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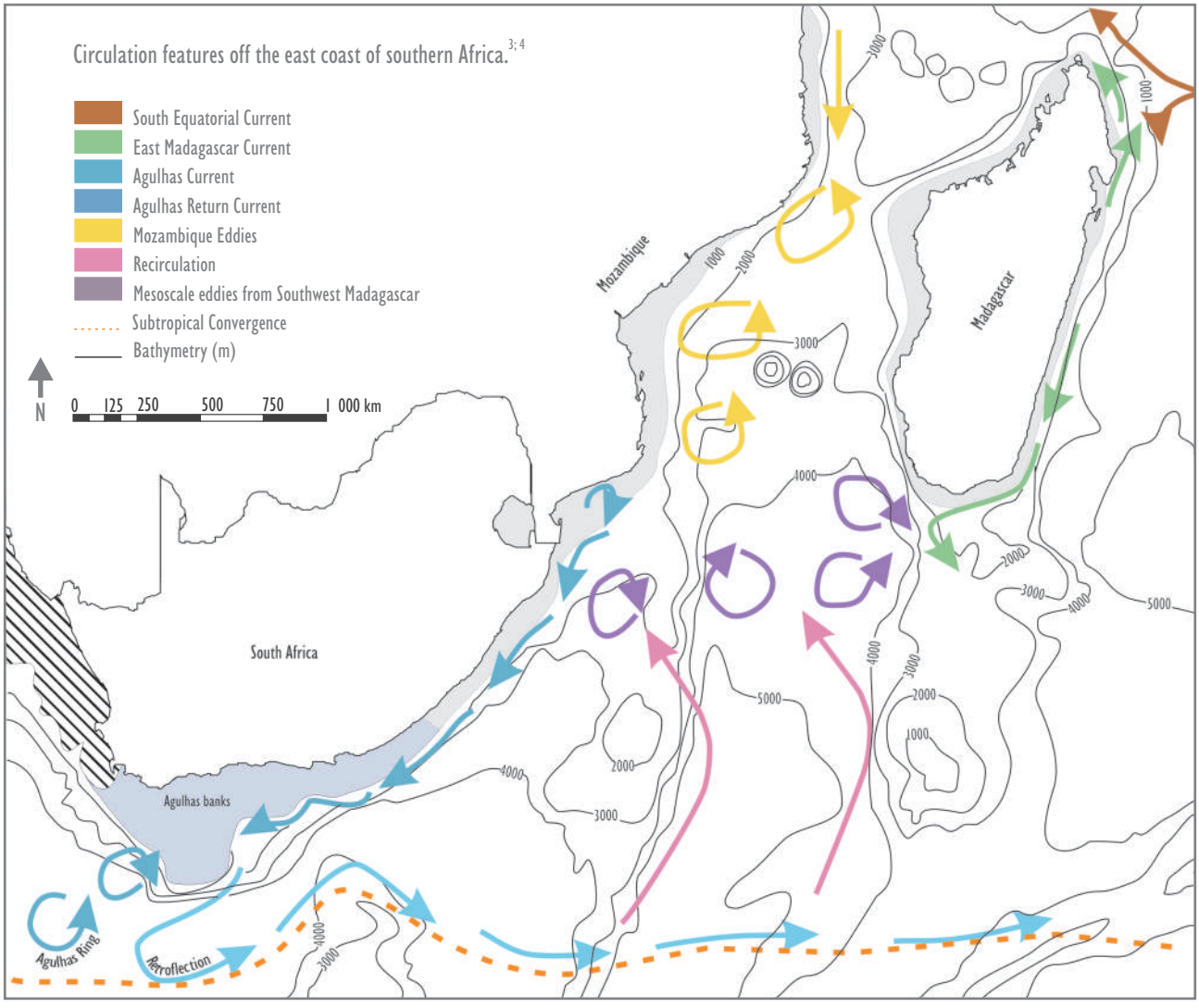
2.3 Physical Oceanography

KZN has a relatively straight, northeast trending coastline, divided into gentle bays by short, low headlands or rocky outcrops. The coast is bathed by the warm waters of the Indian Ocean, with the strong Agulhas Current flowing in a south-westerly direction, transporting warm water polewards.

Bathymetry

The east coast continental shelf of South Africa is generally steep and narrow (6-12 km), and is relatively straight, apart from a section referred to as the KZN Bight, which extends from approximately St. Lucia in the north to Durban in the south. In this region there is an indentation in the coastline and the continental shelf widens to almost 40 km at its greatest extent, off the Thukela River. The shelf-break is approximately at a depth of 100 m off Durban and 90 m off Richards Bay and has a relatively steep gradient of up to 8°.[1] Submarine features offshore include: the canyons off the Maputaland coast in the north (where the "fossil" fish, the coelacanth has been observed (*Section 4.5*); the depocentre of the Tugela Cone, formed by terrigenous sediments deposited by the Thukela River;[2] the Tugela Canyon off the shelf south-east of the Thukela River; the shallow Aliwal Shoal,



shelf south-east of the Thukela River; the shallow Aliwal Shoal, which rises from a depth of 30 m to just 6 m below the sea surface, some 4 km off Green Point;[5] and the Protea Banks, which rise 15-25 m above the sea floor, some 8 km south of Port Shepstone. This bathymetry is an important controlling mechanism with regard to the path and features of the Agulhas Current.

Origin of the Agulhas Current and water properties

The source of the Agulhas Current is complex.[3] However, evidence suggests that the current forms off the northern KZN/southern Mozambique coast, from the confluence of waters that follow complex trajectories south of Madagascar and in the Mozambique Channel.[4; 6; 7; 8] Mesoscale anticyclonic eddies move southward down the Mozambique Channel and a series of mesoscale dipole (paired cyclonic and anticyclonic) eddies, generated south-west of Madagascar, move westward to contribute to the flow, combined with recirculation from the Agulhas Return Current and the South-West Indian Ocean sub-gyre.[9] The waters coalesce to form a strong western boundary current off the east coast of South Africa. The section of the Agulhas Current along the KZN coast falls within what is termed the northern Agulhas Current, which extends from approximately 27°S (Kosi Bay) to 34°S (Port Elizabeth). South-west of Port Elizabeth the current behaves quite differently, owing to the controlling feature of the Agulhas Bank and the current here is termed the southern Agulhas Current.

Temperature and salinity characteristics indicate that the surface and shelf waters off the KZN east coast generally have a tropical to sub-tropical origin.[10] Salinity within the Agulhas Current is relatively high, usually greater than 35.5 parts per thousand (‰); however this can decrease to around 35.0‰ in summer, as a result of fresh water input following summer rains. Lower salinities are recorded on the shelf off the major river mouths, e.g. the Thukela, Mkomazi, Mzimkulu and Mfolozi Rivers, particularly during summer, with a minimum of 33.3‰ being recorded off the Thukela River in January 2010. However, even lower values are possible in the surf zone after any period when there has been significant rainfall, with a salinity of 30‰ 1 km off the Mkomazi River and a minimum of 20‰ 500 m from the river mouth having previously been recorded.[11]

Surface temperatures of the Agulhas Current are warm, varying seasonally from 22-28°C,[12] with temperatures decreasing southwards along its trajectory. There is no apparent seasonal temperature variation at depth.[10] Inshore water is generally cooler than offshore; the core of the Agulhas Current is evident by the warmer water and higher salinity concentrations some 40-60 km from the coast. There is a regular decrease in vertical temperature with increasing depth and waters are usually well mixed; there is no pronounced thermocline i.e. a narrow layer of water that marks a sudden decrease in temperature with depth. At depths of approximately 300-800 m, water of South Indian Central Ocean origin is found. Occasionally this central water is upwelled onto the shelf, resulting in cooler temperatures.[10]

The Agulhas Current waters are described as oligotrophic, i.e. low in nutrients but often high in dissolved oxygen. This means that the open ocean waters do not sustain an abundance of marine life. However, various upwelling mechanisms are capable of bringing cooler, nutrient-rich water from depth onto the shelf, which is important for sustaining marine life. Topographically induced upwelling[13] caused by the Agulhas Current shearing from the shelf edge between St. Lucia and Richards Bay brings this nutrient-rich water from greater depths onto the shelf by a process known as Ekman veering. The St Lucia upwelling cell results in cooler water (18-19°C) and increased chlorophyll-a phytoplankton concentrations inshore, and is an important source of nutrients and primary productivity for the KZN Bight.[14] A small, semi-permanent cyclonic eddy caused by the Agulhas Current leaving the shelf edge at the southern end of the KZN Bight, south of Durban[15] is also responsible for the advection of colder water from depth, resulting in a localised increase in nutrients and primary productivity.

Current speeds, direction and volume transport

The Agulhas Current is regarded as the strongest western boundary current in the world.[4; 16; 17] The current is generally 70-100 km wide[18] and extends to a depth of approximately 1 500 m.[19] The current flow is controlled by the bathymetry and the core of the current flows along the shelf-break; this results in relatively stable flow.[16; 20] The Agulhas Current transports some 70 million tons of warm water per second[21; 22] south-westward, along the east coast of South Africa, with current speeds in the current core attaining 2 $m.s^{-1}$. Even faster speeds of up to 2.5 $m.s^{-1}$ (approximately 5 knots) are attained south of KZN, off the Transkei coast. The current is intense and narrow and has sometimes been described as a "river" in the ocean. It is characterised by strong velocity gradients and a central warm core where the temperatures are highest and

current speeds are fastest. The core is generally just offshore of the shelf break. There is no distinct seasonal variation in the volume flow or current speed,[16; 23] and day-to-day variability is probably greater than any seasonal variability.[15; 23] Temperature variations are also greater over the day-to-day than seasonal period, with nearshore current reversals (mainly associated with meanders and eddies) and upwelling events being the main contributing factor to these shorter term variations.

A series of Acoustic Doppler Current Profiler (ADCP) current metre moorings, deployed for a period of 18 months on the KZN Bight as part of the ACEPII research programme, has provided improved insight into the currents off the KZN coast. An ADCP mooring deployed offshore, in the core of the Agulhas Current as it passes Durban shows predominantly south to south-westward flow, with the highest frequency of currents flowing to the south-south-west, at a rate ranging between 76-114 $cm.s^{-1}$. Currents flowed south to south-westward 77% of the time. The highest current speed measured was 185 $cm.s^{-1}$, flowing to the south-west. The occasional shifts to other directions were associated with low current speeds and were usually due to a Natal Pulse, which typically results in weak currents off Durban, as the core of the Agulhas Current is deflected further offshore. By contrast, a second current meter deployed inshore showed currents that flowed predominantly in a northerly to easterly direction for some 53% of the time, mostly at speeds of between 14-70 $cm.s^{-1}$. Current speeds were generally lower than at the offshore location in the Agulhas Current, although some high speeds were recorded; e.g. a maximum current speed of 135 cm.s-1 was measured flowing to the north-east. The nearshore north-eastward current, counter to the predominantly south-westward flow of the Agulhas Current offshore, is related mainly to the presence of the semi-permanent Durban Eddy.

Variability in the Agulhas Current: the Natal Pulse and Durban Eddy

While the flow of the Agulhas Current is known to be fairly stable,[4; 16] there are occasional, irregular perturbations that can alter the flow. Anticyclonic eddies offshore and upstream of the Agulhas Current can initiate a meander when they interact with the mean flow of the current,[24] forming what is locally known as the Natal Pulse. The KZN Bight appears to be a key region for the development and growth of these instabilities.[25] The meander is evident throughout the water column and grows in amplitude as it passes south of the KZN Bight, sometimes reaching 200 km offshore, off East London. Using satellite altimetry data, it has been calculated that, on average, 1.6 Natal Pulses per year reach as far south as Port Elizabeth.[25] However, previous estimates have put the number at 4-6 per year.[4; 26] The Natal Pulse migrates south-westward down the coast at a speed of approximately 10-20 $km.day^{-1}$, although propagation speeds of 23 $km.day^{-1}$ have been reported,[27] and with a lifespan of some 50-70 days.[25] The resultant cyclonic vorticity and cold core that develops, facilitates enhanced primary production and may be important for the retention of eggs and larvae and concentration of plankton (food).[27]

Semi-permanent cyclonic (clockwise) eddies develop on the inshore region of the southward-flowing Agulhas Current, especially in the lee of large coastal offsets along the coastline.[16; 28] One such eddy is the Durban Eddy, a semi-permanent cyclonic eddy circulation that exists off the south coast of KZN in the lee of the southern end of the KZN Bight, between Durban in the north and Sezela in the south. The Durban Eddy is a mesoscale feature with a size range of approximately 40-50 km wide and 60-90 km long. The eddy is caused by the strong Agulhas Current moving offshore of the regressing shelf edge, south of Durban.[15] The clockwise rotation of the eddy causes north-eastward flowing currents to occur near the coast, opposite to the main south-westward Agulhas Current flow further offshore. The occurrence of counter currents off Durban and the south coast of KZN is well known and has been exploited by mariners for centuries. Off Durban, a northward movement of mobile submarine dune fields has suggested a more dominant north-east trending counter-current at depth, and the persistence of the lee eddy in this region.[14] Examination of 18 months of current meter records and satellite imagery indicates that the eddy occurs approximately 55% of the time and is a major contributing factor to the frequent current reversals inshore, landward of the core of the Agulhas Current. The spread of data at the inshore mooring shows the predominantly north-eastward flow associated with the eddy, but with a secondary peak in the south to south-westerly direction occurring between eddy events. The Durban Eddy is highly variable in occurrence, strength and downstream propagation speeds.[15] The average lifespan is 8.6 days, with a range of 3-19 days, and an average time between eddy events of 7.7 days.[29]

Whereas the Natal Pulse gains momentum and grows in amplitude offshore as it migrates southwards along the coast with the Agulhas Current, the Durban Eddy flattens against the coast and dissipates as it detaches from the Durban area and migrates southwards.[15] Only 41% of Durban Eddies were

evident passing through Sezela, and the percentage of breakaway eddies evident downstream decreases further south. Upwelling along the shelf and in the cyclonically rotating Natal Pulse and eddies facilitates the upward transport of nutrients and primary production, as evidenced by higher values of chlorophyll *a*. Thus these systems play an important role in the ecosystem functioning of the KZN shelf and in the Agulhas Current waters downstream. In addition, it has recently been found that the total suspended solids washed into the sea from the Thukela River are a very important source of organic matter. This nutrient input controls the food web structure and production of the benthic communities of the KZN Bight, stretching from the shallow Thukela Bank to the deep sea floor .[30]

Tides

The KZN coastline is subjected to semi-diurnal tides, meaning that there are two high tides and two low tides per day. Tidal levels are measured with reference to a mean level called the chart datum (CD), which is based on the level of the lowest astronomical tide (LAT). The LAT is the lowest level that can be predicted to occur under average conditions in a 19 year cycle, at a given location. Along the KZN coast, the tidal range generally varies from 0.8 m during neap tides to 1.8 m during spring tides, with the highest astronomical tide (HAT) of 2.3 m (in relation to the CD) for Durban. The tidal range is generally larger during equinoxes than during solstice periods.

Wave regime and littoral drift

The KZN coastline is dynamic and subject to large swells, particularly in autumn and winter. Based on a combined CSIR/Transnet waverider buoy dataset for Richards Bay and Durban for the 18-year period from 1992-2009, the average significant wave height (Hs) for Durban is 1.65 m, with an average swell direction of 130°.[31] Swells from the south-south-east (SSE) dominate the spectrum, particularly in autumn, winter and spring. The SSE swells are generally long period swells generated by cold fronts (refer to *Section 2.1*) that form in mid-latitudes and propagate from west to east, accompanied by intensified winds from the south-west. These systems are generally stronger in the winter months. Although many of the cold fronts are deflected southwards of the KZN coast by a strengthened interior high pressure system (anticyclone) during winter, the swells associated with these systems nevertheless propagate up the coast. While the open ocean swells generated by the frontal systems are originally from the south to southwest, they are refracted as they approach and cross the continental shelf to become SSE to south-easterly. The prevailing SSE swells result in a predominantly south-to-north net littoral drift along the coast. The swell pattern changes to an increased easterly component in summer; these are generally shorter period easterly swells associated with the South Indian Ocean Anticyclone and an increased frequency of north-easterly winds (see *Section 2.1*). The cold fronts are usually weaker during this time, meaning that swells associated with these systems have less of an influence. The easterly swells can cause a temporary reversal in littoral drift from north-to-south.[32]

There are two additional weather systems that may cause extreme wave events along the KZN coast, sometimes with disastrous consequences (see *Section 2.1*), viz. tropical cyclones and cut-off low pressure systems. Tropical cyclones occur over the tropical South West Indian Ocean, mainly during the austral summer to autumn, with peaks in occurrence during January to March.[33] Although these systems seldom reach the KZN coast, the associated east to east-south-east, long period swells can realise great heights, e.g. Tropical Cyclone Imboa (1984), where an extreme swell height of Hs 9 m was attained off Richards Bay.[34]

Cut-off low pressure systems can occur at any time of year, but are generally more prevalent during March to November[35] and when these systems are confined to being over the ocean and their eastward passage is blocked by a dominant South Indian Ocean Anticyclone,[34] significant swells can be generated, e.g. 21 March 2007 where an Hs of 8.5 m and Hs maximum of 12.4 m[31] was generated off Richards Bay. Large (extreme) wave events most frequently occur during autumn off the KZN coast[31] and these are associated mainly with tropical cyclones and cut-off low pressure systems. The effects are exacerbated when they coincide with spring and/or equinoctial tides, storm surge and low atmospheric pressure.

The Agulhas Current flows offshore parallel to the KZN coast, transporting warm water from tropical and sub-tropical regions south-westward. However, circulation over the inshore continental shelf areas is more variable, characterised by occasional meanders in the current, eddies and counter currents. Knowledge of the current circulation is important for shipping, fishing, siting of offshore infrastructure and pollution dissipation. ■