tropical beach locations and during beach erosion leads to exposure of the beachrock parallel to the shoreline.

On arid to temperate carbonate-rich coasts subaerial pedogenesis led to the formation of calcarenite in beach and dune systems, particularly during Pleistocene low sea levels. When these systems are subsequently drowned by rising sea level, they remain as dune or beach calcarenite, and are manifest as reefs, islands, and rocky bluffs and cliffs, all of which exert a geological influence on the shoreline (**Figure 15**).

## See also

**Coastal Circulation Models. Geomorphology. Sandy Beaches, Biology of. Storm Surges. Tides. Waves on Beaches.**

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# BEAKED WALES

*See* **SPERM WHALES AND BEAKED WHALES**

# BENGUELA CURRENT

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## Introduction

The Benguela, which shares its name with a town in Angola, is one of four major current systems situated at the eastern boundaries of the world oceans, and the oceanography of the region is in many respects similar to that of the Canary Current off north-west Africa, the California Current off the west coast of the USA, and the Humboldt Current off Peru and Chile. The Benguela is, however, unique in that it is bounded at both equatorward and poleward ends by warm-water systems. Eastern boundary current systems are characterized by wind-driven upwelling along the coast of cold, nutrient-rich water which supports high biological productivity.

Different interpretations exist as to what constitutes the Benguela Current, its ecosystem and its boundaries. In this article, the broader definition of the Benguela will be used and the currents and physical processes which occur in that part of the South Atlantic between 5°S and 38°S and east of the 0° meridian will be considered. This encompasses the coastal upwelling regime, the eastern part of the South Atlantic gyre, and a series of fronts and transitional zones, overlying some complex bathymetry. The continental shelf along the west coast of southern Africa is variable in width, being narrow off southern Angola, near Lüderitz in Namibia, and near Cape Town, and widest off the Orange River and in the extreme south where the Agulhas Bank protrudes polewards (**Figure 1**). The shelf-break (edge of the continental shelf) lies at depths between 200 m and 500 m, from which a steep continental slope descends to about 5000 m where it meets the abyssal plains of the Cape and Angola Basins which in turn are separated by an extensive submarine mountain chain, the Walvis Ridge (**Figure 1**).

The earliest physical measurements in the area were those necessary for the safe and efficient passage of sailing ships along the trade routes between

Europe and the East – wind, currents, waves. The records of the early navigators contain a remarkable amount of information about the physical oceanography of the region, and charts of currents published in the 1700s display features which were 'discovered' by scientists during the past half century! However, the application of late twentieth century technology to the study of the Benguela –

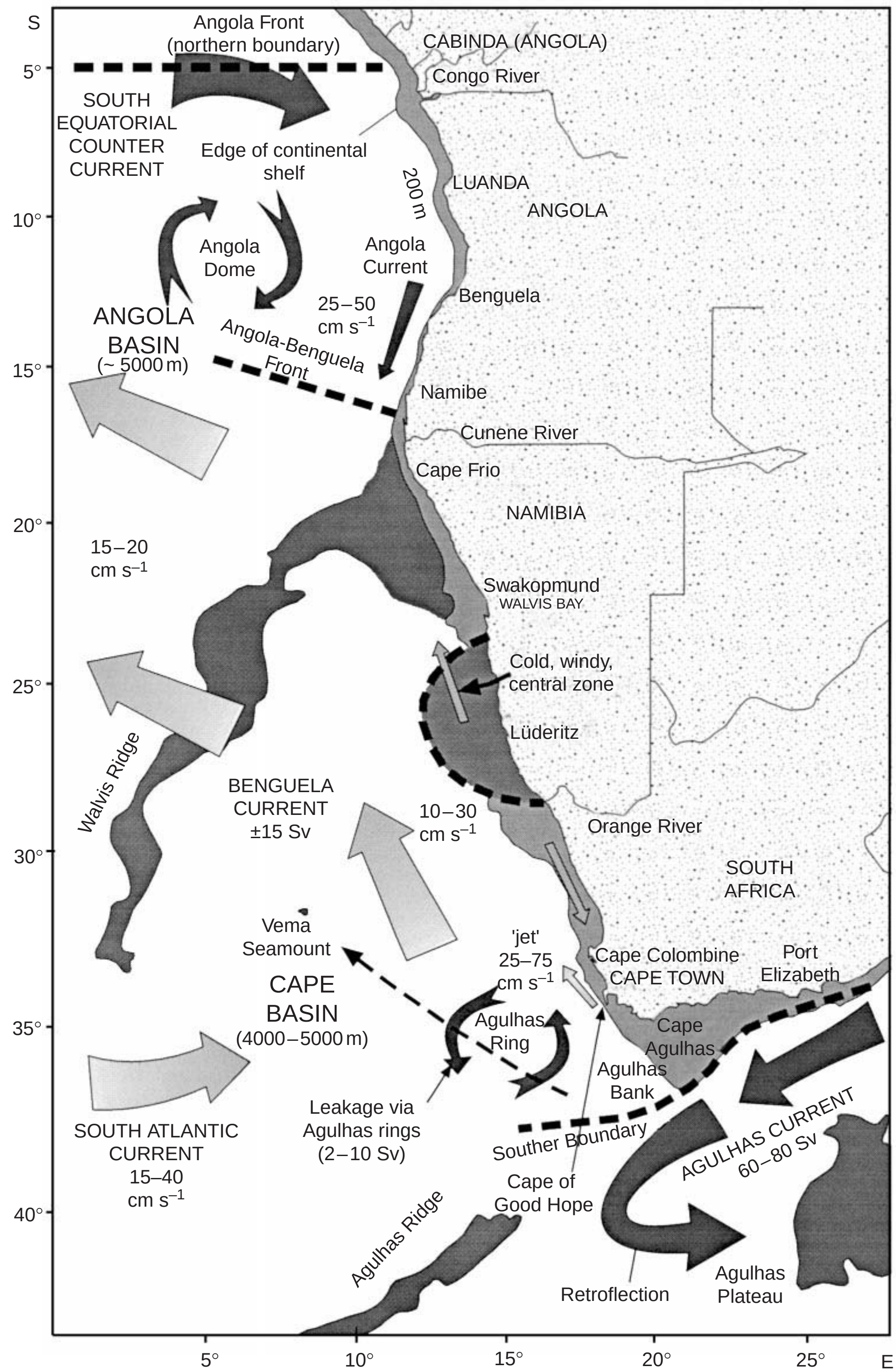



**Figure 1** Schematic of the Benguela Current region showing general bathymetry, currents in the upper layer, and system boundaries.

moored instruments, surface and submerged floats and in particular satellite technology – has highlighted the complexity and variability of the Benguela. Like the adjacent African continent it is an area of contrasts.

## Winds

Winds significantly influence the oceanography of the Benguela region on various time- and space-scales from events of only a few hours duration to basin-wide seasonal and longer period processes. The prevailing winds along the west coast of southern Africa are controlled by the anticyclonic (anticlockwise in the Southern Hemisphere) motion around the South Atlantic High (SAH) pressure system, the seasonal pressure field over the land, and eastward moving cyclones which cross the southern part of the continent. The SAH, part of a discontinuous belt of high pressure which encircles the Southern Hemisphere, is maintained throughout the year but migrates seasonally, being further north in the austral winter. The pressure over the land alternates between a well-developed low during summer and a weak high in winter, and so winds are seasonally variable. The coastal plain acts as a thermal barrier to cross-flow, and hence winds tend to be longshore southerly over most of the Benguela region, steered by the coast. It is these winds which produce coastal upwelling. The essential seasonal and longshore differences in the intensity of the upwelling-producing winds are illustrated in **Figure 2**.

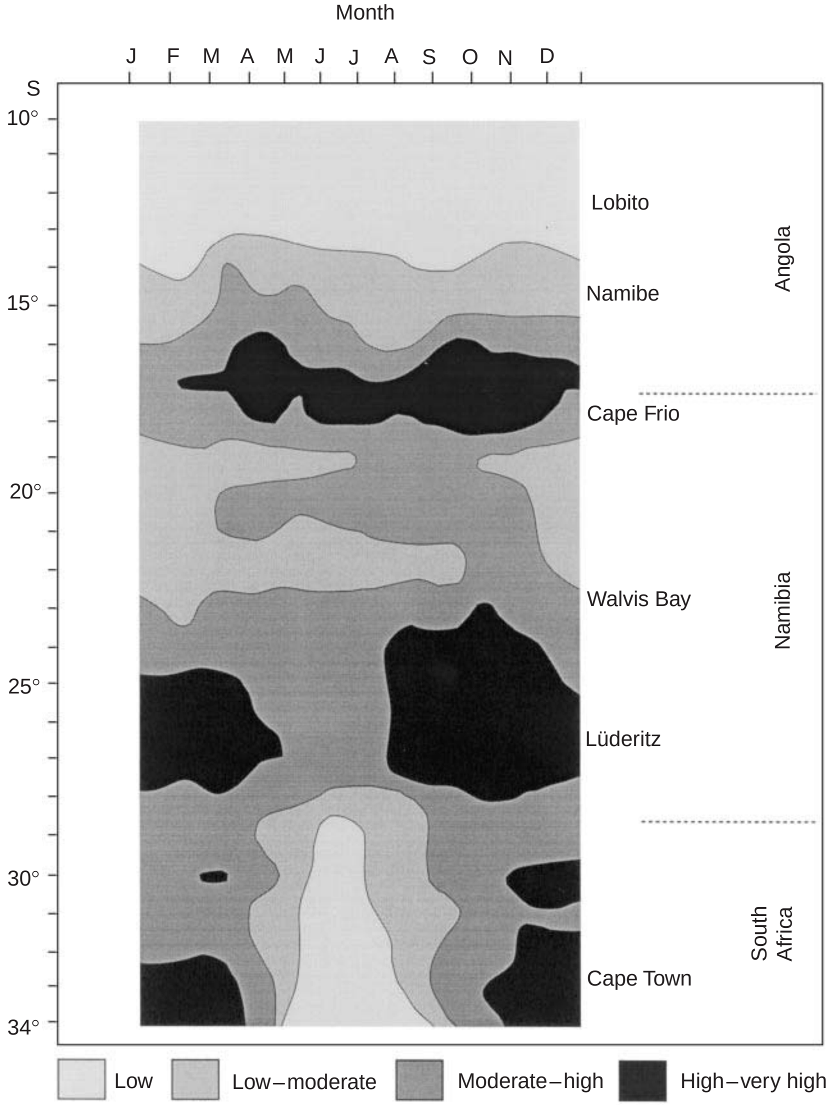



**Figure 2** Monthly wind stress along the west coast of southern Africa 75 km offshore (according to A.J. Boyd, 1987). Note the zones of high wind stress near Lüderitz, Cape Frio and also the seasonality in the south.

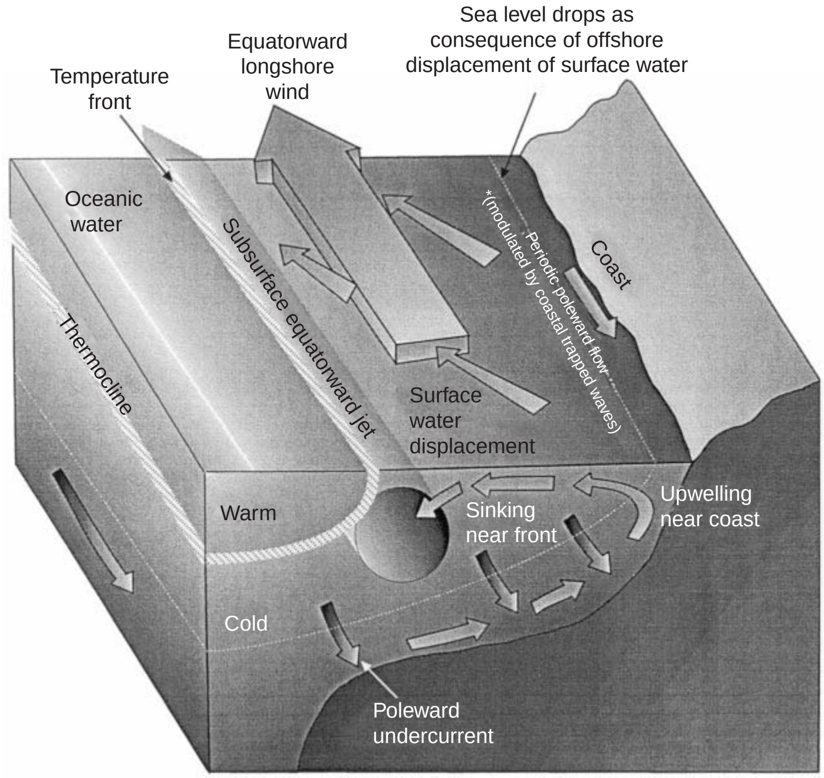



**Figure 3** Schematic showing the structure of coastal upwelling and associated circulation in the Southern hemisphere.

The principal area of perennially strong southerly winds lies near Lüderitz (27°S). In winter the northward shift of the pressure systems has its strongest influence south of 31°S, where there is a relaxation of the southerly winds and increased frequency of westerlies. Off northern Namibia the southerly winds are strongest during autumn and spring, while north of 15°S (southern Angola) winds are weak throughout the year, although still strongest during winter. Hot dry, dusty downslope winds ('Berg' winds) – analogous to the Santa Ana in California – are common during autumn. Coastal winds are pulsed on timescales of 3–10 days over much of the Benguela – particularly in the south (during summer) by the passage of easterly moving cyclones associated with the belt of westerlies which lies south of Africa. This pulsing of the winds and the associated changes in atmospheric pressure are important in terms of the dynamics of coastal upwelling and shelf processes. Diurnal changes in coastal winds are common throughout the Benguela north of 33°S – a classical land–sea breeze effect.

## Upwelling

The process whereby cold subsurface water is brought to the surface near the coast as a consequence of longshore equatorward winds is termed coastal upwelling. In simple terms, longshore winds displace warm surface water equatorwards and, as a consequence of the Earth's rotation, offshore, resulting in a drop in sea level against the coast, and an uplift of water from below (and alongshore) to correct the imbalance. In a simple one cell system, the thermocline (layer where there is a strong vertical temperature gradient) is tilted upwards, and may result in a front (horizontal gradient) between the cool upwelled water and the warmer oceanic water, with water moving at depth over the shelf and upwards, and sinking at the front. Slow poleward undercurrents and fast equatorward jet currents (near the front or shelf-break) are often characteristic of coastal upwelling systems. The process is illustrated schematically in **Figure 3**.

This description is really an over-simplification, as two or three longshore fronts may develop with complex circulations in between, while the actual degree of upwelling and the intensity and direction of shelf currents will be significantly influenced by coastal trapped waves. (The latter is a type of internal wave in the ocean over the shelf which propagates polewards at speeds of around 4–8 $cm\,s^{-1}$, displacing the thermocline and trapped or guided by the coast.) The existence of these coastal trapped waves can result in enhanced or reduced upwelling and larger sea level changes than might be inferred from the wind (*see* **Coastal Trapped Waves**).

The wind field (in particular the curl of wind stress), topographic features on the land and seabed, and orientation of the coast, result in the formation of a number of areas where upwelling is more pronounced. The principal upwelling cell in the Benguela is near Lüderitz (27°S) and strong upwelling occurs there throughout the year. This cell effectively divides the system into two quasi-independent subsystems. Other cells exist north of Cape Frio (at about 18°S), off northern Namibia, and at 31°S, 33°S, and 34°S (Cape Town), the last two being seasonal. In the southern area maximum upwelling occurs between September and March, whereas off northern and central Namibia and southern Angola upwelling is more perennial with a late winter-spring maximum.

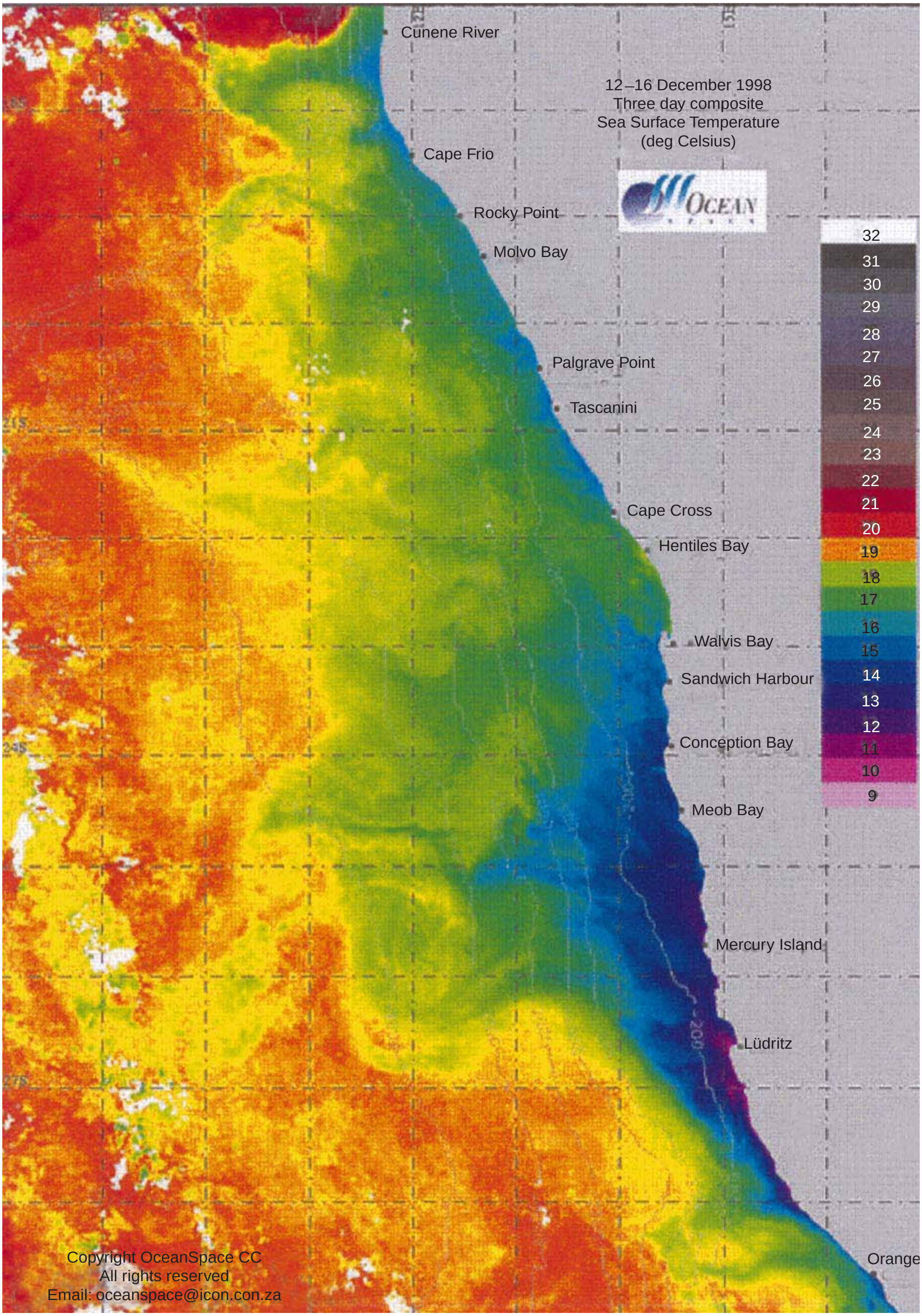
In the northern Benguela, upwelling and insolation (solar heating) are out of phase and inshore sea surface temperatures have a clear seasonal cycle. In the south, upwelling and insolation are in phase and surface temperatures vary little seasonally (in places by only 1°C). The main upwelling areas of the Benguela, i.e. south of 15°S, is a major heat sink, and negative climatological sea surface temperature anomalies of 5–6°C occur off Lüderitz. In sharp contrast the ocean off Angola in summer is a heat source, as is the region south of Africa which is influenced by the warm Agulhas Current where there are positive climatological temperature anomalies of 2–4°C. All this results in some spectacular horizontal temperature gradients or fronts in the south-east Atlantic. These, the complexity of the area and the extent of coastal upwelling are illustrated in **Figure 4**.

## Water Masses and Large-scale Circulation

Overviews of the water masses and general circulation in the Atlantic Ocean are given in **Current Systems in the Atlantic Ocean; Water Types and Water Masses.** respectively. In the broadly defined Benguela region the principal water masses are Tropical and Subtropical Surface Waters, Central (Thermocline) Waters, Antarctic Intermediate Water (AAIW), North Atlantic Deep Water (NADW), and Antarctic Bottom Water (AABW). Central water which corresponds to the linear part of the temperature–salinity curve applicable to the south-east Atlantic (approximately 6°C, 34.5 – 16°C, 35.5; see **Figure 5**), lies below the surface layer, and it is this water which upwells along the west coast of southern Africa. The characteristics of this 'water mass' in the region are quite variable, reflecting different origins, i.e. from the 'open' South Atlantic, the Indian Ocean, and the tropical Atlantic. Except over, or adjacent to, the shelf the flow of central water(s) is similar to that of the overlying surface water(s). A generalized description of the circulation in the upper layer is provided in **Figure 1**. The broad gray arrows between 15°S and 35°S represent the Benguela Current, which is defined as the integrated equatorward flow in the upper layers in the south-east Atlantic east of the 0° meridian. Speeds are in the range 10–30 $cm\,s^{-1}$. North of 30°S, the Benguela Current has a pronounced westward component. The total equatorward transport in the Benguela of surface, central and AAIW is thought to be 15–25 Sv (1 Sv is $10^6\,m^3\,s^{-1}$). In the south the Benguela Current is fed by the South Atlantic Current and by leakage from the Indian Ocean/Agulhas Current. This leakage of 2–10 Sv takes place mainly via the shedding of Agulhas rings at the retroflection of the Agulhas – typically six rings per year which have a translation speed of 5–8 $cm\,s^{-1}$ (*see* **Agulhas Current and Thermohaline Circulation**) and which result in a net equatorward transport of heat in the south-east Atlantic. North of 15°S, the region is dominated by the influence of the South Equatorial Counter Current/Under Current (*see* **Atlantic Ocean Equatorial Currents**) the circulation around the quasi-seasonal Angola Dome and the coastal poleward-flowing Angola Current.

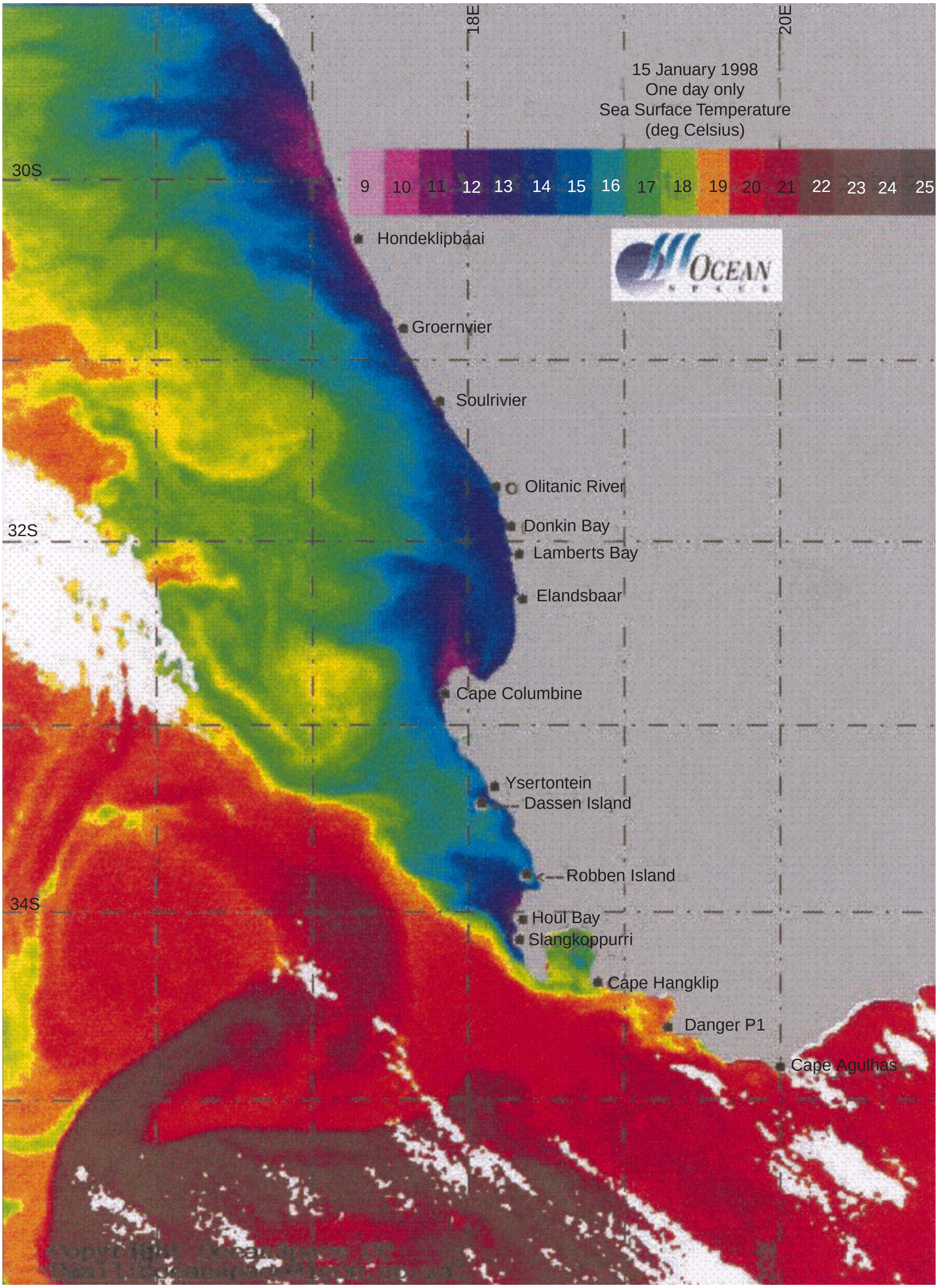
Circulation in the area between 5°S and 15°S has to be considered an integral part of the Benguela Current proper, particularly in terms of subsurface and also biochemical processes. It is here in the vicinity of the Angola Dome and in the area to the east of it that the main oxygen minimum layer in the South Atlantic forms. **Figure 6** illustrates conceptually the linkages between this area and the Benguela shelf system, with organically rich water advected from the highly productive Namibian upwelling area northwards and westwards. The sinking and decay of organic particulates form a marked oxygen minimum at around 400 m. This oxygen poor water subsequently advects slowly polewards adjacent to the continental shelf at depths of 200–400 m. It must be emphasized that **Figure 6** is somewhat speculative; it is only intended to convey a perceived concept.

AAIW which has a core temperature and salinity of 4–5°C and 34.2–34-5 and corresponds to the salinity minimum is present throughout the region at an average depth of 700–800 m, and in volume accounts for about 50% of the water present above 1500 m. It is much fresher in the south west than in




(A)

**Figure 4** Satellite sea surface temperature images (°C): (A) off Namibia, (B) South Africa. (Courtesy of OceanSpace CC.)




(B)

**Figure 4** *Continued*

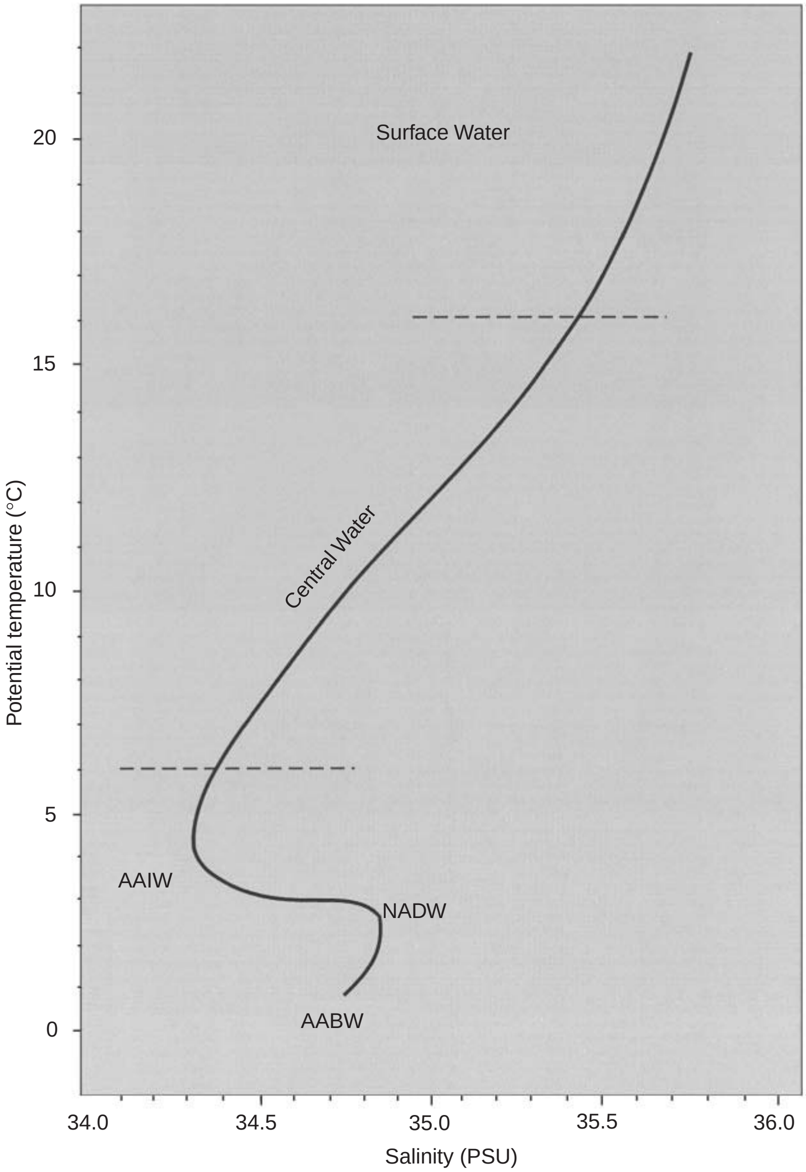



**Figure 5** Characteristic temperature–salinity relationship for the south-east Atlantic between 30° and 35°S.

the south east and in the north, again reflecting different origins, i.e. temperate South Atlantic, Indian Ocean, and tropical Atlantic. A schematic of the origins and mean flow of AAIW based on analysis of water properties is given in **Figure** 7. (A recent international experiment using subsurface 'floats' which can track the movement of water masses such as the AAIW has shown that 'snapshots' of the flow of AAIW around southern Africa is much more complex than the mean pattern given in **Figure** 7.

Below the AAIW lies NADW, corresponding to the deep salinity maximum (typically $> 34.8$ PSU) that comprises a thick layer between 1000 m and 3500 m of relatively warm saline water. West of southern Africa its flow is generally polewards, becoming diluted *en route*. Volumetrically NADW is the main water mass present in the region. The deepest water mass present in the Cape Basin is AABW, and on average it circulates slowly in a clockwise direction over the abyssal plain at depths below 4000 m. The Walvis Ridge forms an almost impenetrable barrier to the northward movement of AABW into the Angola Basin, as a consequence it is not significantly present there. (*see* **Abyssal Currents**).

## Shelf Circulation

Over much of the Benguela shelf, surface currents are largely influenced by prevailing winds. Poleward flow often occurs close inshore near the surface (see **Figure 1**). In the extreme south, there is a convergent flow of surface water from the Agulhas bank funnelling northwards into a shelf-edge frontal jet around the Cape of Good Hope with characteristic speeds of 25–75 cm s$^{-1}$. The surface current then separates into two components near 33°S (Cape Columbine). Over the Namibian shelf surface

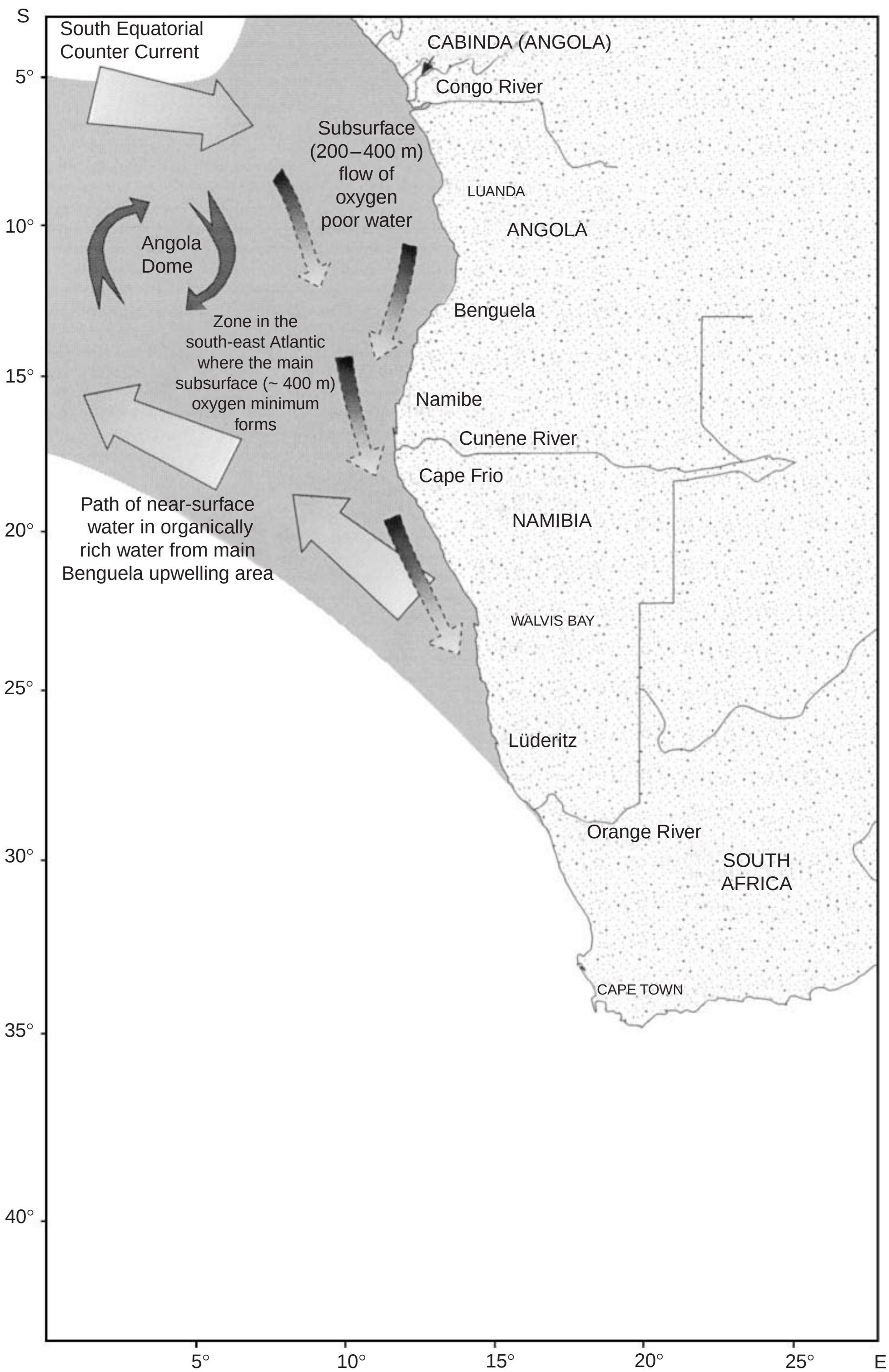



**Figure 6** Schematic showing linkage between the shelf system off Namibia and processes off Angola.

currents are usually in an equatorward direction, aligned to the prevailing wind, but periodic and episodic reversals do occur. Off Angola the coastal poleward-flowing Angola Current is detectable between the surface and 200 m, and current speeds of 70 cm s$^{-1}$ at the surface and 88 cm s$^{-1}$ subsurface have been reported during late summer. The dynamics of the Angola Current appear to be linked with the Angola Dome and the South Equatorward Counter Current. At the surface there is not much

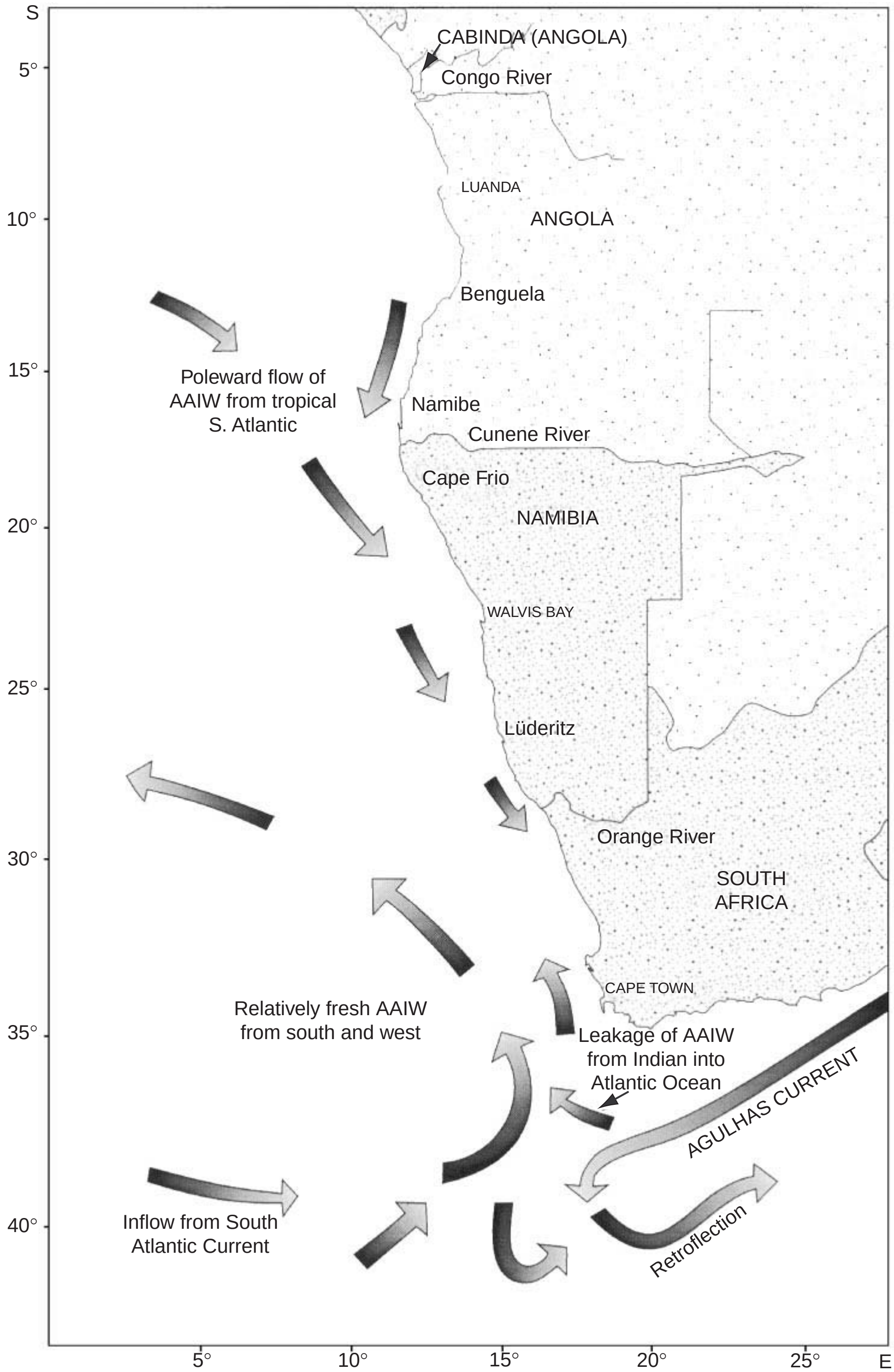



**Figure 7** Deduced circulation of Antarctic Intermediate Water in the Benguela region.

evidence for significant continuity of poleward flow of this current into Namibian waters, as the Angola Current tends to turn westwards just north of the Angola Benguela front. At 400 m the poleward flow does seem to be more continuous.

As in other coastal upwelling systems, a poleward undercurrent is a dominant characteristic of near bottom water over the shelf, extending from the coast to west of the shelf-break. The subtidal currents over the shelf are dominated by coastal trapped waves with periods of 3–10 days. The net poleward flow in the undercurrent is $5\text{–}8\,\mathrm{cm\,s^{-1}}$ or about $5\,\mathrm{km\,d^{-1}}$. On occasions this southwards-moving current can reach the surface, resulting in episodes of poleward flow at the surface, i.e. when the zero flow intersects the sea surface. Tidal currents in the Benguela are of relatively small amplitude.

The characteristics of shelf circulation in the Benguela region can be summarized as follows:

- Wind-driven equatorward flow in the upper mixed layer between about 35°S and 15°S.
- Poleward-flowing coastal Angola Current north of 15°S
- Shelf-edge/frontal jets associated with the upwelling system in the southern Benguela.
- Poleward-propagating coastal trapped waves resulting in reversals with a period of 3–10 days.
- Small amplitude tidal and inertial high-frequency oscillations ($10\text{–}15\,\mathrm{cm\,s^{-1}}$).
- Poleward undercurrent over the shelf with net flow of about $6\,\mathrm{km\,d^{-1}}$.

Viewed simplistically, much of the region can be viewed as having an equatorward-moving surface layer overlying water moving slowly polewards.

## System Boundaries, Fronts, and Filaments

The physical boundaries of, and within, the Benguela are usually associated with fronts (see **Figure 1**). These tend to form barriers to the horizontal movement of water and small particles. Over much of the area between Cape Frio (18°S) and the Cape of Good Hope (34°S) there is a meandering (wave-like) longshore temperature front which approximately follows the shelf-break (see **Figure 4**). This is the boundary between the area influenced by coastal upwelling and the warmer oceanic water lying further west. The greater part of the total equatorward flow in the south-east Atlantic, i.e. the Benguela Current proper, takes place between the upwelling oceanic front and the 0° meridian. Major perturbations of the front produce filament-like features. These filaments are characteristic of upwelling systems, and have life spans of days to several weeks. Usually orientated perpendicular to the coast they cause the front to be highly convoluted. Benguela filaments are generally (but not always) site specific. Water circulation tends to follow the filament/front, so filaments may not be a significant source of transfer of water between coastal and oceanic systems.

The southern boundary of the Benguela system is the Agulhas retroflection area, characteristically between 36° and 38°S. This boundary is highly variable. Rings shed from the retroflecting Agulhas Current every 2 months on average result in periodic bursts of water leaking from the Indian Ocean into the Atlantic (discussed previously and in **Agulhas Current**). The main path of these rings is west-north-west. When a major ring is shed this can appear like a flooding of the south-east Atlantic by tropical surface water, as evident in **Figure 4B**. On occasion, Agulhas rings may interact with the Benguela shelf and draw shelf water around the ring in the form of a large curved filament. In addition to rings, there is a small almost continuous leakage of Agulhas water around the Cape of Good Hope and this tends to strengthen the shelf edge/upwelling front there (**Figure 4B**).

At about 5°S there is a pronounced front between the system of equatorward current and the Benguela region, i.e. the Angola Front, which is particularly marked at subsurface depths. There is differing opinion as to whether the Angola Front is the northern boundary of the Benguela or whether the boundary should rather be taken as the Angola-Benguela Front off southern Angola which is the northern extent of pronounced coastal upwelling. The latter front is most evident as a sharp horizontal surface temperature gradient, maintained throughout the year between 14° and 17°S. The Angola-Benguela Front (ABF) is orientated perpendicular to the coast and is in reality a collection of two or three fronts, at times rather convoluted. On average the ABF lies furthest south in summer. It is detectable to a depth of 200 m and appears to be maintained primarily by a contribution of bathymetry, coastline orientation, and wind stress.

## System Variability

Processes on many orders of temporal and spatial scales impact on the Benguela system. Of the physical features, the distribution of the wind field in time and in space is of overarching importance, significantly influencing coastal trapped waves, upwelling, frontal dynamics, currents in the upper mixed layer, stratification, etc. Seasonal changes in insolation exert an important influence on the surface waters. (One third of the upwelling area and the entire Angolan system lie within the tropics and receive high levels of thermal radiation and light.) Tides and tidal currents are only really important in near-shore environments.

### Event-scale Variability

The processes which occur on timescales of hours to several days and space scales of meters to tens of kilometers (i.e. event-scale) are characteristic of upwelling events. The southern Benguela displays more event-scale variability than the central and northern parts of the region as a consequence of the influence of eastward-moving cyclones which pass south of the continent with periods of 3–10 days. Further north, upwelling tends to be more consistent than in the south, although the diurnal changes in wind forcing become more important (land–sea breeze influence). There is a substantial body of literature on event-scale oceanography and biology of the Benguela.

### Seasonal Variability

The seasonal migration of the weather systems and changes in insolation is manifest in changes in the upper mixed layer – intensity and distribution of upwelling, stratification, and intrusion of tropical water from the south and from the north into the upwelling area. Off Angola and Namibia there is a distinct seasonal cycle in near surface temperature with a maximum in March and a minimum in August/September with a range of 4–6°C. In the south the range in seasonal average temperature is only 1–2°C. The seasonal signal in the south-east Atlantic is in general larger than that in the eastern Pacific.

### Interannual Variability and Episodic Events

While the seasonal signal is large in comparison with some eastern boundary current systems, the interannual signal in the Benguela is smaller. Nevertheless, interannual changes in the wind field do significantly impact on the Benguela. This interannual variability manifests itself in two main ways, i.e. through system (or subsystem)-wide change in upwelling as a consequence of large-scale changes in wind speed and/or direction – resulting in cool and warm years – and through major perturbations at the boundaries of the system which are a result of basin-wide or global changes in the ocean–atmosphere system.

In the south, extreme disturbances in the Agulhas retroflection can be manifest as a major incursion of Agulhas Current water penetrating into the Benguela – either in the form of shallow filaments or occasionally shed rings which take a more northerly path than usual. There is evidence that major events occurred in 1957, 1964, 1986, and 1997/98. Occasionally these are followed by equatorward pulses of subAntarctic water, e.g. 1987.

Major perturbations of the Angola-Benguela Front – termed *Benguela Niños* – occur in the south-east Atlantic. These events have a character similar to their Pacific *El Niño* counterpart, but are not necessarily linked to the latter. Every few years the tropical eastern Atlantic becomes anomalously warm as a consequence of relaxation of trade winds, deepening of the thermocline, and reduced loss of heat from the ocean. Occasionally, every 10 years on average, this warming is more extreme, as a consequence of sudden relaxation of winds off Brazil, and when this happens a Kelvin wave is generated and there is an apparent intensification in the South Equatorial Current with more warm water than usual pushing eastwards and southwards, displacing the Angola-Benguela Front and flooding the northern Benguela shelf with tropical water. The most recent Atlantic or *Benguela Niño* occurred in 1995. Previous events were recorded in 1934, 1949, 1963, and 1984, while others may have occurred in 1910, the mid-1920s and in 1972–74. Although not necessarily in phase with Pacific *El Niños*, they do appear to be a regional response to changes in the global ocean–atmosphere system.

## Concluding Remarks

While there is a fairly substantial body of knowledge about the structure and functioning of the Benguela, there are still several notable gaps. These include a proper understanding of the linkages between shelf and offshore processes, processes occurring at the northern and southern boundaries of the system, teleconnections between the Benguela and the global ocean–atmospheric system, and the effect of global climate change on the region. Research priorities for the future must focus on modeling to improve predictability of system variability and response to climate change.

## See also

**Abyssal Currents. Agulhas Current. Atlantic Equatorial Currents. Canary and Portugal Currents. Coastal Trapped Waves. Current Systems in the Atlantic Ocean. Current Systems in the Southern**

**Ocean. Indonesian Throughflow and Leeuwin current. Open Ocean Fisheries for Large Pelagic Species. Small Pelagic Species Fisheries. Thermohaline Circulation. Water Types and Water Masses.**

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# BENTHIC BOUNDARY LAYER EFFECTS

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## Introduction

The benthic boundary layer (BBL) is a discrete layer of flowing sea water above a benthic substrate, delimited vertically by its contact with free stream flow. The degree of turbulence within the BBL and boundary shear forces exerted on the substrate are determined by the free stream velocity and the roughness characteristics at the substrate interface. Roughness elements may either be of geological origin, e.g. sand ripples of soft sediments, or of biological origin, e.g. tubes constructed by macrofauna that extend into the BBL.

Typical structure of a smooth BBL consists of a bed layer, inclusive of a viscous sublayer (laminar sublayer) closest to the substrate interface. Here, the flow is laminar and only a few millimeters thick, dictated by the free stream velocity. Next is the logarithmic layer, where mean velocity varies as the logarithm of the height above the substrate interface, and where the flow is often turbulent. In the outer layer of the BBL, turbulence decreases with distance from the substrate interface and is bounded by the free stream flow, situated immediately above it. In coastal and estuarine habitats, where many of the benthic animals discussed here live, BBL depth may vary from 10 cm to 5 m. In some conditions the BBL of coastal waters may extend throughout the water column. Such shallow environments are much influenced by tidal and wind forcing; the latter inducing oscillatory water movements in the bed layer.

A useful measure of the flow conditions for biologists is Reynold's number. It expresses the relative proportions of inertial and viscous forces within a flow as a dimensionless number. It is determined by measuring a characteristic length of a solid in flow measured in the same direction as the flow, multiplied by the velocity and divided by the kinematic viscosity of sea water. Other hydrodynamic measures useful for this presentation are lift and drag coefficients. A flat body resting on the substrate and in a flow field will experience lift due to Bernoulli's principle. This occurs because the velocity is locally higher on the upper than on the lower surface, due to the already mentioned effect of height on velocity within the BBL. The resultant pressure differences – the pressure is higher where flows are low – cause a lift force to be generated. The lift is resisted by the negative buoyancy of the body but, if exceeded as velocity increases, it is 'lifted' and carried downstream. The drag of a body