Chapter 1

The Benguela

The fisheries of the South African West Coast being of large economical importance, an important effort has been directed by South African marine research institutes to analyze the ecosystem. Thus, numerous studies have been undertaken in the last 30 years, involving for the physical part: hydrological samplings, current meters deployments, aerial atmospheric and sea surface temperature measurements, ADCP current measurements, drifters deployments, satellite data analysis and theoretical studies. As a result, a thorough description of the system is available and the understanding of many important processes has significantly progressed. These results have been summarized in several reviews [*Nelson and Hutchings,* 1983, *Shannon,* 1985, *Shannon and Nelson,* 1996, *Shillington,* 1998].

The aim of this chapter is to produce a general description of the Benguela system and its peculiarities. A more specific goal is to identify the characteristic patterns of the Benguela dynamics and to extract the key processes that affect the recruitment of sardines and anchovies along the South African West Coast. This analysis leads to the identification of a few key questions relevant for this study.

Les pêcheries le long de la Côte Ouest de l'Afrique du Sud étant d'une importance économique majeure, un effort considérable a été réalisé par les instituts de recherches marines Sud-africains pour analyser l'écosystême du Benguela. Ainsi, de nombreuses études ont été conduites durant les 30 dernières années, comprenant pour la partie physique: des échantillonages hydrologiques, le déploiement de mouillages courantométriques, des mesures aériennes des composantes atmosphériques et de la température de surface de l'eau, des mesures courantométriques par ADCP, le larguage de flotteurs dérivants, l'analyse d'images satellitales, et des études théoriques. Il en découle une descrition détaillée du système; et des progrès significatifs ont été obtenus dans la compréhension des principaux processus. Ces résultats ont été résumés dans différentes revues d'articles [*Nelson and Hutchings,* 1983, *Shannon,* 1985, *Shannon and Nelson,* 1996, *Shillington,* 1998].

L'objectif de ce chapitre est de produire une descripton générale du système du Benguela et de ses particularités. Un but plus précis est l'identification des motifs caractéristiques de la dynamique du Benguela et d'extraire les processus clefs pouvant affecter le recrutement des sardines et des anchois le long de la Côte Ouest de l'Afrique du Sud. Cette analyse conduit à la formulation de quelques questions clefs, pertinantes pour cette étude.

1.1 Geographical settings

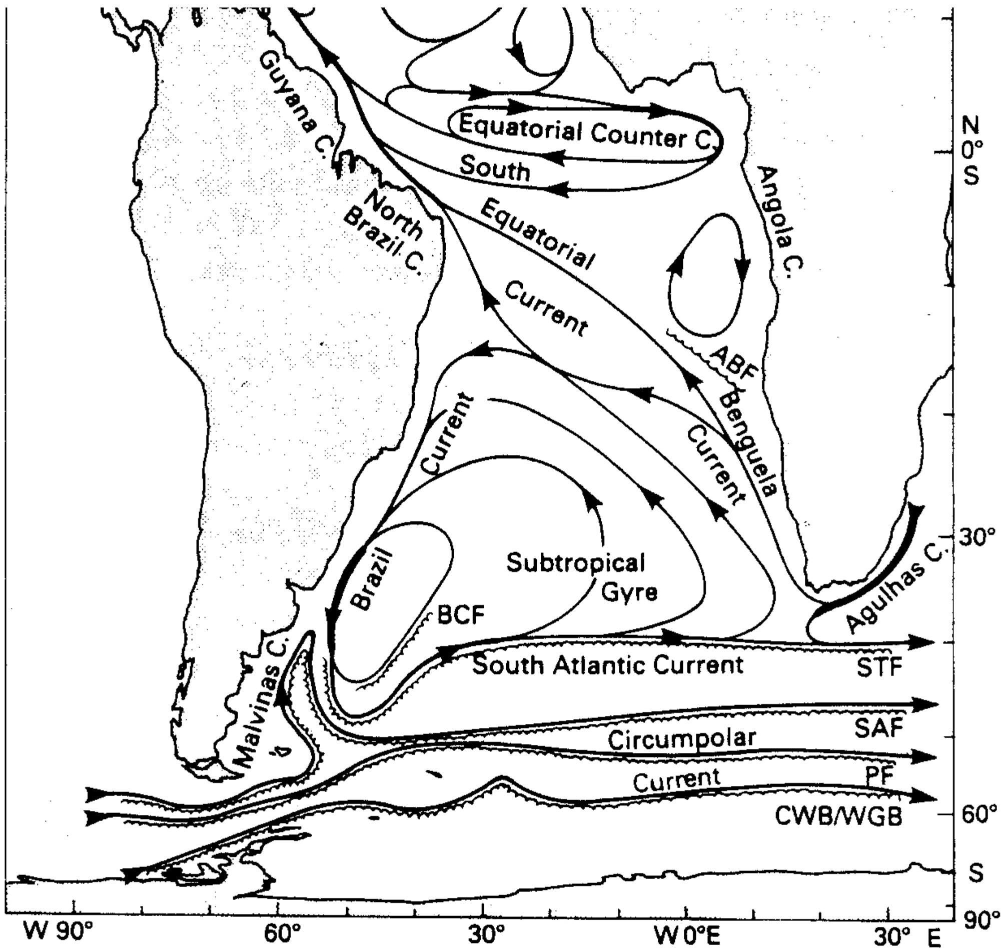

Figure 1.1 Surface currents of the South Atlantic Ocean. Abbreviations are used for the Angola-Benguela Front (ABF), Brazil Current Front (BCF), Sub-tropical Front (STF), Sub-antarctic Front (SAF), Polar Front (PF) and Continental Water Boundary / Wedell Gyre Boundary (CWB/WGB). Adapted from Tomczak and Godfrey [1994].

The Benguela Current is the eastern boundary current of the South Atlantic sub-tropical gyre
[*Peterson and Stramma,* 1987] (figure 1.1). It can be described as a broad northward flow that follows the west coast of southern Africa from the southern tip of Africa (i.e. the Cape Agulhas at 35^o S) to Cape Frio (18.4^o S) near the border between Angola and Namibia [*Garzoli and Gordon,* 1996]. The similar paths of 2 drifters released near Cape Peninsula with an interval of two years exhibit the coherent equatorward surface movement of the current (figure 1.2) [*Nelson and Hutchings,* 1983].

The Benguela system is bounded in the North at about 16^o S by the warm Angolan current, which flows poleward. It is bounded in the South by the warm Agulhas Current, the western boundary current of the Indian Ocean that follows the South Coast of South Africa [*Shillington,* 1998]. The terminology "Benguela Current" describes as well the coastal upwelling system and the large scale eastern limb of the sub-tropical gyre [*Peterson and Stramma,* 1987], thus no precise offshore boundary of the system is defined. For Garzoli and Gordon [1996], at

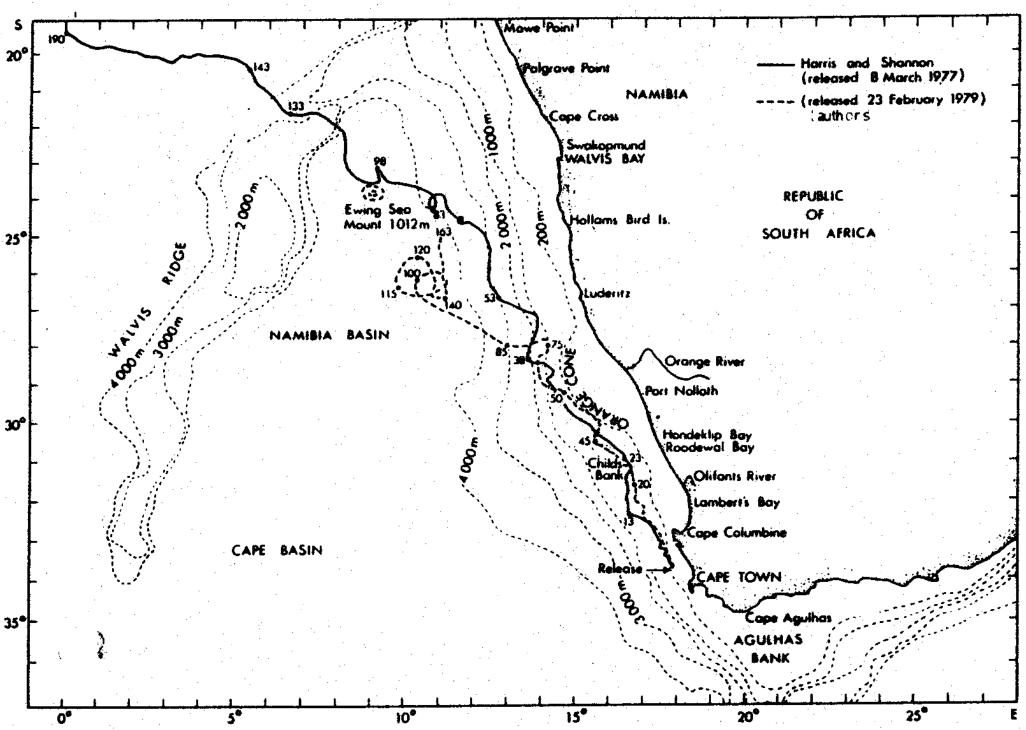

Figure 1.2 Paths of two satellite-tracked drogues released west of Cape Town in March 1977 and in February 1979. Adapted from Nelson and Hutchings [1983].

30^o S, the entire Benguela Current is confined between the South African West Coast and the Walvis ridge ($\sim$ 1200 km from the coast). In this manuscript, we will limit our definition of the Benguela Current to the part of the current that flows over the shelf and the continental slope.

The West Coast of Southern Africa is a narrow coastal plain which rises to the main continental escarpment situated between 50 and 200 km inland. North of 32^o S (Cape Columbine), the coastline is regular and runs in a north-westward direction. South of 32^o S the coastline is irregular, with several capes (Cape Columbine 32^o S, Cape Peninsula 34^o S, Cape Agulhas 35^o S) and bays (St Helena bay, Saldanha Bay, Table Bay, False Bay). One thousand meters-high mountains ranging along the Cape Peninsula can play an important role in perturbing the local wind field [*Shannon,* 1985].

Most of the coastal region is arid with the Namib Desert that extends between 14^o S and 31^o S. The southern region has a cooler Mediterranean type climate.

The continental shelf is highly variable in width (figure 1.3). It can be narrow with minimums located South of Lüderitz (75 km) and in front of Cape Peninsula (40 km), and it can be relatively wide with maximums located off the Orange river (180 km) and on the Agulhas Bank (230 km). The shelf break is deep (200 m) and quasi-rectilinear, running North westward roughly parallel to the coast. It is cut in a north-south direction at 60 km offshore of Cape Columbine by the Cape Canyon. The Agulhas Bank is a wide and shallow feature that forms the southernmost margin of the African continent [*Shannon and Nelson,* 1996].

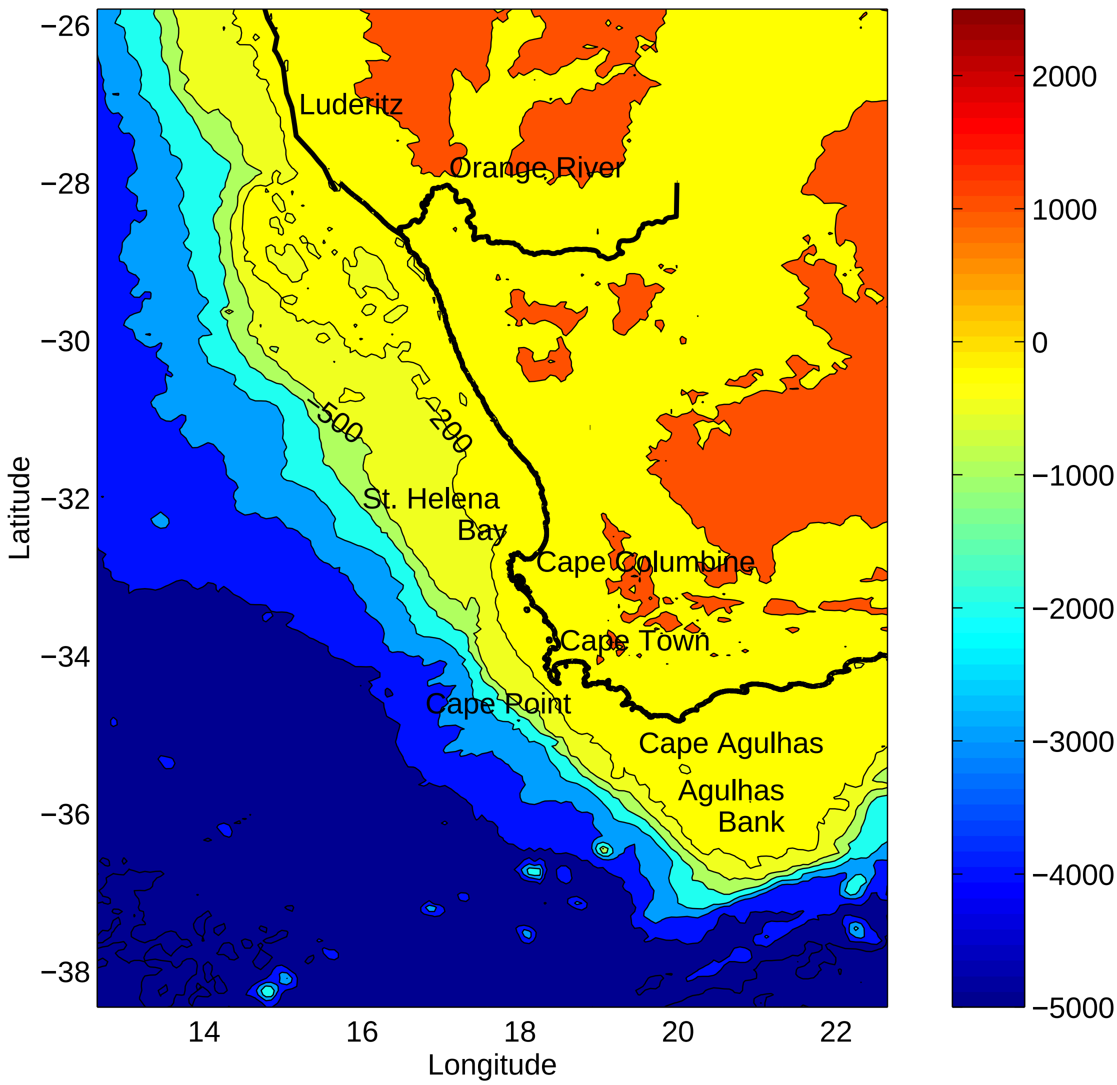

Figure 1.3 Bathymetry of the South-east Atlantic Ocean derived from the ETOPO2 dataset.

1.2 Large scale

The Benguela current flows northward from the Cape of Good Hope. It bends towards the northwest to separate from the coast at around 30^o S while widening rapidly [*Peterson and Stramma,* 1987]. Three currents are feeding the Benguela Current: the South Atlantic Current, which is the southern part of the sub-tropical gyre, the Agulhas current and the Antarctic Circumpolar Current. The composition of the Benguela Current water is as follows: 50 % of Atlantic water, 25 % of water from the Indian Ocean and 25 % of a blend of Agulhas and tropical Atlantic water [*Garzoli and Gordon,* 1996].

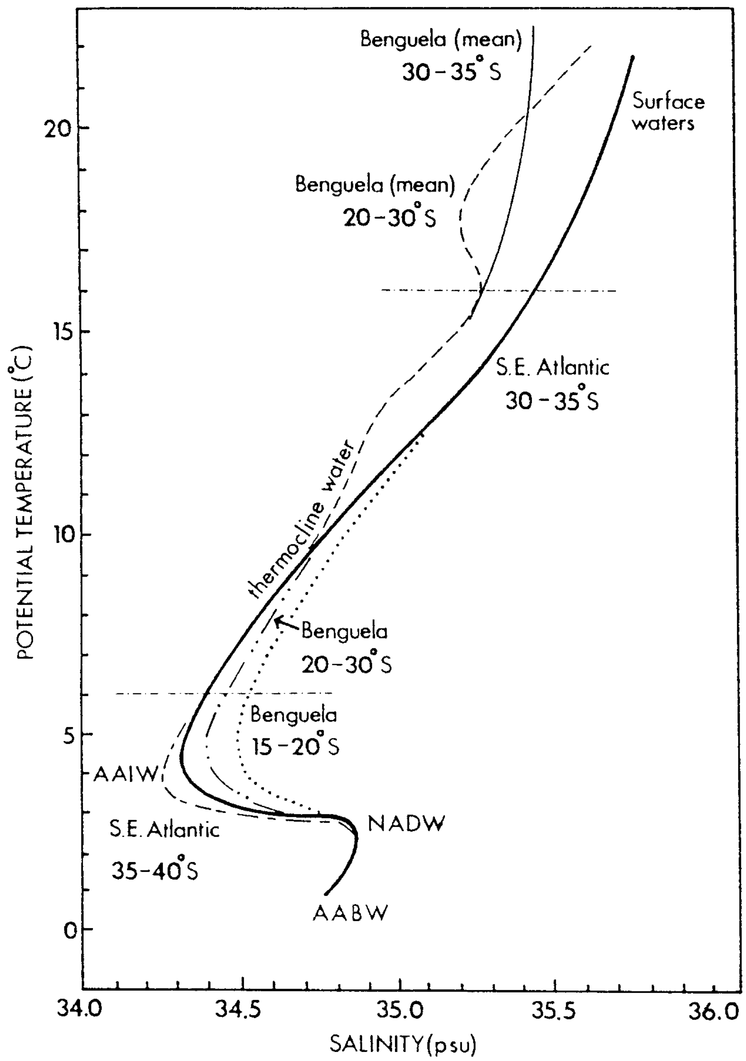

Figure 1.4 The principal water masses and potential temperature - salinity characteristics of the South-east Atlantic and Benguela system. Adapted from Shannon and Nelson [1996].

A T-S diagram exposes the hydrological characteristics of the principal water masses in the Benguela system (figure 1.4). The surface waters are composed of tropical surface water and subtropic surface water. Three kinds of thermocline waters are present: the South Atlantic Central Water (SACW), the South Indian Central Water (SICW) and the Tropical Atlantic Central Water (TACW). Under these, the fresh Antarctic Intermediate Water

(AAIW), characteristic of the South-East Atlantic Ocean by its core of minimum of salinity around 700-800 m, flows toward the equator [*Shannon and Nelson,* 1996]. 4-5 Sv of AAIW is carried this way northward in the Benguela. Underneath, the relatively warm and saline North Atlantic Deep Water (NADW) spreads southward from the North Atlantic between 1000 m and 3500 m. It generates a poleward current along the African continental margin. The Antarctic Bottom Water (AABW) lies below the NADW under 3800 m. Blocked in the North by the Walvis ridge (figure 1.3) , the circulation of the AABW in the Cape Basin is cyclonic. Thus the AABW produces as well a poleward current along the African continental margin with typical speeds of 5 to 10 cm.s^{-1} [*Nelson,* 1989].

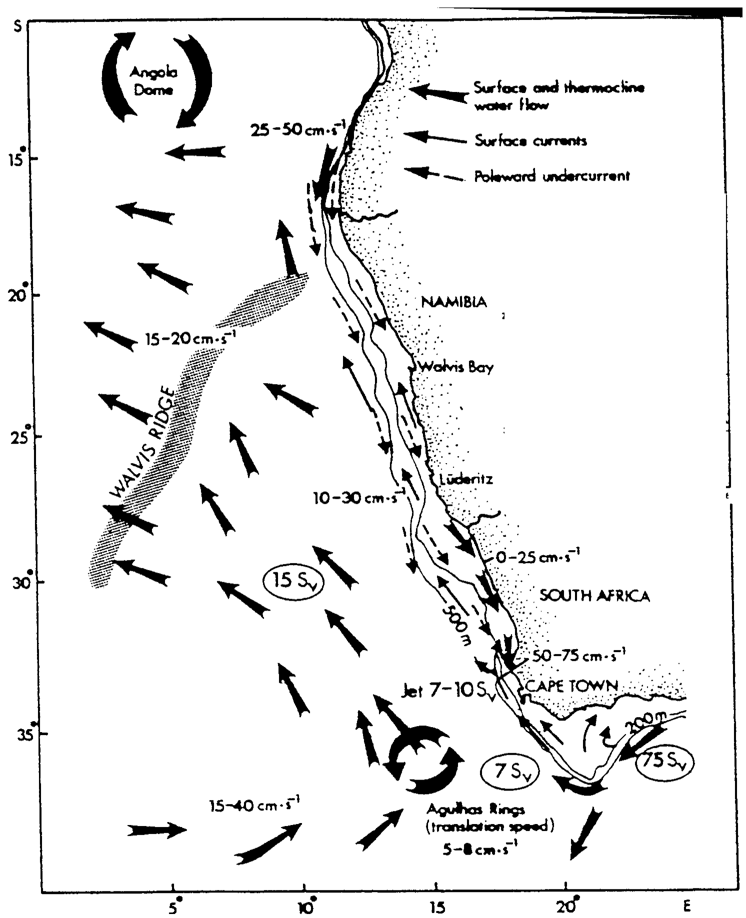

Figure 1.5 Schematic flow field of surface and thermocline waters. Current speeds refer to surface values. Transports (circled) refers to total transport above 1500 db (i.e. includes AAIW). Adapted from Shannon and Nelson [1996].

Equatorward flow occurs in the surface to depth of several hundred of meters. In the surface friction layer, the Ekman drift is typically 20 to 35 cm.s^{-1} [*Nelson,* 1989]. Recent measurements showed that in the upper 1000 m, the Benguela current carries 13 Sv towards the equator across 30^{o} S [*Garzoli and Gordon,* 1996]. The upper layers averaged circulation and transport is summarized in figure 1.5.

One can note in figure (1.5) the large transport (75 Sv) carried by to the Agulhas Current, the western boundary current of the Indian Ocean subtropical gyre, just South-East of the Benguela system. As it flows along the South and East coasts of South Africa, the Agulhas Current reaches an intensity unmatched by any other western boundary currents

[*Beal and Bryden,* 1997] at up to 6 knots (300 cm.s^{-1}) [*Boyd and Oberholster,* 1994]. Its follows the shelf break along the eastern margin of the Agulhas Bank, developing meanders, reverse plumes and counter current on the shelf [*Lutjeharms et al.,* 1989]. It generally leaves the coast just East of the tip of the Agulhas Bank before turning back on itself and flowing eastward into the South Indian Ocean. In this retroflection area, the largest eddies found in the oceans (with diameters up to 300 km), the Agulhas rings, detach from the current and transport warm and salty waters into the South Atlantic. They account for a time-averaged transfer of 10-15 Sv in the upper 1000 m and thus play an important part in the global thermohaline circulation [*Peterson and Stramma,* 1987]. Regularly, warm filaments detach from the southern tip of the Agulhas Bank and develop into the Benguela system [*Lutjeharms and Cooper,* 1996]. Along the East coast of South Africa (32^o S) the presence of a persistent Agulhas undercurrent with velocities as large as 30 cm.s^{-1} and a core at depth around 1200 m has been recently measured [*Beal and Bryden,* 1997].

1.3 Atmospheric forcing

1.3.1 Large scale

The wind field in the Benguela is mainly controlled by the South Atlantic high pressure system (figure 1.6). This anticyclone oscillates seasonally along a North-West (austral fall) / South-East (austral spring) axis. It generates equatorward, upwelling favorable wind stress all around the year in the Northern Benguela and mostly in summer in the Southern Benguela. The flow is steered equatorward along the coast by a thermal barrier set-up by the desert in the North and by the mountain range along the Cape Peninsula in the South. In winter, the Southern Benguela system is under the control of westerly moving depressions that travel past the southern tip of Africa, the dominant winds being more North-Westerly [*Shillington,* 1998]. The upwelling season in the Southern Benguela occurs between September to March. The along shore wind maximum is situated offshore, inducing a cyclonic wind stress curl along the coast [*Shannon and Nelson,* 1996].

1.3.2 Mesoscale modulations

Low pressure cells propagate freely south of the African Continent over a typical period of 1 to 2 weeks. Coastal cells of low pressure develop in association with the approach of the cyclonic systems. These features, named coastal lows, form near Lüderitz and travel South around the continent as coastal trapped waves [*Nelson and Hutchings,* 1983]. Sometimes, a flow of dry adiabatically heated air blows of the western escarpment when high pressure cells form over the subcontinent: the so called "berg" winds [*Shannon and Nelson,* 1996]. The typical cyclic summer weather pattern is portrayed on figure (1.7). It has been proposed that this cycle induces a strong variability in coastal upwelling and shelf currents of a period of 3 to 6 days [*Nelson and Hutchings,* 1983]. Pulsing of the Benguela ecosystem has been related to the resonance between shelf waves and the passage of coastal lows [*Jury et al.,* 1990] and an optimum resonant pulse interval of 10 days has been suggested [*Jury and Brundrit,* 1992]. Strong diurnal rotary winds induced by land-sea breezes occur north of Cape Columbine [*Shannon and Nelson,* 1996].

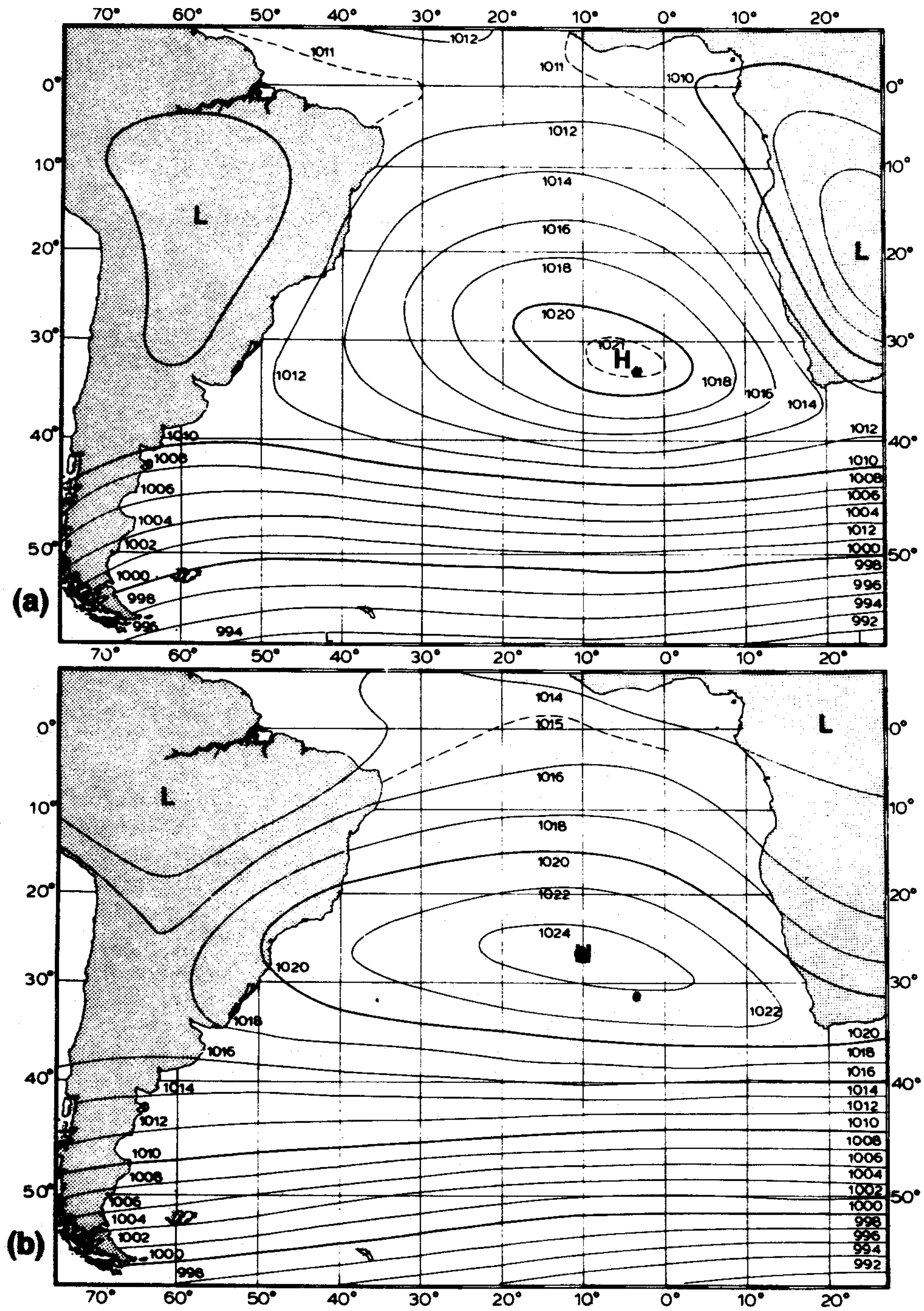

Figure 1.6 Mean atmospheric sea level pressure (hpa) for (a) January, and (b) July. Adapted from Peterson and Stramma [1987].

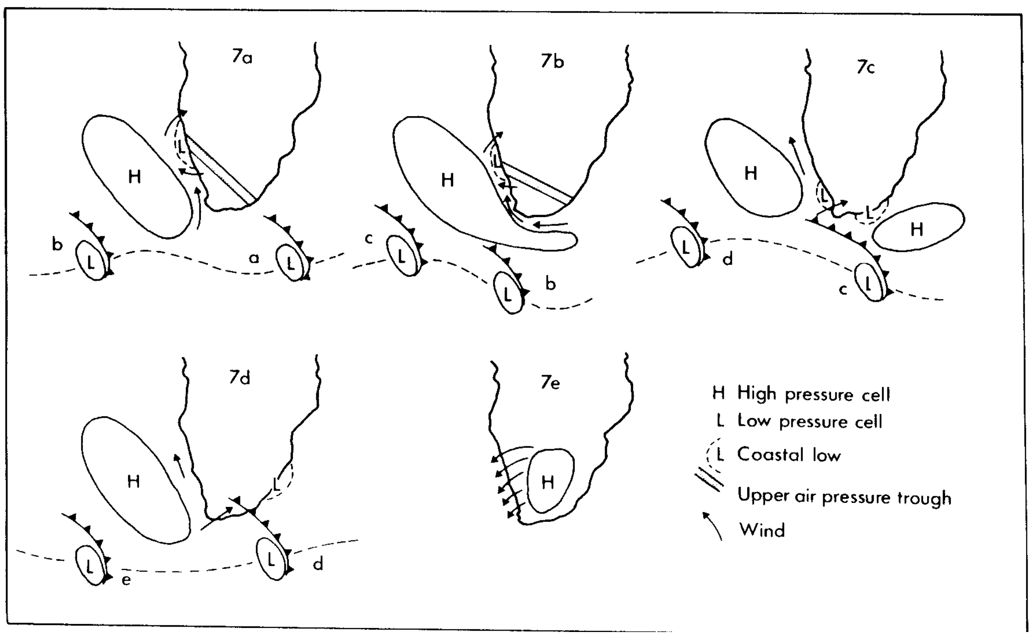

Figure 1.7 Cyclic weather pattern over the Benguela system, typical of summer conditions. (a) South Atlantic high established - coastal low at Lüderitz - southerly winds at Cape Town. (b) South Atlantic High ridging - gale force winds at Cape Town - coastal low moves south. (c) South Atlantic High weakens - North West winds at Cape Town, following the passage of the coastal low. (d) South Atlantic High strengthens - southerly winds along the west coast. (e) Berg wind conditions. Adapted from Nelson and Hutchings [1983].

1.3.3 Local structures

Numerous studies have been conducted on local wind structures with the aim of relating them to mesoscale structures observed in the Benguela upwelling system [*Jury,* 1985a, *Jury,* 1985b, *Jury et al.,* 1985, *Jury,* 1986, *Jury,* 1988, *Kamstra,* 1985, *Taunton-Clark,* 1985]. Areas of cyclonic wind stress curl have been identified. They are induced by land topography in the lee of Cape Columbine (i. e. in St. Helena Bay) and in the lee of Cape Peninsula or by locally intensified atmospheric thermal front between warm land and cool sea along the Namaqualand coastline (30^o S) [*Jury,* 1988]. The cyclonic wind stress curl induced by the wake in the lee of Cape Columbine has been measured during typical events for the vertical atmospheric structure [*Jury,* 1985a]. The wake (and then the cyclonic curl) is stronger in shallow events (low inversion layer) than in deep events (high inversion layer). The presence of upwelling plumes in the lee of Cape Peninsula and Cape Columbine has been related to those topographically induced cyclonic wind stress curls [*Jury,* 1985a, *Jury,* 1985b, *Jury et al.,* 1985, *Jury,* 1986, *Jury and Taunton-Clark,* 1986, *Jury,* 1988, *Kamstra,* 1985, *Taunton-Clark,* 1985]. However, a complete dynamical demonstration of the plume / wind stress curl relationship is missing. In the same way, the presence of cyclonic eddies in the vicinity of Cape Peninsula has been related to mesoscale temporal and spatial variations in surface winds [*Jury et al.,* 1985], but the formation of these eddies does not appear to be correlated to local winds [*Lutjeharms and Matthysen,* 1995].

1.4 Along the West Coast

1.4.1 Upwelling

The wind induced coastal upwelling is characterized by a pronounced negative sea surface temperature anomaly found mainly within the 150-200 km off the West Coast of southern Africa [*Shannon,* 1985, *Lutjeharms and Stockton,* 1987]. Four major semi-permanent upwelling centers are present in the Southern Benguela: the Lüderitz cell at 27^o S, the Namaqualand cell at around 30^o S, the Cape Columbine upwelling plume at 33^o S and the Cape Peninsula upwelling plume at 34^o S. The presence of these cells has been related to local maximums in wind stress curl [*Jury,* 1988], change in coastline orientation [*Shannon and Nelson,* 1996] or narrowing of the shelf [*Nelson and Hutchings,* 1983]. The upwelled water originates from 200-300 m [*Nelson and Hutchings,* 1983]. It is separated all along the coast from the offshore warmer water by a well developed oceanic front [*Brundrit,* 1981]. Although highly convoluted and variable, the front coincides approximately with the shelf break. It shows large scale stationary features that have been related to the existence of propagating barotropic shelf waves, although the latter cannot explain the standing nature of the process [*Shannon,* 1985].

1.4.2 Circulation

A strong equatorward surface baroclinic jet is in geostrophic balance with the upwelling front [*Shillington,* 1998] and follows the 200-300 m isobath [*Nelson and Hutchings,* 1983]. The speed of this semi-permanent jet ranges from 40 cm.s^{-1} to 80 cm.s^{-1} west of Cape Town [*Boyd and Nelson,* 1998] and is typically in excess of 50 cm.s^{-1} offshore of Cape Columbine (figure 1.8) [*Nelson and Hutchings,* 1983]. It can be strengthened near Cape Peninsula by the vicinity of Agulhas waters with high steric height offshore [*Strub et al.* 1998]. Its width has been estimated at some 20-30 km [*Nelson and Hutchings,* 1983]. As represented on figure (1.8), this jet separates in two branches just north of Cape Columbine, one branch bending into St. Helena Bay, the other, with a

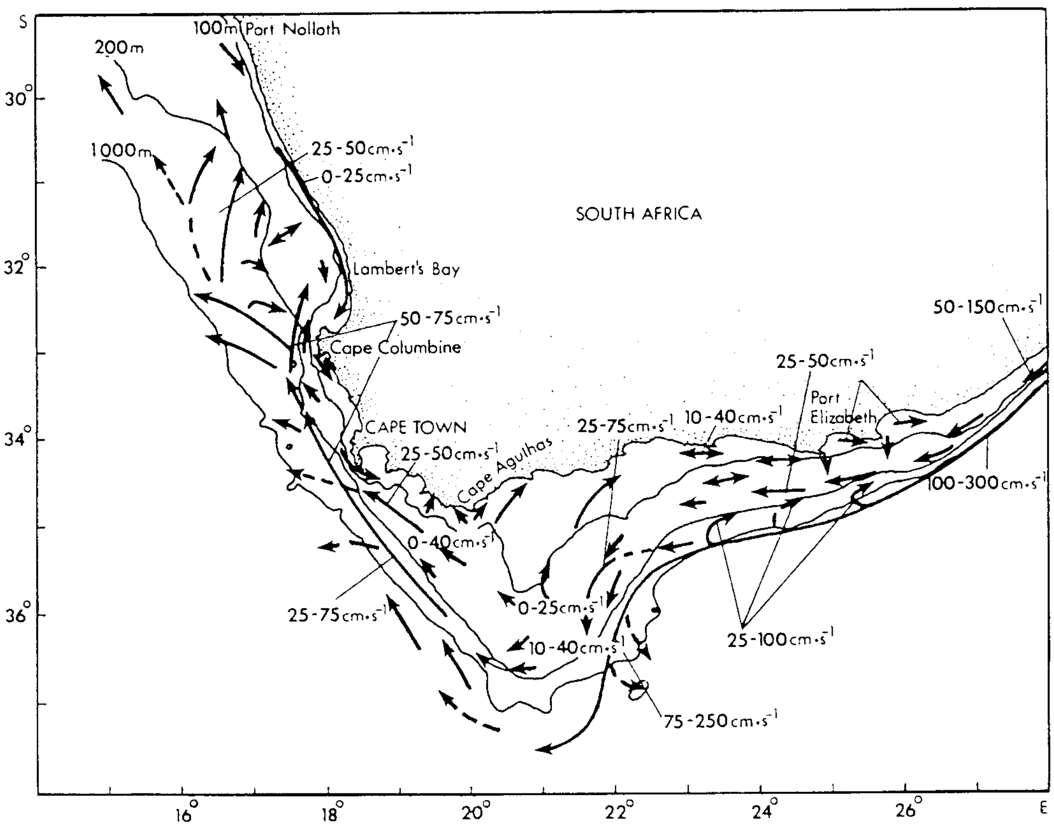

Figure 1.8 Schematic flow-field of near-surface currents based on ADCP data collected between November 1989 and January 1992. Velocity ranges indicated are typical values. Adapted from Boyd and Shillington [1994].

stronger intensity, flowing offshore. Altimeter data show a convoluted equatorward jet several hundred kilometers offshore North of 33^o S [*Strub et al.* 1998].

A net subsurface poleward flow, with averaged velocities of 4.5 cm.s^{-1} to 6 cm.s^{-1}, has been observed close to the shore along the entire west coast [*Boyd and Oberholster,* 1994, *Nelson,* 1989]. It exhibits a wave-like motion with periodicities of approximately three days. The cause of this flow along the inner shelf is still unknown [*Nelson,* 1989].

Another characteristic feature of the Benguela system is the existence of the shelf edge poleward undercurrent [*Nelson and Hutchings,* 1983]. It has been directly observed in a number of cross sections and an average speed of 5-6 cm.s^{-1} is given [*Shannon and Nelson,* 1996]. It is part of a more extensive poleward motion stretching from the coast across the bottom of the shelf to the Cape Basin [*Nelson,* 1989]. The observation of oxygen-deficient water coming from a source area off Angola along the shelf edge and onto the the shelf is another confirmation of the existence of the poleward undercurrent [*Dingle and Nelson,* 1993]. Recent current measurements off Cape Columbine have revealed a deep poleward undercurrent of 11 cm.s^{-1} in autumn, 6.8 cm.s^{-1} in winter, 7.4 cm.s^{-1} in spring and 8.3 cm.s^{-1} in summer [*Nelson et al.,* 1999].

The averaged bottom temperature shows a cross-isobath trend on the shelf and numerous hot-spots on coastal locations. It exhibits a flooded area North of Cape Columbine, where the 8^oC isotherm intrudes onto the shelf. On the shelf, the bottom mixed layer has seldom a thickness less than 3 % of the total depth and it can be 2 or 3 times thicker on the shelf edge [*Dingle and Nelson,* 1993].

Tides along the West Coast are semi-diurnal, with a maximum spring range of about 2 m. The phase arrives almost almost simultaneously everywhere along the West Coast. Tides induces small oscillations in the current in the order of 10-15 cm.s^{-1} [*Shillington,* 1998].

1.4.3 Mesoscale features

The most impressive aspect of the Benguela system, and surely of the most importance either from both a physical or a biological point of view, is the high mesoscale activity that develops all along the coast. Four classes of characteristic mesoscale features have been extracted from satellite images of sea surface temperature [*Lutjeharms and Stockton,* 1987]: upwelling plumes, upwelling filaments, upwelling eddies and Agulhas current filaments. The impact of mesoscale activity on primary production in the Southern Benguela has been illustrated by satellite imagery [*Shannon et al.,* 1985]. Mesoscale activity can also affect the transport pattern of fish larvae [*Lutjeharms and Stockton,* 1987]. The Agulhas rings that have been described in section 1.2 might interfere sporadically with the Benguela system.

Upwelling plumes are variable, semi-permanent tongues of cold water spreading from the major upwelling centers. Four sites of generation off upwelling plumes have been recognized in the Benguela: Cape Peninsula, Cape Columbine, Hondeklip Bay-Namaqualand and Lüderitz. The Cape Peninsula upwelling plume is present during the summer months [*Taunton-Clark,* 1985], whereas it can be masked during Northerly winds. It shows an elongated shape extending north-westward (figure 1.9) enclosing cooler water at the coast. The funneling of cold water through a canyon in the south-west (the Cape Point Valley) [*Shannon et al.,* 1981] and the influence of the coastal mountains on local winds [*Jury,* 1988] has been advanced has explanations of the presence of this plume. A similar tongue of cold water has been observed extending from Cape Columbine (figure 1.10) [*Shannon,* 1985, *Jury,* 1985a, *Jury,* 1985b]. It has an inverted "S" characteristic shape, suggesting topographic control [*Shannon,* 1985]. Whereas upwelling in Namaqualand is confined into a coastal strip, a broad plume of cold wa-

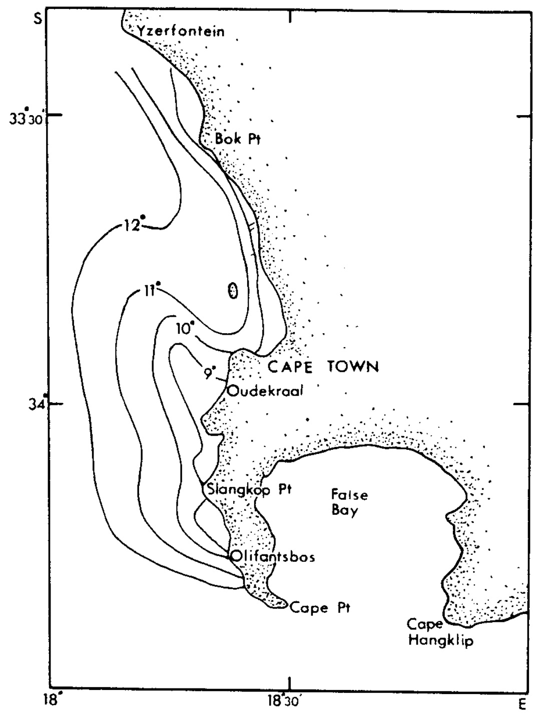

Figure 1.9 A schematic sea surface temperature (^{o} C) map of a typical developed Cape Peninsula upwelling tongue. Adapted from Taunton-Clark [1985].

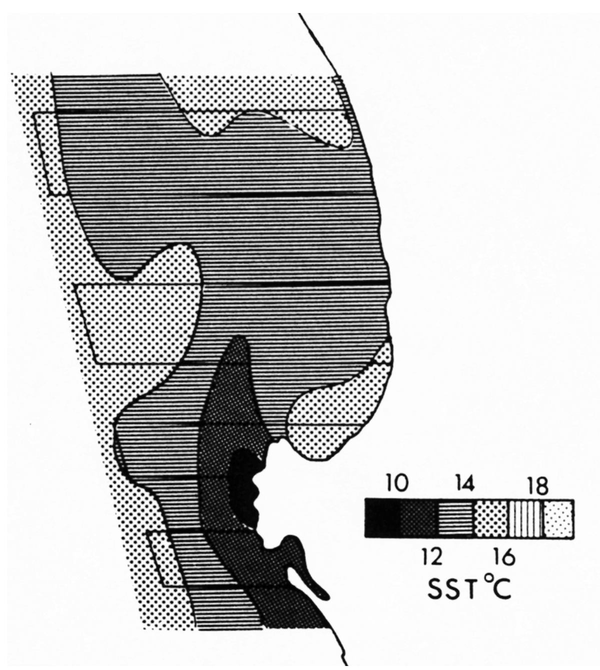

Figure 1.10 Sea surface temperature (^{o} C) distribution in St Helena Bay for 1 November 1980. An upwelling plume extends from Cape Columbine. Adapted from Jury [1985a].

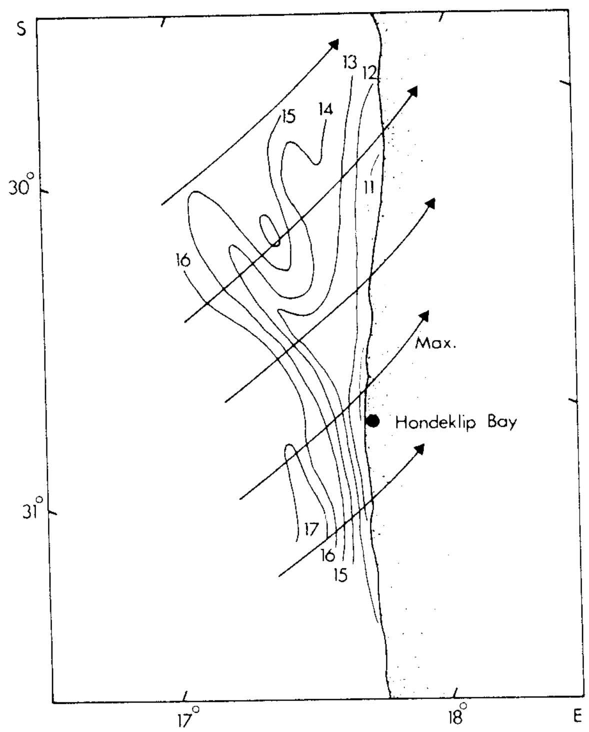

Figure 1.11 Namaqualand sea surface temperature (^{o} C) and wind streamlines for 25 November 1980 (Max. = area of highest speed). The Namaqualand upwelling plume develops from the coast. Adapted from Jury and Taunton-Clark [1986].

ter extends offshore near 30^o S (figure 1.11). The base of this plume coincides with a maximum in along shore winds and a broadening in the continental shelf [*Jury and Taunton-Clark,* 1986]. The Lüderitz plume doesn't grow from a fixed location on the coastline, but as it develops, it makes roughly always the same angle with the coast [*Lutjeharms and Stockton,* 1987].

In comparison with upwelling plumes, upwelling filaments are narrower, not standing, and short-lived features (between five days and five weeks) extending from the upwelling front [*Lutjeharms and Stockton,* 1987]. An in-situ investigation off a filament have shown that it is a relatively shallow feature that is confined in the upper 50 m. Filaments have typical elongations of 200 km [*Shannon and Nelson,* 1996], ranging from 50 km to 600 km [*Lutjeharms and Stockton,* 1987]. In extreme cases, they may extend 1000 km or more offshore [*Lutjeharms et al.,* 1991]. On average, two times more filaments develop from Lüderitz than from the Cape Peninsula [*Lutjeharms and Stockton,* 1987]. ADCP measurements have revealed the interaction between eddies and filaments North of the Cape Peninsula [*Nelson et al.,* 1999].

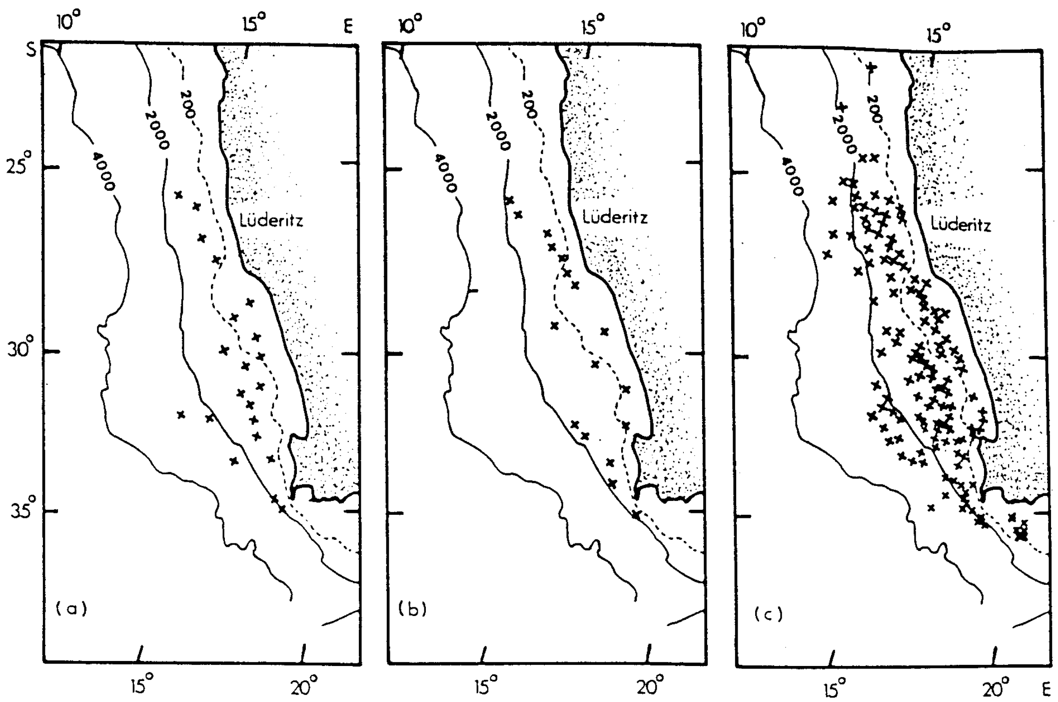

Figure 1.12 Location of frontal eddies on the upwelling front from (a) February 1985, (b) August 1985 and (c) the whole of 1985, according to imagery from NOAA-9 satellite. Adapted from Lutjeharms and Stockton [1987].

Eddies are numerous in the system with a preponderance off-shore and downstream of the four major upwelling centers (figure 1.12). Their distributions show no clear seasonal patterns [*Lutjeharms and Stockton,* 1987]. The Cape Peninsula has been recognized as a highly productive area of cyclonic eddies with averaged diameters of 42 km ± 16 km. No correlation exists between the formation of these eddies and the local winds [*Lutjeharms and Matthysen,* 1995]. Vortex dipoles composed of eddies of about 50 km diameter has been observed near Cape Columbine and Lüderitz [*Stockton and Lutjeharms,* 1988]. Altimeter data has revealed the generation of cyclonic eddies from the coast and their propagation offshore to the west [*Strub et al.* 1998].

One possible link between the Agulhas and the Benguela systems is the spreading of long streak of warm water from the Agulhas current along the western edge of the Agulhas Bank: the Agulhas filaments. They can interact with the Cape Peninsula upwelling front and catalyse eddy formation from the cape [*Lutjeharms and Stockton,* 1987] or increase steric height gradient at the front [*Strub et al.* 1998]. Intrusion of Agulhas water within 30 km of Cape Peninsula, flowing northward at around 40-60 cm.s^{-1} has been regularly observed [*Boyd and Nelson,* 1998]. Most of the Agulhas filaments detach from the Agulhas Current just downstream of the southern tip of the Agulhas Bank. Six or seven are formed per year, each usually lasting 3-4 weeks. Their average width is around 50 $\pm$ 16 km and their average length 530 $\pm$ 166 km. They do not appear to extend deeper than 85 m, but they can be responsible of between 5 % and 15 % of the total interbasin salt flux generated by the Agulhas Current [*Lutjeharms and Cooper,* 1996].

1.4.4 The nursery ground of the West Coast: St Helena Bay

St Helena bay can be defined in a broad sense as the wide shelf area extending 200 km North of Cape Columbine (figure 1.3). South of Cape Columbine, the width of the shelf is narrow (50 km) and becomes broader further north (up to 150 km).

The size repartition of anchovy larvae have shown that the area North of Cape Columbine is the major nursery ground of the West Coast, with large numbers of small anchovy larvae being advected into the area from the South [*Boyd and Hewitson,* 1983]. High concentrations of juvenile fish have been observed in the area [*Hutchings,* 1992].

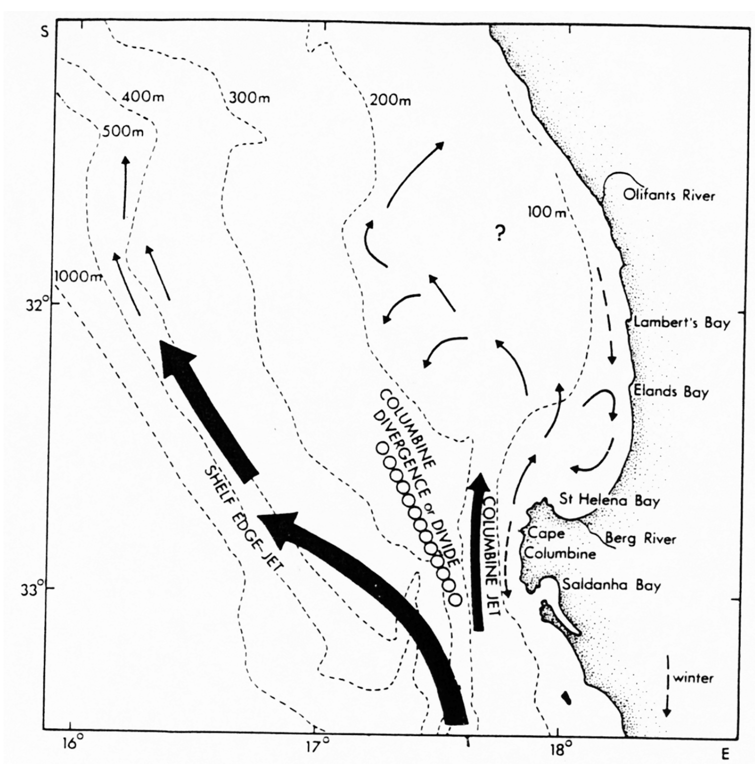

Figure 1.13 Schematic representation of currents in the Cape Columbine-St Helena Bay area. Adapted from Shannon [1985].

The Cape Columbine upwelling plume develops during upwelling events. Kamstra [1985] and Jury [1985a] have related the generation of the plume to the cyclonic wind stress curl in the vicinity of Cape Columbine. This curl is generated by topographic effects on wind around the cape and it appears to be pronounced during "shallow southeasterly events" (marine layer thickness comparable to land elevation). Using radio tracked drifters, Holden [1985] shows that whereas the flow is predominantly northward and perturbed by small eddies, a cyclonic vortex remains in St. Helena Bay. It connects to a southward current flowing along the coast (figure 1.13). ADCP measurments show the same pattern in St Helena Bay with an inshore curvature of the surface currents, bounding a broad area of weak mean currents [*Boyd and Oberholster,* 1994]. Whereas stratification might be important in the bay [*Bailey and Chapman,* 1985], current meter moorings near Cape Columbine [*Lamberth and Nelson,* 1987] have demonstrated the transient barotropic nature of the flow. Offshore and associated with a subsurface front, the baroclinic jet described in section (1.4.2) follows the shelf edge with estimated surface velocities of 60 cm.s^{-1} (figure 1.13) [*Shannon,* 1985].

1.5 The spawning area: the Agulhas Bank

The Agulhas Bank forms the southernmost extremity of the African continent. It is a wide triangular shelf extending up to 230 km south from the coast (figure 1.3). It has been recognized as the main spawning area for sardines and anchovies in the Southern Benguela. The transport of eggs and larvae between the western part of the Bank and the nursery grounds of the West Coast is a major factor for the success of sardines and anchovies recruitment [*Fowler and Boyd,* 1998].

The coastal boundary of the Agulhas Bank is forced by the wind. Easterly winds can drive episodic coastal upwelling in summer. Inshore of the 100 m isobath, the currents are weak and/or variable in speed and direction, with a net North-West flow West of Cape Agulhas. This convergent North-West current system funnels into the shelf edge jet of Cape Peninsula [*Boyd and Oberholster,* 1994], it is supposed to be the path followed by the larvae to reach the West Coast [*Fowler and Boyd,* 1998]. Within the Bank, the summer vertical structure shows a strong stratification, whereas it is well mixed in winter due to erosion by winter storms. Coastal sea level and coastal current reversals reveal the passage of eastward traveling coastal trapped waves [*Boyd and Shilligton,* 1994].

The eastern and offshore part of the Agulhas Bank is highly influenced by the Agulhas current. It flows along the shelf edge, developing meanders, shear edge features, borders eddies and reverse plumes on the Bank [*Lutjeharms et al.,* 1989]. A ridge of cool water surrounded by a cyclonic circulation has been observed from the eastern to the central Bank [*Boyd and Shilligton,* 1994]. Vertical cross sections have shown that uplift of cold water can be associated with reverse plumes and border eddies [*Lutjeharms et al.,* 1989]. There is not yet an explanation on how this feature is formed [*Boyd and Shilligton,* 1994].

1.6 Variability

Typical currents spectra on the Benguela shelf show significant peaks between 2.5 and 4 days [*Nelson,* 1989]. This have been related to modulations in atmospheric forcing [*Jury,* 1986] or the passing of coastal trapped waves [*Shillington,* 1998]. Jury and Brundrit [1992] have suggested a resonant optimum pulse between oceanic and atmospheric coastal trapped waves of 10 days. Pulsing in the upwelling cycle has been found to range between 10 days and more than 20 days [*Jury et al.,* 1990]. A spectral analysis of tide gauge measurements in Cape

Town has exhibited a wide peak at around 10-15 days [*Schumann and Brink,* 1990].

At the seasonal scale, upwelling is less variable in the Northern Benguela than in the South where it stops during winter. Garzoli and Gordon [1996] have found the strongest seasonal pattern in transport near the shelf edge at 30^o S.

The system shows definite interannual variability with the occurrence of cold and warm events [*Shannon and Nelson,* 1996]. The possibility of high sea-level events propagating poleward from the equatorial Atlantic in the manner of the Pacific El Niño has been confirmed [*Brundrit et al.,* 1987]. Less intense and less frequent than Pacific El Niño, the warm Benguela Niños events are characterized by the advection of tropical water southwards along the coast of Namibia [*Shannon and Nelson,* 1996]. Benguela Niños are not necessarily in phase with the El Niño Southern Oscillation.

1.7 Summary

The Benguela current differs from the other eastern boundary systems by the poleward limitation of the coastal boundary at 34^o S. This allows the South Indian western boundary current to approach closely and to interact with the system. The dominant equatorward wind regime induces a strong coastal upwelling separated from the open ocean by a well developed oceanic front. This front is highly convoluted and follows roughly the shelf edge. It is associated with a strong surface baroclinic jet that is present from Cape Peninsula to Cape Columbine. After dividing near Cape Columbine, the outer branch of the jet is found further offshore northward. Whereas the wind forcing is mainly equatorward, poleward motion occurs in the Benguela in the form of a poleward coastal counter current, a poleward undercurrent and a deep poleward motion at the base of the shelf edge. High mesoscale activity is a major characteristic of the system. It includes localized upwelling plumes, upwelling filaments extending sometimes far offshore from the front, upwelling eddies that can carry coastal products offshore in the ocean, Agulhas filaments that sometimes interact with the upwelling front, coastal trapped waves, and the famous Agulhas rings that are shed from the Agulhas Current. This variability is exhibited on spatial scales ranging from around ten kilometers to hundreds of kilometers and temporal scales ranging from a few days to several months.

Sardines and anchovies have adapted their life strategy to the complexity and peculiarities of the system by spawning on the Agulhas Bank, upstream of the upwelling centers. St Helena bay, in the lee of Cape Columbine and hundreds of kilometers away from the spawning grounds, appears to be the most important nursery ground of the South African West Coast.

The Benguela has been extensively studied, but the complexity of the system is such that numerous questions are still open. I would like to present here a few that seem to be relevant for this manuscript:

- What is specific in the dynamics of St Helena Bay that make it a successful nursery ground ?
- How does the transport work from the Agulhas Bank to the upwelling centers ?
- What is the impact of mesoscale activity on the transport patterns?

There are several ways to explore these questions. During the last 30 years, a large quantity of data has been collected, providing numerous insights regarding the dynamics of the

Benguela upwelling system. More data and new oceanographic cruises could be set up to answer the questions listed to the previous paragraph. However, numerical tools are now widely available and become more and more relevant to explore coastal processes. In the Benguela, modeling is in its infancy and we have taken the opportunity to explore the dynamics of the system using an approach, as well as tools, that have never been used in the region.