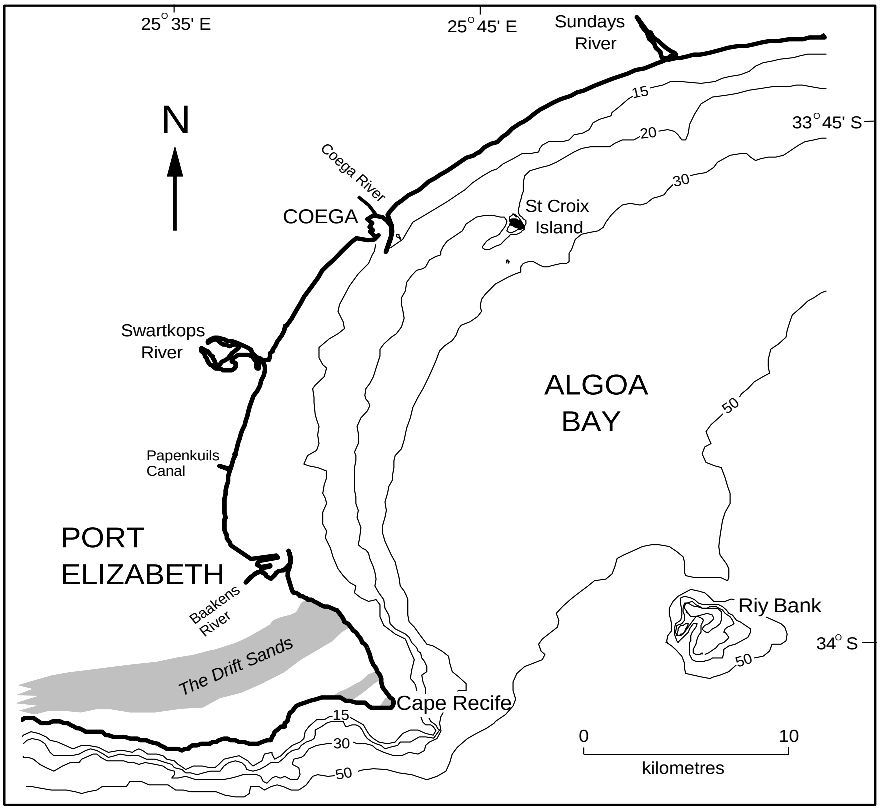


**Figure 49: This depicts the situation in the western sector of Algoa Bay, showing Port Elizabeth in the lee of Cape Recife, with the newly-constructed port at Coega to the north. The positions of the by-pass dunefields that used to transport sand over Cape Recife are also shown (from Lord et al., 1985).**

This section seeks to summarize the situation as it is at present. At the same time, it is acknowledged that there are still substantial gaps in knowledge about the details of sediment movement along the coast. Moreover, the consequences of climate change, with forecasts of sea level rise and the increase in the frequency of extreme events, are still largely unknown.

## *11.2 Waves, sediments and beach processes*

This section discusses what is known about the ocean waves, sediments and beach dynamics in Algoa Bay. It includes, where necessary, a brief description of relevant oceanographic processes; more information can be obtained in a number of good textbooks, e.g. The Open University (1989) and Carter (1988).

Knowledge of the local winds is important to understand both the waves occurring in Algoa Bay and sediment movement. Thus the winds will generate waves which will move sediment on beaches and in the nearshore, as well as moving sediment in the large dunefields on land. A review of the winds over Algoa Bay has already been given in section 3. This has shown that the dominant winds are orientated approximately parallel to the coastline, with the greatest percentage from the west/southwest and the other major direction from the east/northeast.

## *11.3 Ocean waves*

The waves to be considered here are generated by the wind, and are characterized by their period, wavelength and height. They range in size from very short waves with wavelengths in the centimetre range and periods of less than a second, to wavelengths of hundreds of metres and periods as long as twenty seconds. Strong gales, with wind speeds in excess of 20 m/s, can generate waves with heights in excess of 10m.

Once generated, waves can propagate for thousands of kilometres, eventually expending their energy on distant shores. In the open ocean waves of different period and wavelength travel at different speeds, which means that the group will spread out, with the longest waves at the front. In addition, shorter waves lose more energy, and eventually dissipate, while the longer waves maintain their integrity; such regular, even waves are called *swell*. Such swell, generated in the vast reaches of the Southern Ocean, is an important component of the wave climate of Algoa Bay.

In contrast, local winds will generate choppy, disorganised waves called *sea*, with wave periods less than 8s. Local gales do not have a long enough fetch, or distance over which the wind blows, to develop longer-period waves, with the result that steep, short waves ensue.

In deep water the motion of water particles when a wave passes through is in the form of a circle. As the water becomes shallower, the circular motion becomes more elliptical at the seabed, eventually degenerating into a to-and-fro surge in very shallow water. Such a depth-influence of waves depends on their wavelength, and a general rule of thumb is that waves start to feel the seabed when the depth is approximately half the wavelength. This means that longer-period waves with longer wavelengths will feel the bottom first.

In shallow water where the depth is less than 1/20$^{th}$ of the deep-water wavelength, the wave speed can be taken to be only dependent on the water depth, and this leads to the phenomenon of refraction. Waves approaching a coastline at an oblique angle will slow down on the inner side because of the shallower water, making the deeper crests swing around. The net result is that the wave crests will tend to line up parallel to the depth contours. It also means that waves can refract around a headland such as Cape Recife, and penetrate into Algoa Bay; this effect will be greater for longer waves.

The study of nearshore sediment transport depends on wave action, and as such on detailed information on wave conditions. WHP (1986) used wave data from deepwater locations to the south and south-west of Algoa Bay, as well as local winds, and applied a refraction model to obtain nearshore wave conditions. More recent and more local data is available, e.g. from measurements for the new Coega harbour and from satellite measurements, but appropriate analyses are not available. Consequently for this report the results from WHP (1986) will be used.

Figure 50 shows the statistical spread of wave energy directions for the deepwater data. It can be seen that the majority of energy is associated with waves approaching from the south to west quadrant, while there is also a noticeably higher energy level in waves coming from the east. Wave rays – lines drawn perpendicular to the wave crests – are also shown for swell with a period of 12.6 s coming from the southwest and shorter-period (7.9 s) waves from the east.

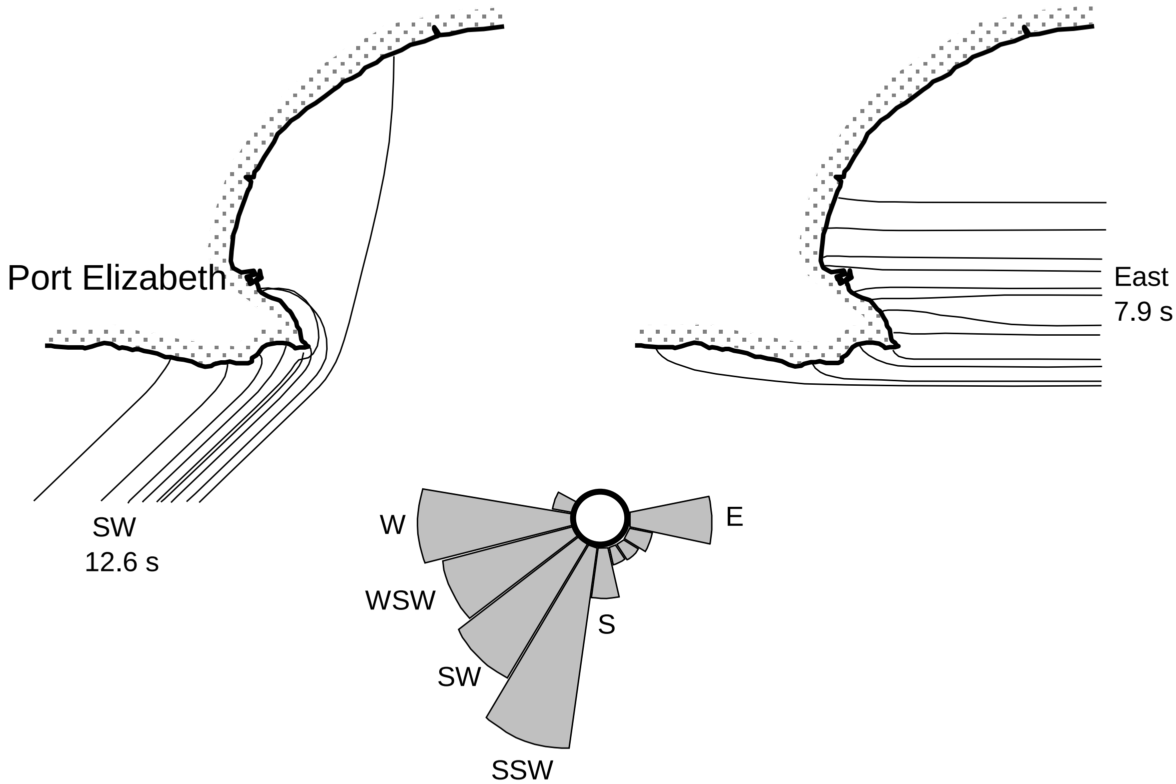


**Figure 50: The wave energy rose giving the statistical spread of deepwater wave directions is shown at the bottom. On the left the wave rays are shown for 12.6 s southwesterly swell, while on the right are the rays for 7.9 s easterly swell (from WHP, 1986).**

Port Elizabeth beaches are clearly directly exposed to waves from the east, however, greater energy is associated with the deep ocean swell from the southwesterly sectors. In areas where wave rays converge the wave heights will be greater than farther offshore, whereas in areas where the rays diverge wave energy is decreased. It can be seen from the figure that, although waves penetrate around Cape Recife, generally their energy is much reduced; on the other hand, bathymetric features can result in wave energy being focused in some areas.

WHP (1986) also calculated the potential sand transport based on the wave data discussed above; these values are derived assuming that there is enough sand to be moved by whatever waves occur. Their calculated values are given in Figure 51.

Considerable variability occurs along the coast, depending on the local orientation of the bathymetry and coastline, as well as the approach angle of the waves. Two values are given south of Cape Recife, denoting sand transport values with dominantly easterly and southwesterly waves. North of Cape Recife only northward transport occurs, since both easterly and southwesterly waves move sand in this direction.

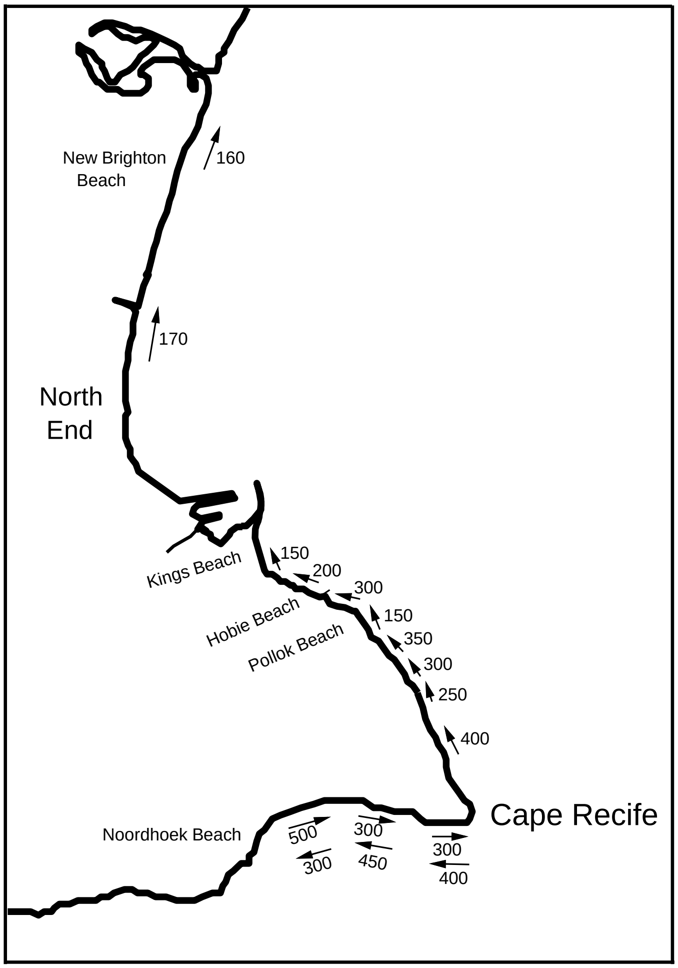


**Figure 51: Potential sand transport values using the wave data shown in Figure 50. Values are in $m^3 \times 10^3$ per annum.**

## *11.4 Sediments of Algoa Bay*

Bremner et al*.* (1991) sampled the sediments of Algoa Bay on a fairly coarse grid of stations. These results show that, in the western section of the Bay extending along the coast from Cape Recife to Coega, sand is the dominant textural component. The sediments contained, on average, 60.7% by weight of terrigenous material, i.e. quartz and clay minerals etc.

However, a detailed inspection of the coastline from Cape Recife to the harbour reveals that it can be described as rocky-sandy shores interspersed with small pocket beaches. The seafloor slopes very gently (< $15^{O}$) towards the south-southeast (de Meillon, 1993), and rocky marine wave-cut platforms remnants and rocky outcrops buffer the narrow sandy beaches (Molyneux, 2008). The section from the harbour to New Brighton Beach has been totally modified by man's activities, while extensive sandy beaches occur further north.

The results of Phipps (1997) show that there are shallow reefs along much of the southern section of the coast, and Figure 52 depicts conditions north and south of the harbour.

It should be noted that, with the high mobility of sand in the region (see later sections), that the distributions shown in Figure 52 will vary over time. Depending on wave and ocean conditions, volumes of sand will at times cover the low reef areas, while at other times they will be stripped bare.

Molyneux (2008) performed an extensive analysis of sediments from ten beach sites, two from Noordhoek Beach, three between Pollok and Kings Beach, and six between New Brighton Beach and Joorst Park (Figure 49). This included offshore sites to a depth of 9.5 m, as well as foredunes.

For the beaches in the southern section, up to the harbour (Figure 52), it was found that small changes in sand grain size occurred across the beach profile, but the sediments were generally fine-grained in the range from 0.178 mm to 0.225 mm; at Pollok beach the sand from the deepest sampling points was the finest-grained. In contrast, the sea-facing slopes of adjacent foredunes were coarser-grained.

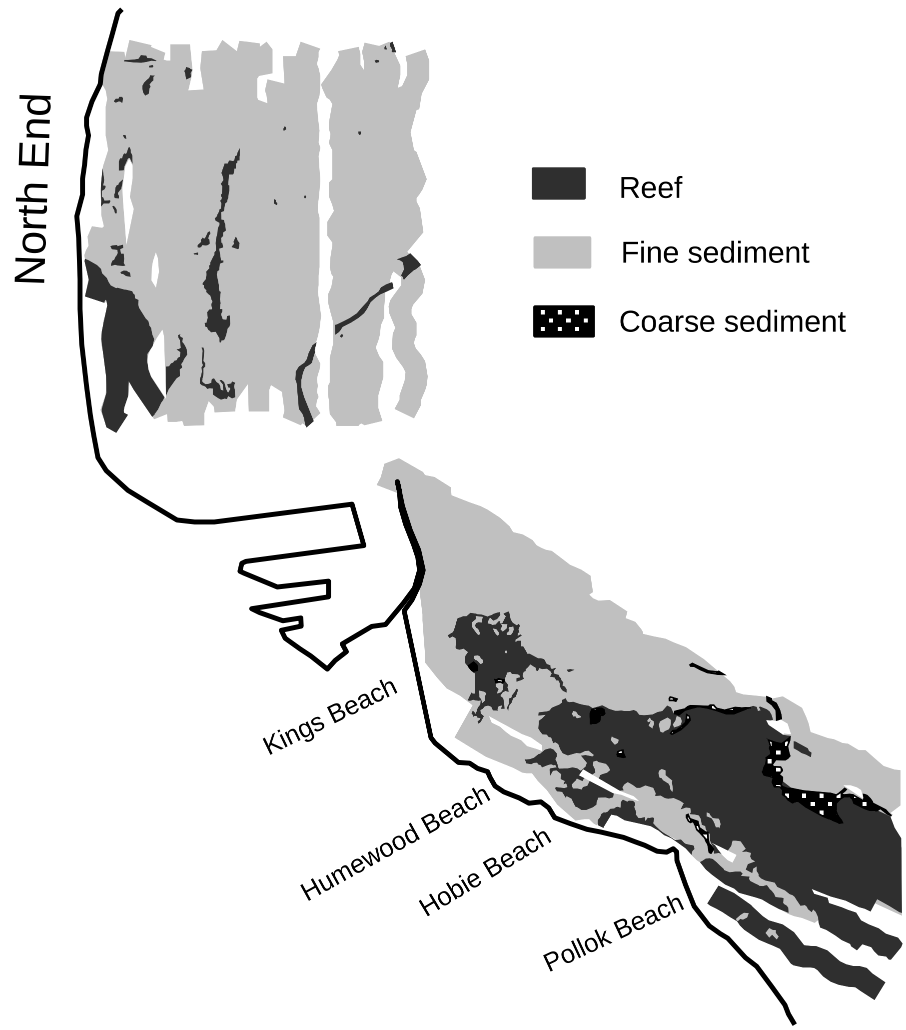


**Figure 52: The facies distribution in the nearshore north and south of the Port Elizabeth harbour (from Phipps, 1997). Conditions are shown only where surveys were conducted, and valid results obtained. The areas identified as 'reef' include high relief reef, low relief reef with a thin veneer of coarse sediment, and low relief reef.**

On the other hand, sand from the rocky-sandy shores in this same section was coarser-grained, from 0.184 mm to 0.54 mm. In particular, it was found that the coarser-grained shell material was retained in the mid to lower parts of the sandy sections, probably sourced from shell material on the adjacent wave cut platforms. The sand becomes finer-grained and better sorted towards Kings Beach.

Farther north, the sandy beaches beyond New Brighton Beach consisted of fine to medium-grained sand, from 0.183 mm to 0.327 mm. Subaerial beach sand coarsens slightly north of Bluewater Bay, with an increase in the amount of shell fragments; it is postulated that the origins of this shell material may be in the offshore islands.

Analysis of the carbonate content of sand gives the percentage of shell material, with the other dominant component being quartz fragments. The specific gravities of quartz (2.65) and calcite (2.71) are very similar, so these percentages are in terms of volume or weight.

Molyneux (2008) found that the carbonate content of the southern beaches varied between 31 and 46%, with a decreasing trend from the low to high water mark, and 1 to 6% more carbonate in the foredunes; the lower beach at Humewood contained an anomalously high 74% carbonate. The rocky-sandy shore carbonate content was generally higher at between 30 and 54%. Highest carbonate values (49 to 80%) were found offshore of Pollok Beach.

The beaches north of New Brighton contained between 33 and 57% carbonate; as indicated already, possibly due to sources on the offshore islands.
Molyneux (2008) also analysed the sand samples for organic and mud content. Low values of organic matter, ranging between 1 and 2% were found for all beaches, although the fine-grained offshore sand at Pollok Beach contained between 3 and 6%. Generally all beaches had less than 1% mud, although again the offshore sites at Pollok Beach had up to 2% mud.

### 11.4.1 Beach and sedimentation process

Beach and sedimentation processes associated with wave action are complex, and relevant aspects will be dealt with very briefly. Of particular importance are the ocean waves causing sand movement. This movement can take place alongshore, as well as onshore, resulting in an accretion of the beach, and offshore, resulting in erosion of the beach. In addition, it is important to know where in the beach profile most of the sand movement takes place, as well as the depth to which waves can move sediment.

The wave characteristics involved here are period, height and direction, with the ensuing wave properties dependent on water depth. The resulting sediment movement is then dependent on sand grain characteristics, as well as the beach formations left from previous wave events.

Alongshore sediment movement is dependent on an oblique approach of wave crests to the shoreline; wave refraction will act to align the crests parallel to the coast, but a longshore current will be generated. For planar beaches maximum longshore currents occur at about the mid-surf position, and can exceed 2 m/s (Carter, 1988). Sediment put into suspension by wave-orbital currents will be moved by the longshore current, in addition to a bedload transport in which sand grains roll and skip at the sand surface. The rate at which sand is transported increases with increasing wave power and the angle between wave crests and the coastline.

Sediment transport also occurs by swash and backwash on the beach face. When a wave breaks obliquely to a shoreline, the swash drives sediment up the beach face at an angle, while the backwash drags the sediment back directly, resulting in a zig-zag pattern with successive waves. However, this movement seldom exceeds 15% of total alongshore sediment transport.

Erosion of a beach occurs under steep wave conditions, generally associated with storms and high wave amplitudes. Sand is transported offshore, forming an offshore bar. During lower wave conditions waves will again transport this sand onshore. These simple concepts are further complicated by phenomena such as rip currents and alongshore variations produced by infragravity waves, beach cusps, etc.

It is important to assess the depth at which sediment movement occurs under waves, and that this movement can occur both as bedload - rolling and skipping at the sediment interface – or as a suspended load. Thus it is known that high waves (> 10 m) will move sediment at depths of 100 m and more, but for symmetrical waves such movement will be oscillatory and involve no net mass transport. As waves move into shallow water, their profile becomes more asymmetric, and a net forward momentum ensues, moving sand forward at the wave base. Considering that 15 s waves have a deep-water wavelength of over 350 m, they are considered shallow-water waves at depths of 15 m, and will certainly cause forward movement of sediment at that depth. Furthermore, net movement increases with wave height squared, so that mass transport is enhanced towards the beach (Silvester and Hsu, 1993).

Furthermore, differential refraction of waves with different periods will cause the waves to be angled to each other, producing short-crested wave systems with a greater ability to transport sediment. Actual mechanisms at the seabed and the rates of growth and migration of ripples also affect sediment transport rates.

Silvester and Hsu (1993) specifically note that significant movement of sediment takes place seaward of the breaker zone.

Strong enough oscillatory flows at the seabed will also put sediment into suspension, and this can then be moved by unrelated ambient currents. Such currents may be due to tides – which are themselves oscillatory on much longer time scales – or otherwise wind or pressure-driven currents.

De Meillon (1993) investigated sediment movement at two sites off Hobie Beach, one in 6 m depth and the second in 17 m. In one experiment dyed sand was released and traced over 5 hours, while wave and current measurements were also made. He found that, under moderate wave conditions, sand at both sites moved predominantly inshore and alongshore, with little difference in the rate of spreading at the two sites.

It is important to recognise that sand movement, alongshore and onshore-offshore, does not occur in a regular fashion. A single storm can cause large changes to beach bathymetry, moving thousands of cubic metres of sand in the process, primarily offshore, but also alongshore. On the other hand, during low wave conditions the sand can be returned to the beach, with smaller volumes progressing alongshore.

## *11.5 Kings Beach and sediment movements*

A brief overview of changes to the Algoa Bay coastline over the last two centuries is given in the Appendix; this section analyses in more detail specific aspects of more recent sediment movement and the related sand budgets.

Central to the changes was the building of the harbour breakwater in 1930 and the development of Kings Beach. This development is depicted in Figure 53, with the changes in the high water mark as well as the measured 5 m and 10 m isobaths shown.

The accumulation of sand is clearly evident, with the most obvious aspect the gradual movement offshore of the high water mark. This reached its maximum offshore extent in the early 1990’s, at the base of the Burton Breakwater. At the same time the sand filled out the deeper water, and from both the 5 m isobaths and 10 m isobaths it can be seen that, in the mid-1980’s, sand was starting to extend along the front of the breakwater. By the mid 1990’s this had also reached its maximum offshore extent, with the sand then moving around and into the mouth of the harbour. This meant that regular dredging had to be done to keep the approach channel clear.

Using measured beach profiles, the volume of sand forming Kings Beach in various years can be calculated, and these results are given in Figure 54. As already shown in Figure 53, Kings Beach reached its maximum extent in the early 1990's, and this is confirmed by the fact that there is little difference in the calculated volumes in 1992 and 1994.

It can be assumed that harbour breakwater initially acted as a terminal groyne, allowing no sand to pass. The build-up of Kings Beach over more than sixty years then enables a fairly accurate assessment to be made of the average rate at which sand moves along this section of the coastline.

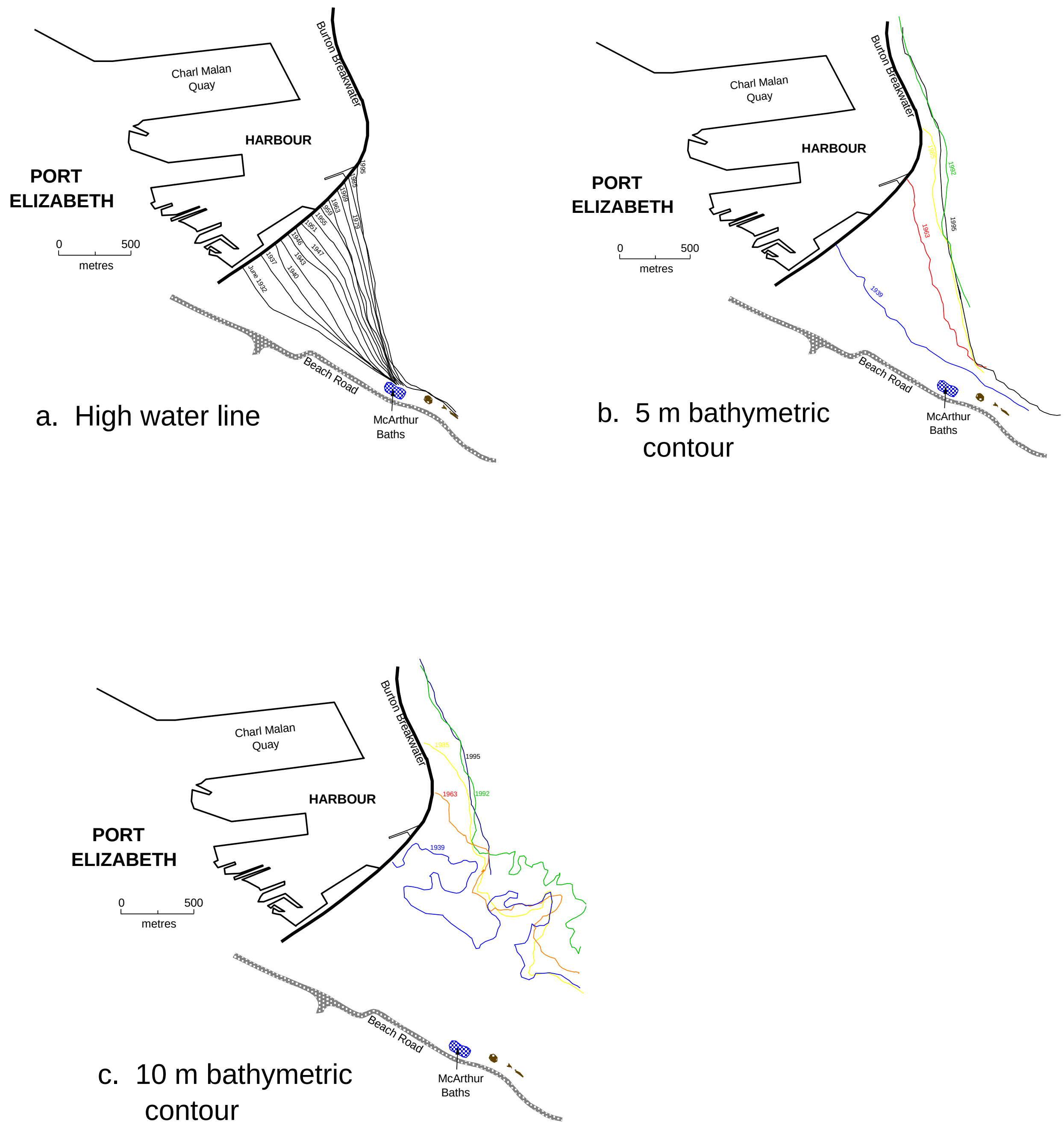


**Figure 53: Development of Kings Beach due to the building of the breakwater in 1930. The high water lines (a), 5 m bathy-metric contours (b), as well as the 10 m bathymetric contours (c) are shown in various years (adapted from CSIR, 1970; WHP, 1986 and Phipps, 1997).**

In particular, Figure 54 shows that the rate of volume increase of Kings Beach changed very little over the approximately sixty years from 1932 to 1992. A linear regression performed on the data points gives an annual average accumulation rate of 151 000 $m^3$ (with a correlation coefficient of 0.99). This is in agreement with the value of 150 000 $m^3$ calculated by WHP (1986) for the years 1931 to 1985. Note that WHP (1986) report that SATS had removed of the order of 30 000 $m^3$ per annum from inside the harbour as a result of sand percolation through the breakwater, thus giving a total alongshore sand transport of 180 000 $m^3$ per annum.

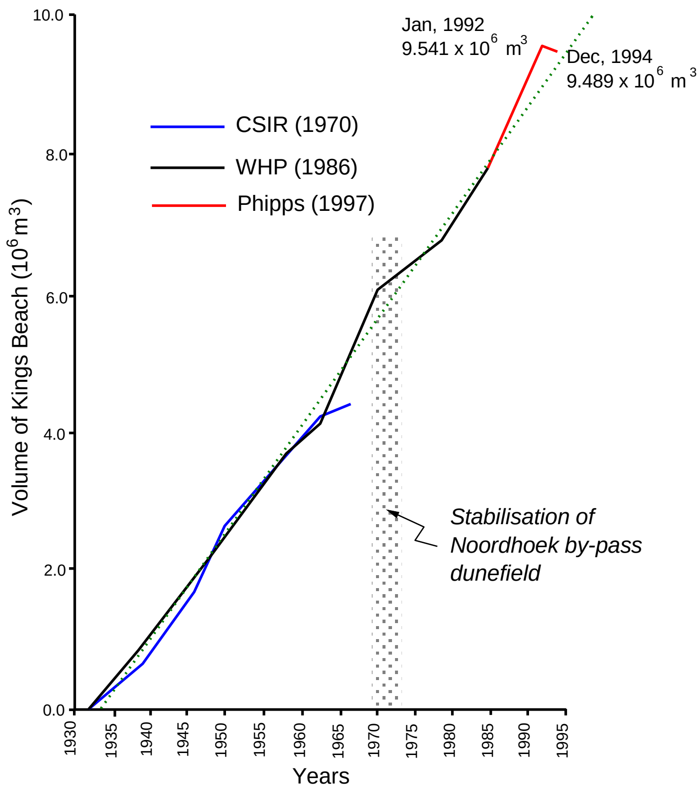


**Figure 54: Rate of accumulation of sand at Kings Beach from three studies. The years over which the Noordhoek dunefield was stabilised are shown, while the linear regression line is shown dotted in green.**

As indicated already, there is uncertainty about the part played by the by-pass dunefields in providing sand to the Port Elizabeth beaches. Lord et al. (1985) estimated that the three by-pass dunefields – Driftsands, Noordhoek and Cape Recife – supplied of the order of 260 000 $m^3$ per annum, although this was likely to occur in sporadic pulses of sand. Closure of Driftsands in the early 1900's reduced this to about 78 000 $m^3$, while blocking Noordhoek in the early 1970's removed a further 50 000 $m^3$; on the other hand, WHP (1986) estimated the annual transfer via the Noordhoek dunefield to be between 18 000 and 40 000 $m^3$, with an average of 30 000 $m^3$. The one dunefield still remaining – Cape Recife – is estimated to provide a maximum of 26 000 $m^3$ per year.

It would be expected that the loss of this sand input to the Port Elizabeth beaches should have serious implications for their maintenance, but there is no clear evidence of this happening. Thus the closure of the Noordhoek dunefield in 1970 should have affected the rate at which sand accumulated on Kings Beach, but Figure 54 shows no change occurring over the next twenty years. Indeed, PRDW (2006) state that the dredge volumes removed from the harbour mouth by the NPA amounted to 230 000 $m^3$ per year over the years 1996 to 2006, considerably more than the average rate of 181 000 $m^3$ reported above.

There is no clear answer to this conundrum, but it does indicate the lack of knowledge of where sediment movement is occurring, and what reservoirs of sand are available. In particular, there is no definite knowledge of the volume of sand rounding Cape Recife, though Lord et al. (1985) used circumstantial evidence to conclude that it is *unlikely to exceed 25 000 $m^3$* per annum. However, WHP (1986) had no problem in concluding that the necessary sand volume of over 150 000 $m^3$ per annum could be provided via wave action around Cape Recife.

## *11.6 Discussion*

Port Elizabeth's beaches form one of its main tourism assets, yet there appears to be little effort on the part of the authorities to manage the beaches, or indeed to assess whether they will be a permanent part of the coastline in the future.

The small southern beaches – Pollok, Hobie and Humewood – as well as the much larger Kings Beach, form the core of these tourism nodes. To the north New Brighton Beach is being steadily eroded away, while beyond the Swartkops River there are extensive sandy beaches from Bluewater Bay to Joorst Park; however, these are high energy beaches and not suitable for family outings.

At present it is unclear whether the southern beaches are in a steady state, or whether they are losing sand in the long term. Large changes do occur with high energy wave events eroding back sand and exposing bedrock as well as pebbles and cobbles. However, when calmer conditions prevail, sand is brought back again, burying the bedrock and pebbles and making the beach user-friendly. Molyneux (2008) documents a storm in April, 2007, which stripped bare Pollok Beach, yet by May much of the sand cover had returned.

The problem with the situation at these beaches is the shallow bedrock, and the relatively thin veneer of sand that forms the beaches. It doesn't take much to remove the sand, though correspondingly the sand does return again very quickly. However, it is then very difficult to determine any longer-term changes, though the public does seem to remember when the beaches are bare, and there is therefore a substantial public opinion that the sand on the beaches is decreasing.

The issue does revolve around the question of the source of the sand to supply the volumes that are moved northward along the coast by wave action each year, as depicted in Figure 51. At present there is no reliable value for the volume of sand in the nearshore prism in the beaches and farther offshore, particularly south of the harbour. Such a value would enable the sand transport to be put into context, e.g. if the transport is a small percentage of the total, then a major storm would not have a lasting impact. On the other hand, if the sand reservoir is of the same order as the transport value, then a mass movement of sand along the beaches would take time to replenish.

The question then is where does the sand originate? Unfortunately some reports, e.g. Lord et al. (1985) have assumed that sediment is not moved by waves below 10 m to 15 m depth, and this has also been assumed by subsequent investigators. As already indicated, sand is moved by waves and currents in substantial depths, probably up to 40 m or 50 m, but details need to be known before reliable assessments can be made.

The sequence in which events occur can also be critical. Thus Figure 52 shows that at Cape Recife there is actually a potential sand movement westwards which is greater than that eastwards and into Algoa Bay. However, sand moved eastwards by southwesterly waves will probably be taken around the cape, and if taken far enough will be inaccessible to subsequent waves from the east. It means that the *potential* sand movement westwards is not realised, whereas the sand sources to the west will allow the full potential movement eastwards.

The existence of large sand spits extending out from the capes to the west, and not at Cape Recife, is also an indication that sand is not trapped and does move around Cape Recife. However, the movement of the sand is not known, and it may possibly move into deeper water. As such, there may be unknown reservoirs of sand available in Algoa Bay.

In that context, very large volumes of marine sand were dredged during the construction of the new harbour at Coega. Unfortunately there is no overall management plan for Algoa Bay, and the sand from the dredging was dumped in deeper water offshore. Used judiciously, this sand could have done much to replenish the beaches immediately north of the harbour, curb further erosion, and possibly even form the base of the revitalisation of the North End beachfront.

At the present time the situation appears to be in limbo. Proposals for a sand by-pass at the harbour have dragged on since 1996, with the result that harbour dredging and dumping of spoil continues. Moreover, shoreline protection measures north of the harbour are being extended as the coastal erosion edges farther. Imaginative plans including artificial offshore reefs and marinas gather dust as planners obfuscate. Little is being done to understand the overall sand budgets, and the city of Port Elizabeth suffers as a consequence.

# 12 Recent Developments

In October 2008, SAEON began deploying instruments measuring physical oceanographic variables in and around Algoa Bay as part of the Algoa Bay Long Term Monitoring and Research programme, run jointly by the SAEON Elwandle and Egagasini Nodes (Figure 55). To date, two years of high quality data has been collected (Figure 56) and this is likely to continue. The main variables measured are sea temperatures, sea currents and water pressures, but the programme also has access to tidal data (SA Navy Hydrographic Office), weather data (South African Weather Service), wave data (Council for Scientific Research, CSIR) and satellite images (Marine Remote Sensing Unit, UCT).

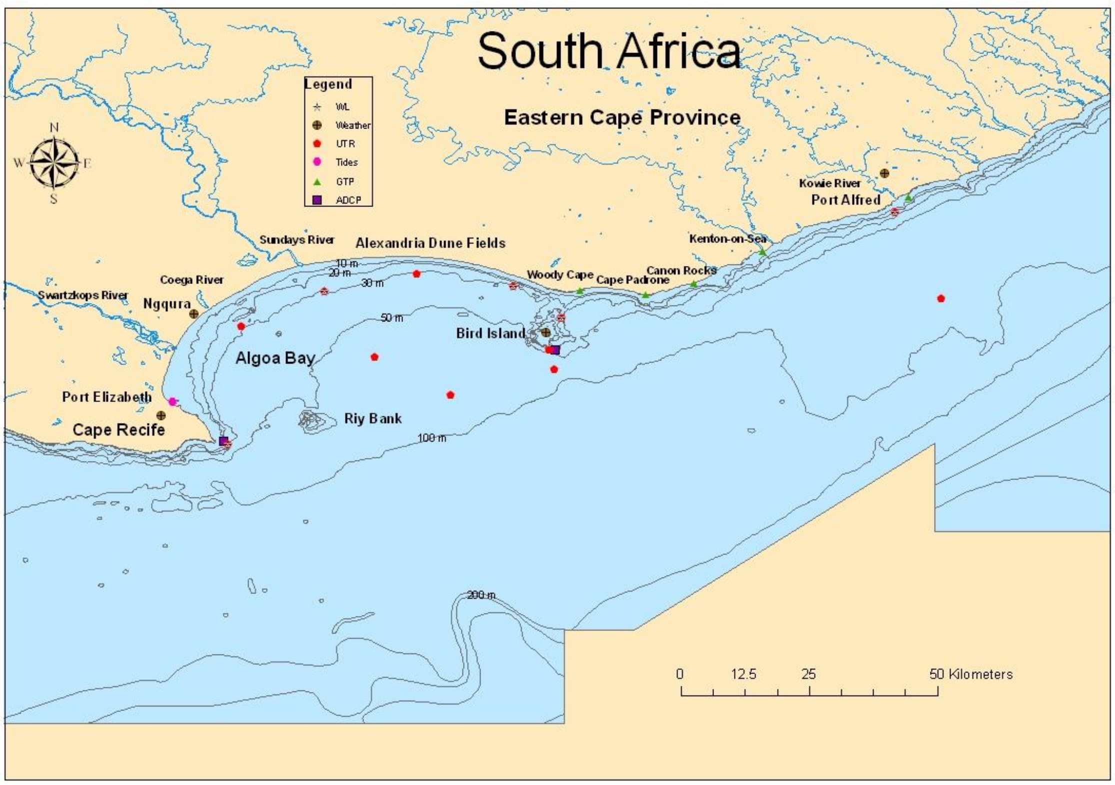


**Figure 55: The locations of moorings (at end 2010) deployed as part of the Algoa Bay Long Term Monitoring and Research programme. The moorings consist of water level (pressure) recorders (WL), underwater temperature recorder strings (UTR), gully temperature probes (GTP) and acoustic Doppler current profilers (ADCP). The location of the SAWS weather stations (Weather) and the SA Navy Hydrographic Office tide gauge (Tides) are also shown.**

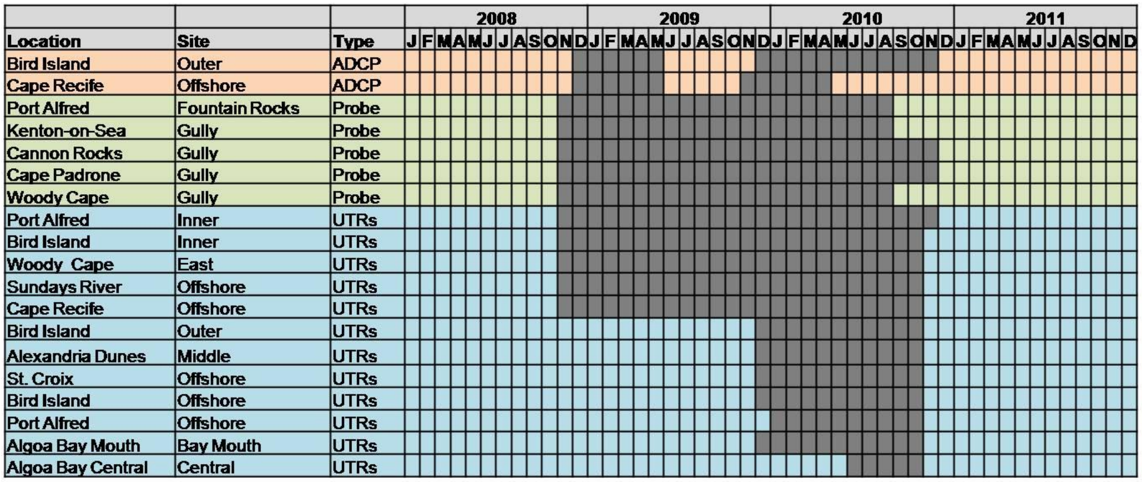


**Figure 56: The return of data (shaded blocks) from the moorings deployed in and around Algoa Bay, as at the end of 2010, as part of the Algoa Bay Long Term Monitoring and Research programme.**

Physical data is collected for the following reasons: in order the gain knowledge of the long-term trends in the physical ocean, to understand better the dynamics of the ocean in that region and to support the biological research underway in Algoa Bay. Furthermore, the physical ocean in the northern area of Algoa Bay has received little scientific attention in the past, mainly due to its inaccessibility by boat-based scientists, and these measurements will extend the knowledge of ocean processes in this area. Some of the main (initial) results obtained from the first year of physical measurements are described below.

Visual inspection and statistical analysis of data from an ADCP deployed off the east side of Bird Island, and wind from the Bird Island weather station, showed a high coherency between winds and currents. Moreover, a small amount of lag between wind and currents was evident, implying that currents were forced directly by local wind stress. In addition, the currents were predominantly barotropic, with the strength in current speed decreasing with depth. The average longshore currents were about 20 cm/s on the surface (10 m) and about 8 cm/s on the bottom (30 m), with the net currents towards the south-southwest. The rotary spectra showed the $M_2$ tidal constituent to be a strong component of currents, although less linearly polarized with depth. Inertial currents were evident, but not strongly so.

As part of an upwelling experiment, five underwater temperature recorders (UTRs) were deployed in nearshore gullies in the inter-tidal zone between Woody Cape and Port Alfred. It was found that cold bottom water upwelled almost simultaneously at all sites during a northeasterly wind and often penetrated to the surface at the deeper moorings. From these measurements, it was evident that the nearshore water responded rapidly to wind forcing along this stretch of coastline. The sea temperatures ranged from about 12 °C to 24 °C during the summer upwelling months, while during the winter the range decreased to about 15 °C to 18 °C. On occasion Agulhas Current influences in the form of shear-edge eddies, plumes, episodic meanders (Natal Pulses), inshore edge upwelling and other phenomena overrode wind-driven effects and altered the structure of the entire water column.

In addition to the gully UTRs, underwater pressure sensors were attached to several UTR arrays moored in Algoa Bay (with one off Port Alfred). Analysis of the data showed that large disturbances (> 50 cm) in sea level were occasionally recorded at all moorings, although clearly more evident in the exposed regions of the capes of Algoa Bay as well as at Port Alfred. It is known that coastal trapped waves (CTWs) occur off this coast, associated with the anti-clockwise passage of weather systems around South Africa. Further investigation of the currents measured by the Bird Island ADCP showed that a northeastward longshore current was associated with the peak of a CTW, and that the current reversed direction as the wave trough propagated past the site toward the northeast.

# 13 Appendix

## *13.1 History of Algoa Bay shoreline*

In order to understand the present condition and dynamics of the Algoa Bay shoreline, it is necessary to understand what has happened in the past, in particular the man-made changes. As expected, most of these changes have been in the vicinity of Port Elizabeth, where the first European settlement occurred. More recently, the new Port of Ngqura at Coega River has seen further substantial construction extending into the Bay.

The indigenous peoples who lived along the shores of Algoa Bay before the European settlers arrived probably had little influence on sedimentation processes. In essence, their numbers were small, and their lifestyle was not intrusive.

However, the sea and ocean transport played a vital part in the lives of the early settlers, particularly after 1820, and as such they had to ensure safe anchorage if Port Elizabeth was to develop. A number of ships were wrecked, and after the *Charlotte* struck rocks at the bottom of Jetty Street in 1854 with the loss of 62 soldiers, 16 women and 26 children, a breakwater south of the Baakens River was built. However, silting was a problem, and after a flood in 1867 the breakwater was unusable and had to be demolished; the Harbour Board resident engineer and designer resigned as a consequence (Harradine, 1994).

Bad weather, in particular southeasterly gales, continued to cause havoc with shipping. In 1859 10 vessels were wrecked on North End beach, while in 1869 11 of 13 vessels at anchor in the Bay were beached. In 1871 a steamship grounded at the foot of Jetty Street after going to the assistance of other disabled ships. In 1870 a wooden North Jetty was built, replaced in 1880 by an iron pile jetty, while the South Jetty was completed in 1884, and extended in 1894.

However, these jetties did not provide safe anchorage and also required baskets for passengers in poor weather. In 1872 a southeasterly gale wrecked 4 ships, in 1888 another gale beached 9 vessels, and in 1892 another 2 ships were wrecked. Then the great gale of 1902 beached or destroyed 21 ships. The following year 6 more sailing ships were forced on shore.

On land the new settlement also faced problems, in particular from the vast swath of sand extending across Cape Recife and known as the Drift Sands (Figure 49). It originated on the south coast, and was brought across the Cape by the dominant southwesterly winds. The piece of land called the ‘Fishery’ had a small cove which provided safe landing for boats near the present Humewood slipway, but this was engulfed by the drift sands in 1876 (Markman, 2009). The Drift Sands also posed a major threat to the new harbour plans, covering tram tracks and destroying rolling stock.

Reclamation of the Drift Sands began in 1872, involving stabilization of the dunes by covering them with brushwood and seeds. This was only partially successful, and from 1890’s the town’s daily garbage was taken out to the Drift Sands by railway and spread out to provide a fertile bed for vegetation. By 1897 the shoreline had been contained, and the work was finally completed in 1910, stopping the transport of sand in the main corridor across Cape Recife.

However, two other by-pass dunefields were still operational at that time, namely the Noordhoek dunefield, and the much smaller dunefield at Cape Recife (Figure 49). In 1969 the Summerstrand/Cape Recife sewage works were built, with maturation ponds situated on the Noordhoek dunefield (Lord *et al.* 1985). At the same time the dunefield was artificially vegetated, and by the mid-1970’s there was no more sand passing through. This is still the situation at present, with the very minor by-pass dunefield at Cape Recife being the only one still operating. The outer works for the new harbour were sanctioned in 1914. The Dom Pedro Jetty, which was an open piled structure and forms the basis of the breakwater, was completed in 1920. The first block of the breakwater was laid in November, 1922 (Harradine, 1994), and construction was finished in March, 1931. The area under the Dom Pedro Jetty was also filled with rock, thus blocking any further movement of sand northwards. With the Burton Breakwater curving around the sheltered waters inside the harbour, Port Elizabeth finally had a safe anchorage.

However, it did not take long for the consequences of blocking the longshore transport of sediment to become apparent (Figure 51). A new bathing house and cafe had been opened in 1932 at the very popular North End Beach, but the beach eroded rapidly because of the lack of sand replenishment. In 1935 the buildings were declared redundant, and in 1938 the beach was closed.

The sand which had been blocked from North End Beach accumulated on the southeastern side of the harbour, forming a new beach – Kings Beach. This beach continued to grow over the next sixty years, extending the land adjacent to the harbour wall by more than 1 km; Kings Beach itself reached its maximum storage capacity in about 1990 (see Figure 54). As it extended into deeper water, the sand started to move along the offshore side of the harbour breakwater, eventually rounding the end of the breakwater and entering the harbour mouth.

The presence of sand entering the harbour has meant that regular dredging by the National Ports Authority (NPA) is now necessary to maintain the harbour approach channel at the specified depth of 14.5 m (Figure 49). Moreover, sand has also entered the harbour through the porous breakwater, at times forming a shallow beach on the inside.

Over this whole period, erosion of the beach on the northern side of the harbour has continued. The CSIR analysed changes in the coastline from 1899 to 1969 (CSIR, 1970), and found that the coastline has been eroded by more than 200 m in places. Before 1939, erosion occurred only in the area between the harbour and the Papenkuils River mouth. This erosion was then limited by the construction of a beach wall, rubble barrier and dolosse to a position more than 2 km north of the mouth; beyond that a rock barrier carries on the beach protection measures for another kilometre. Erosion now extends well beyond this position, and New Brighton Beach has already lost substantial volumes of sand.

As indicated in a previous section, large volumes of sand can be moved during storms, and the event of September, 2008, caused substantial erosion along the whole coastline (McGillivray, pers. com.). Moreover, waves overtopped the dolos beach protection, and substantial damage was caused to coastal property by the subsequent flooding. Regular maintenance, requiring replacement of dolosse, is required to maintain the coastal protection, in particular because of the close proximity of the railway line.

Similar scenarios have played themselves out in many parts of the world, and in 1996 a pre-feasibility report (PRDW, 1996) assessed the feasibility of constructing a sand by-pass system for the harbour. Such a system will fluidise and pump sand from Kings Beach, take it under the harbour and deposit it on the northern side, thus replicating the natural movement of sand past the harbour position. This will also require the sand accumulated off the breakwater to be removed, while part of Kings Beach itself would be dredged to form a reservoir from which the by-passed sand would be sourced.

The sand by-pass system was not constructed, and was re-assessed in 2006 (PRDW, 2006). A major change noted is the dredging that has been required to keep the mouth of the harbour open. It was also proposed that dredging or a sand bypass system would be used to reclaim land at North End by the time of the World Cup in 2010, but again no final decisions were made.

On a much smaller scale, in 1989/1990 a pier was built at Shark Rock utilising slats which could be inserted at the pier base to obstruct the longshore movement of sand; this led to the formation of Hobie Beach. The volume of sand trapped in this way is estimated to be between 20 000 $m^3$ and 30 000 $m^3$ (Phipps, 1997), and has led to the establishment of a very popular facility. Moreover, this volume of sand is small relative to the volumes passing naturally, and the pier has had no adverse consequences on other parts of the coastline.

However, the Port of Ngqura at Coega has a substantial breakwater, and therefore the same possibility as Port Elizabeth of starving coast to the north if no measures were taken to replicate the natural movement of sand past the harbour. A sand by-pass system has been installed, and though there were numerous teething problems, it has now been commissioned.

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