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ARTICLE

Ocean Current Dynamics and Renewable Energy from the Agulhas Current

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ABSTRACT

The Agulhas Current is a major western boundary current flowing polewards on the southeast coast of South Africa. This analysis assesses its characteristics and suitability to generate power as a source of clean renewable energy. On a section of coastline some 400 km long, over a period spanning more than 5 years an extensive set of current measurements was obtained. These data confirmed that south-westward currents with a speed greater than 1.2 m s^{-1} occurred over more than 60% of the recorded time; such ocean current speeds compare very favourably to winds required for energy generation. These currents occurred at the continental shelf break in water depths around 100 m, in the upper 50 m of the water column. Occasional current slowdowns and reversals did occur, with the major influence coming from 'Natal Pulses', which are large-scale meanders in the Current that temporarily reversed the currents at the measurement sites. However, because of the surface temperature structure of the relevant water masses, such meanders can be identified in satellite imagery giving a few days advance warning of such current reversals. The characteristics of western boundary currents have been known for many years, but at Present, there is no operational system where this source of power is being utilised. It has tremendous potential for renewable energy generation, but is symptomatic of the many engineering challenges that still have to be solved to make such generation economically viable.

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1. Introduction

Climate changes occurring as a consequence of increases in greenhouse gases in the atmosphere are now an accepted phenomenon [1]. In order to counter these effects, there have been concerted efforts by most nations to move away from the use of coal, oil and gas as a means of generating power.

As a consequence, renewable energy sources are making up an increasingly greater proportion of the energy mix of most countries. While solar and wind energy comprise the dominant proportion of such renewable energy, there are other energy sources that remain underutilised. In particular, the oceans should be able to provide massive amounts of energy through a variety of different processes, e.g., ocean thermal energy, waves, osmotic pressure, salinity gradients and currents [2]. The review by Sitoe, Hoguane and Haddout [3] of ocean renewable energy in Africa concluded that mini tidal power plants and salt gradient power are the most suitable coastal power sources. An earlier review of the situation off the east coast of South Africa by Schumann [4] highlighted the potential posed by the Agulhas Current.

As is the case with all such renewable energy sources, extraction of power must be economically viable. In this case, the ocean currents need to be flowing consistently at speeds great enough to extract power for a substantial percentage of the time. Moreover, this should happen in ocean regions close to areas on land where the generated power can be utilised.

Suitable ocean currents only occur in specific areas, and in particular tidal currents in selected estuaries have been used for many years to generate electricity. The Rance tidal power station in France was opened in 1966 and has an average output of 57 MW, with peak values of 240 MW [5]. It was only surpassed in 2011 by the Sihwa Lake tidal power station in South Korea, which generates up to 254 MW [6]. However, there are limited places with sufficient tidal variation and suitable estuarine and channel configurations for such power stations.

Ocean currents are generated primarily by the wind [7], and at coastlines geostrophic currents along the coast can be set up by on-and-offshore pressure gradients. However, such currents are too variable and generally too slow to extract power in any meaningful manner.

On the other hand, the wind regimes over the large-scale ocean basins are responsible for setting up basin-wide anti-cyclonic gyres, i.e., clockwise in the northern hemisphere and anti-clockwise in the southern hemisphere [8]. Then, because of the rotation of the Earth, these currents are constrained to flow along the western boundaries of the ocean basins, polewards along the eastern coasts of the corresponding land masses. As such, these currents form narrow, fast flowing "rivers in the ocean" termed *western boundary currents*. The corresponding equatorward currents on the eastern boundaries of the ocean basins are sluggish and widely dispersed.

The characteristics of the various western boundary currents vary considerably, depending on the configuration of the ocean basins and adjacent land masses. The most famous of these western boundary currents is the Gulf Stream, flowing northwards off the eastern United States. Other western boundary currents are the Kuroshio off Japan and the Agulhas Current off South Africa, while the East Australian Current and the Brazil Current are relatively minor western boundary currents.

Whether or not such western boundary currents can be utilised for power generation depends on the local conditions, in particular the structure of the continental shelf. Thus a narrow, well- defined shelf will mean that the current structure is not complicated by intrusions and deflections, while proximity to the coast will mean shorter power transmission lines.

The idea of extracting power from such currents is not new; e.g., Hansen et al. [9] discuss a workshop in 1974 in which the possibilities of extracting power from the Florida Current (the southern section of the Gulf Stream) were assessed.

The structure and dynamics of the Agulhas Current have been well-established over years of measurement and analysis [10, 11]. Moreover, specific measurements were made over the years 2005 to 2010 which enable an assessment to be made whether conditions are suitable for the practical utilisation of this renewable energy resource. While adding to the general knowledge of the Agulhas Current, the objective is not directed to specific research, per se, on the Current.

However, the engineering challenges associated with the extraction of power from such a current are considerable. Not only does it involve the deployment of suitable turbines in water depths of 100 m and more, but the power must then be assembled and delivered to the shore generally more than 10 km away. It is only then that it can be incorporated into the nationwide electricity grid.

Ocean Current Turbines (OCTs) are producing 24/7 clean, reliable, predictable and stable baseload energy in tidal regimes. It is anticipated that such OCT technology can be modified for use in western boundary currents, and this analysis serves to establish the ocean current structures and the possibilities for power generation along the southeast coast of South Africa. It also identifies the optimum locations for such OCTs and suggests possible techniques for taking the transmission lines to shore and into the national grid.

2. The Agulhas Current

The Agulhas Current forms the western boundary current section of the anticyclonic gyre in the South Indian Ocean. In the northern section of the gyre the island of Madagascar forms an obstruction to the westward-flowing South Equatorial Current, and it is only when the waters flowing south around Madagascar meet those flowing south in the Mozambique Channel that the Agulhas Current is formed [10]. This occurs in the region off the northern coastline of the province of KwaZulu-Natal (KZN) in South Africa, depicted in **Figure 1**.

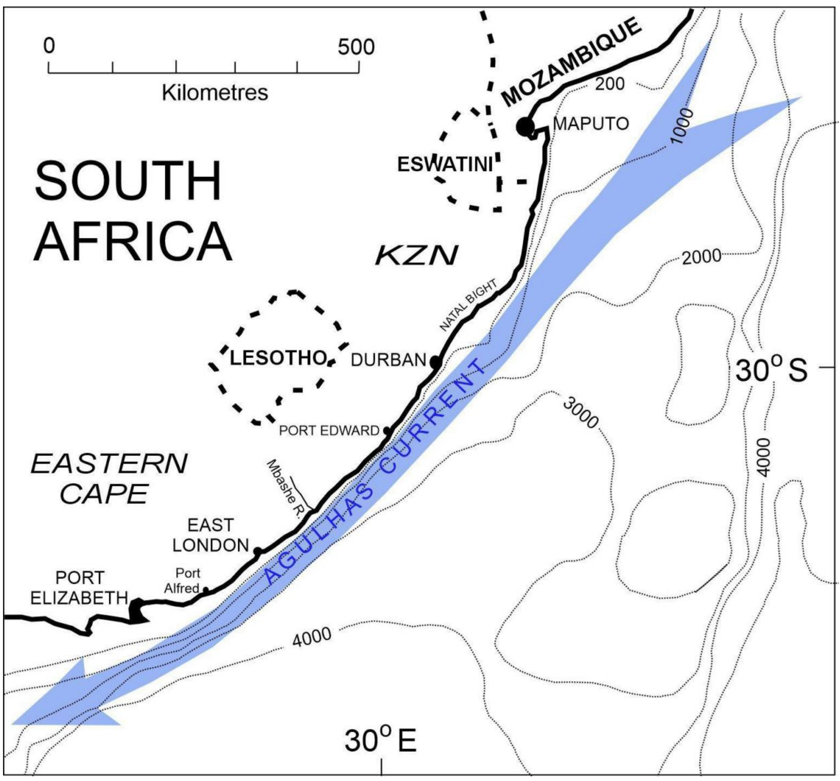

Figure 1. A depiction of the general flow of the Agulhas Current off the east coast of South Africa.

The Agulhas Current is also an important component of the global heat balance, transporting warm water from the tropics and subtropics southwards. Water masses with a temperature greater than 15 °C have a wide range of salinities and are generally shallower than 200 to 300 m. Near the equator an excess of precipitation over evaporation leads to high temperature (>25 °C) and lower salinity (<35.0 ppt) water, while farther south greater evaporation increases salinity to more than 35.5 ppt. The warm surface waters comprising the Agulhas Current are of particular importance, since this means that the current can be clearly identified using satellite imagery measuring sea surface temperature (SST).

The current structures in the formation region of the Agulhas Current off northern KZN are complicated, particularly because of the varying shelf structure and the existence of the wide KZN bight. A cyclonic circulation occurs in the Natal Bight north of Durban [12, 13], while Guastella and Roberts [14] identified a small cyclonic eddy immediately south of Durban. Gill and Schumann [15] developed a two-layer model that simulates the structure of the Agulhas Current as the shelf narrows to the Port Edward region.

Figure 2 shows an offshore section off Port Edward, with the Agulhas Current core on average just offshore of the shelf break and following the bathymetry. There are strong offshore gradients both in current speed and temperature, particularly near the surface, i.e., both speeds and temperature increase with distance offshore. Water temperatures decrease with depth, with little evidence of any intense thermocline structure.

Under steady conditions the ocean surface rises offshore providing an onshore pressure gradient for the resulting geostrophic Agulhas Current. As a requirement of the dynamics the isotherms slope upwards on the inshore side, and in accordance with the thermal wind equation vertical changes in current speed are balanced by the horizontal changes in temperature along an isobaric surface [7].

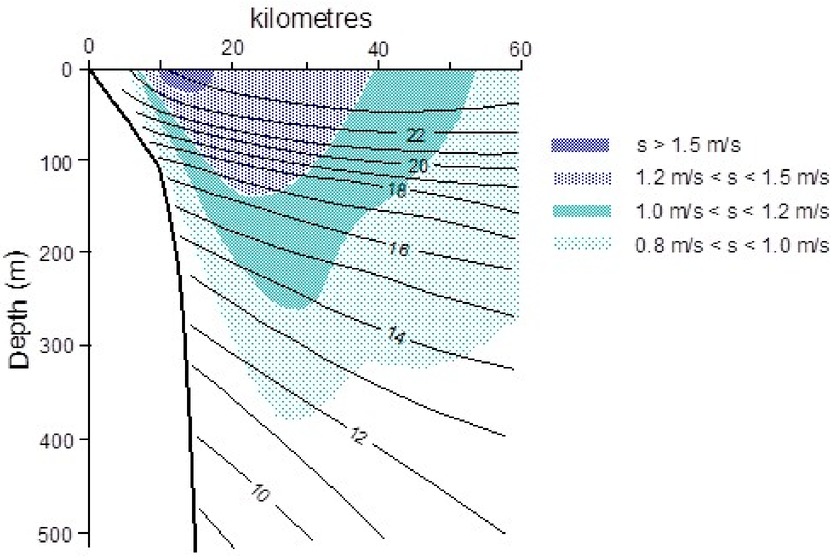

Figure 2. An offshore section at Port Edward showing the temperature structure (°C), and associated currents with speed ‘s’.

Source: Adapted from Pearce [16].

Due to friction in the bottom boundary layer current speeds decrease closer to the seabed. These slower current speeds result in an imbalance in the geostrophic flow, with the result that the flow moves onshore as it slows down This has been termed Ekman veering and causes a bottom flow of colder, deeper Central Water onto the shelf [17].

Peak current speeds of more than 1.5 m s^{-1} occur in the core of the Current, and the flow can extend to depths of more than 2000 m, decreasing with depth. Volume flows of more than 70 Sv (70 × 106 m^3 s^{-1}) occur, and while Pearce and Grundlingh [18] found no major seasonal variation in mean flow, a recent analysis by Beal and Elipot [19] indicated a seasonal variation with greater flows in summer.

Occasionally, very large meanders originate off the KwaZulu-Natal coast, possibly as a result of an offshore anti-cyclonic eddy coalescing with the Current [20], or the effects of varying bathymetry [21]. These large meanders have been termed ‘*Natal Pulses*’, and can take the core of the Current more than 100 km offshore, propagating south-westward at speeds of around 20 km day^{-1}. Smaller, more frequent cyclonic eddies with dimensions of 30 to 40 km also occur on the inshore boundary of the Agulhas Current south of Durban. These are generated by the interaction of the Current with a subsurface ‘bight’ in the bathymetry between the depths of 100 and 800 m [14]. This results in a cyclonic eddy spun up over a period of around two weeks which then becomes detached from the geographic feature and moves down the inshore side of the Agulhas Current. These eddies are a ubiquitous feature of the region and at times follow Natal pulses forming ‘wave trains’ which can take several days to move past a given point.

Natal Pulses occur irregularly, and Lutjeharms [11] reported a mean frequency of 4 to 6 per year. On the other hand, Rouault and Penven [22] analysed the occurrence of Natal Pulses over a period of 6 years, finding an average of 1.6 pulses per year. A later analysis by Meyer et al. [23] found 4 Natal Pulses over a period of 11 months.

At the latitude of Port Elizabeth (Gqeberha), the South African coastline veers westward to lie more east-west, and the continental shelf widens to form the Agulhas Bank. The rapidly changing bathymetry means the Current also moves offshore, and the scale of meanders also increases [11].

3. Coastal Dynamics

On the shallower shelf region inshore of the Agulhas Current it can be expected that coastal dynamic processes will be dominated more by wind, with bathymetry, insolation and river outflows also contributing. Wind directions along the coast tend to follow the coastline [24], with consequent upwelling and downwelling at the coast forced by northeasterly and southwesterly winds respectively; coastal currents generated by these winds flow in the same direction. Sporadic upwelling and downwelling events occur, with Lutjeharms, Cooper and Roberts [25] postulating an upwelling cell off Port Alfred.

Goschen et al. [26] found that upwelling progressed northeastwards from Algoa Bay with the wind and weather systems. In a later analysis Goschen et al. [27] found that upwelling was also associated with Natal Pulses.

Coastal trapped waves (CTWs) with periods of days and amplitudes up to 0.5 m are a feature of the south and southeast coast of South Africa [28, 29]. These are wind-generated and propagate eastwards with the crests lying essentially perpendicular to the coast and the amplitude decreasing offshore. Beyond Algoa Bay they are dissipated by the opposing flow of the Agulhas Current [30]. Nonetheless, the larger waves can have a substantial effect on shelf currents even north of East London, causing reversals over periods of a day or two as the waves pass through.

Coastal insets also affect the inshore current structures, and Roberts et al. [31] describe a cyclonic eddy in the lee of a slight inset south of Port Edward. This was also associated with shelf-edge upwelling, and a northward counter-current developed with transient breakaway eddies and Natal Pulses.

4. Measurements

The presence of the Agulhas Current has been known for centuries [32], but details of the flow and its variability were not sufficiently understood at the level required for an assessment of the feasibility of power generation. Consequently, a measurement programme was set up to elucidate the current structures and their variability.

Using the known characteristics of the Agulhas Current, the area with the best prospects of providing suitable current structures for energy generation was identified as the flow regime from Port Edward southwards to around Port Alfred – a distance of some 400 km (**Figure 1**).

This programme was sponsored by Eskom, the electricity supply commission of South Africa. It carried on from September 2005, to September 2010, and involved 16 experiments each deploying between one to four Acoustic Doppler Current Profilers (ADCP) for periods of up to 5 months; in total there were 51 deployments with data retrieval. Water depths varied between 37 m and 201 m.

Figure 3 shows the approximate positions of these deployments, indicated in four bracketed sites along the coast, namely Port Edward (PE), Mbashe River (MR), East London (EL), and Port Alfred (PA). Teledyne RDI and Nortek acoustic Doppler current meters were used, utilising frequencies from 75 to 600 kHz. The majority of meters also had pressure sensors to measure depth, while temperature was measured in all cases.

The current meter mooring depths considered here varied between about 87 m and 103 m at the three southern sites, while the three deployments off Port Edward had water depths of between 65 m and 67 m.

The acoustic current meters measured a current profile through the water column, and for all deployments a current bin size over a depth of 2 m was chosen; the number of such bins varied from 20 to 50, depending on depth. There were cases of data loss in some bins, particularly near the surface because of turbulence from ocean waves. However, all the analyses here consider mean current values over specified depth ranges incorporating a number of bins, and therefore the loss of data is not significant since only one or two valid bin values within a depth range are still sufficient to provide a mean value in the bin.

The mooring structures were such that the current profiler with its pressure and temperature sensors were situated about 2.7 m above the seabed, and because of technical constraints current measurements only started at a given distance above the transducers. For the deeper, lower frequency meters this distance was about 10.8 m and for the higher frequency shallower meters this was as low as 3.1 m. For the majority of moorings the distance from the meter to the centre of the lowest measurement bin was around 4.5 m.

The data interval was set at either 30 minutes or 60 minutes, with the recorded value being the mean current velocity (speed and direction) measured in each bin over this period. The temperature and pressure values were similarly determined at the meter, with one value per current profile ensemble.

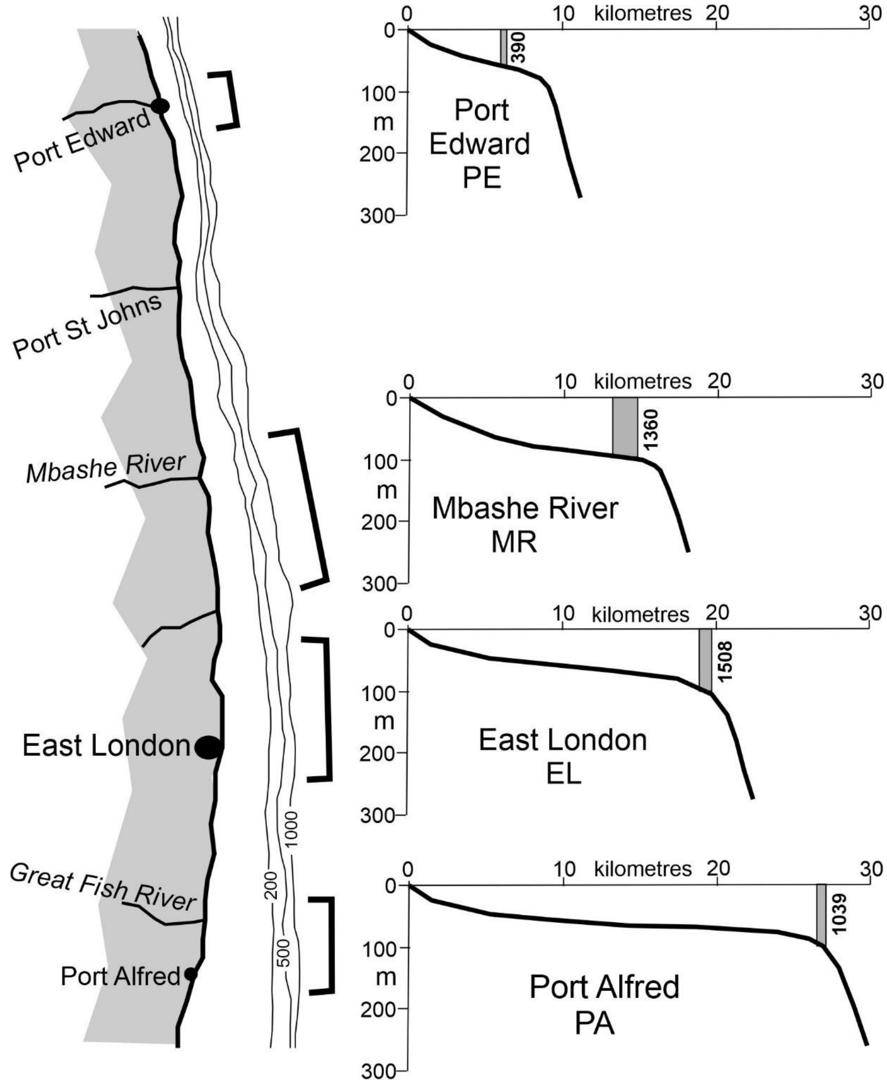

Figure 3. Positions of the current meter deployments considered in this report, bracketed into four groups: Port Edward (PE), Mbashe River (MR), East London (EL) and Port Alfred (PA).

Note: Within each group the deployment depths varied as depicted by the grey box; the adjacent value is the number of days of data available.

4.1. Current Profiles

In order to provide an assessment of the variability of the Agulhas Current over the 400 km of coastline considered here, selected statistics are given for the four bracketed sites in **Figure 3**. In **Figure 4**, a comparison is given of the different current profiles. The mean southwestward currents over a wide angle from 195 °T to 255 °T were considered and are shown at the various depth intervals; these covered more than 80% of the measured currents. Note that, as discussed in Section 4.4, currents shallower than 20 m are not considered.

These results show that the most opportune area for extracting current energy lies in the Mbashe region: it is here where the currents are consistently strongest. This agrees with the analyses of Duncan[33] and Schumann[4], while more recently Meyer et al.[23] reached the same conclusion, though they referenced the area after Cape Morgan, some 70 km to the south. On the other hand, the continental shelf is narrowest farther north at Port Edward, leading to easier transmission of power to shore.

Of interest is the slight Ekman veering to the west at the deepest depth range at all four mooring positions.

In this analysis, the conditions at Mbashe are investigated further as this will give an indication of the optimum current structures along this section of coast.

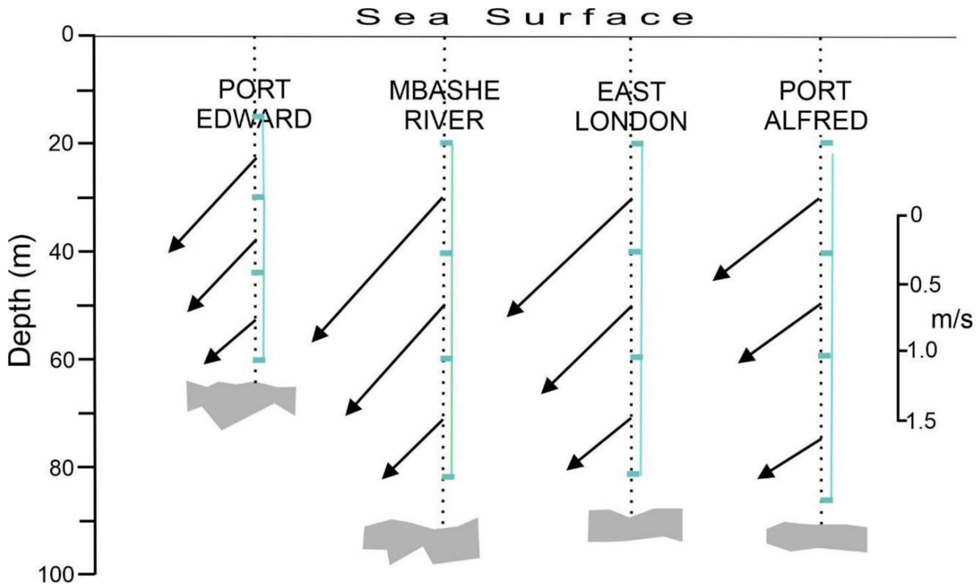

Figure 4. Approximate offshore current profiles from the four sites, over a wide angle from 195 °T to 255 °T and within broad depth intervals shown by the blue brackets.

Thus, the depth intervals for Port Edward were 15 m to 30 m, 30 m to 45 m and 45 m to 60 m, while for the other three sites the depth intervals were 20 m to 40 m, 40 m to 60 m and 60 m to 85 m. The average measured current speed is indicated on the right-hand side scale.

4.2. Current Duration

Table 1 gives the current speed duration spread for the moorings off Mbashe in a direction of 220 °T, and over a depth range from 20 m to 50 m where **Figure 4** shows maximum currents are found. The time duration in days of a particular current speed range as a percentage of the total deployment period is given in the columns, while the different speed ranges are given in the rows.

The last column gives the total percentage of time that currents were measured in the corresponding speed range. Thus current speeds of more than 1.5 m s^{-1} were measured for 35.6% of the record, with speeds between 1.2 m s^{-1} and 1.5 m s^{-1} occurring for 27.3% of the record. Moreover, for almost 9% of the record a current of more than 1.5 m s^{-1} lasted continuously for longer than 4 days.

4.3. Current Time Series

As a direct visual representation of the ocean currents, time series of the measurements for seven of the deployments at the Mbashe River over a 27-month period are given in **Figure 5**. Water depths varied from 86.3 m to 90.5 m, and the figure shows this record for the depth range of 18 to 60 m. The series have been filtered using a long-period filter to reduce the number of vectors, and because periods less than a day are not significant in this analysis; the subsequent series are represented by 6-hourly values.

Table 1. Duration table for all the deployments at the Mbashe site, in the depth range 20 to 50 m and in the direction 220 °T. The rows represent the speed ranges in m s^{-1}, given in the first column on the left. The columns – labelled in the second row – represent the duration ranges in days given as percentages of the total deployment time. Total percentages in each speed range are given in the last column on the right.

Speed Range m s^{-1}	Current Speed Duration (Days)											Total %
	>5	4.5 5	4 4.5	3.5 4	3 3.5	2.5 3	2 2.5	1.5 2	1 1.5	0.5 1	<0.5	
0.0	1.4%	0.1%	0.6%	0.3%	0.2%		0.2%	0.2%	0.4%	0.4%	0.7%	4.6%
0.0 0.5	2.4%	0.9%	0.3%	0.6%	0.6%	0.8%	0.6%	0.7%	0.9%	1.2%	1.4%	10.3%
0.5 0.8				0.2%		0.2%	0.2%	0.6%	0.8%	1.5%	2.4%	6.0%
0.8 1.0			0.1%					0.0%	0.5%	1.4%	4.6%	6.5%
1.0 1.2							0.1%	0.3%	0.5%	2.1%	7.7%	10.6%
1.2 1.5	0.2%			0.2%	0.4%	0.1%	1.0%	2.2%	3.7%	7.3%	12.1%	27.3%
>1.5	6.8%	1.4%	0.6%	1.5%	1.7%	2.0%	2.1%	3.6%	3.7%	5.1%	7.0%	35.6%

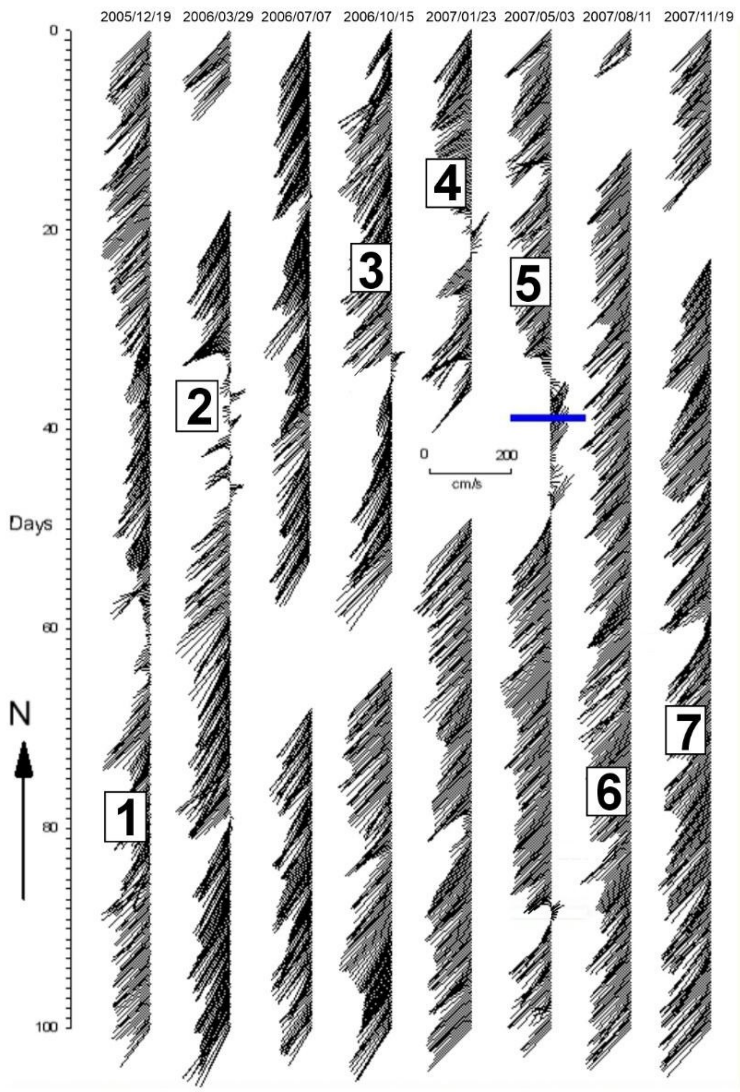

Figure 5. Time series of current vectors in the depth range 18 to 60 m, measured in the first seven deployments off the Mbashe River.
Note: The data have been filtered using the 12-hour filter, while the record consists of subsequent 6-hourly values. The records run sequentially starting on the left, with the starting time of each vertical series given at the top and progressing downwards. The north direction and a speed scale are given. The blue line in deployment MR5 shows the time of the satellite image in **Figure 6**.

The consistency of the current flow at this site is clear from the figure. Over the approximately 800 days, there were only about six 'events' where actual current reversals occurred. Of these, four reversals persisted for periods of a day or two, while it was only on two occasions that the reversals persisted longer – the variable structure on about day 40 in deployment #2, and the sustained reversal also at about day 40 in deployment #5.

A substantial advantage of ocean currents along this coast is that advance warning of changes can be identified with a lead time of days from satellite imagery depicting SST. This is particularly relevant in identifying Natal Pulses moving southwestwards in the Agulhas Current at speeds of about 20 km per day.

It is beyond the scope of this report to analyse each of these events in detail; however, the major reversal encompassing several days in deployment #5 is inspected briefly in **Figure 6**. This shows a satellite image taken on 10 June 2007, indicated with a blue line in **Figure 5** during the current reversal. It is clear from the image that there were major perturbations in the flow of the Agulhas Current at the time due to what appears to be two consecutive *Natal Pulses*. This is probably a very unusual circumstance and contributed to the extensive period of reverse flow over 13 or 14 days. According to the record in **Figure 5**, the first reversals occurred about five days before the image, when the first pulse went through. It had progressed about 120 km over the five days, giving a speed of 25 to 30 cm s^{-1}, in agreement with the accepted speed of *Natal Pulses* [11]. Of interest is the colder surface water evident within the pulse closer to the coast. However, between the two pulses the warmer surface water again reached the coast (**Figure 6**).

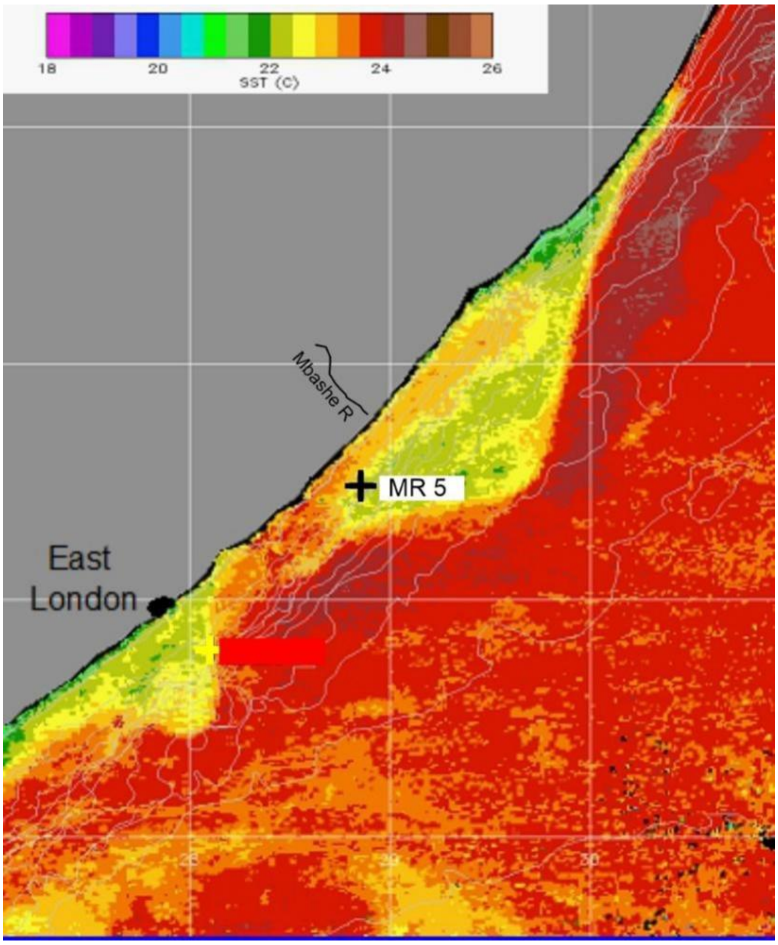

Figure 6. A satellite image taken on 10 June 2007, as indicated by the blue line in **Figure 5**.

Note: SST is shown in accordance with the scale at the top, while the position of deployment MR5 is shown.

There are a number of other periods of current reversal or slowing down of the current which have not been investigated. In particular the current variability in the previously mentioned day 40 in deployment #2 could be due to a sequence of CTWs. Other current reversals, e.g., day 37 in deployment #3, day 21 in deployment #4 and day 90 in deployment #5 also require further investigation. Inspection of SST from satellite imagery at these times did not reveal appreciable meanders or upwelling structures.

Nonetheless, it is important to determine whether there is any possibility of forecasting whether currents will change due to CTWs, wind-driven upwelling or smaller meanders on the inshore boundary of the Agulhas Current.

4.4. Temperatures and Waves

Water temperatures are not a significant characteristic in the generation of power, provided they are not extreme. **Figure 7** provides histograms of such water temperature variability near the seabed in summer and winter at the MR sites.

The overall distribution is very similar in the two seasons, but with the summer record having a greater spread at higher temperatures. In assessing these differences, it is important to remember that the sensors were situated 2.3 m above the seabed. As such, they would have been in a position where they would have intercepted the cold water being forced up the shelf slope and shelf by Ekman veering, upwelling and the current dynamics. Since these deeper waters have limited seasonal temperature changes, this would explain the similarities in the two seasons.

Alternatively, on occasion warmer water may cover the whole shelf area, giving rise to the warmer summer lobe.

From **Figure 2** the temperatures in the water column above the meters can therefore be expected to be a few degrees warmer than those represented in **Figure 7**.

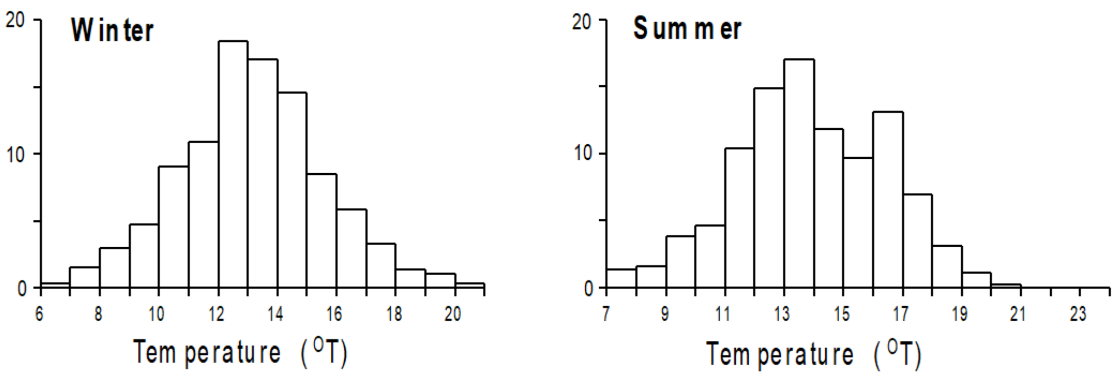

Figure 7. Temperature distributions measured at the MR site.

Note: The winter record covers the second deployment (April to August, 2006) and fifth deployment (March to August, 2007), while the summer record covers three deployments: first (December, 2005 to April, 2006), fourth (December, 2006 to March, 2007) and seventh (December, 2007 to March, 2008).

Surface gravity waves in the region derive from coastal winds as well as those from storms or strong wind events in the broader reaches of the Southern Ocean and the Indian Ocean. A complicating factor is the interaction of the Agulhas Current with opposing waves from the southwest, where 'freak waves' have on occasion damaged ships [34]. The influence of waves with depth is dependent on wave period and wavelength, but throughout this analysis depths greater than 20 m have been considered to minimise wave effects.

It should also be noted that the draughts of large ships can be more than 20 m, which means that any power generation system should be kept well below that depth.

5. Ocean Currents as a Source of Energy

To extract power from an ocean current, the momentum of moving water is used to turn turbine blades. This principle is used extensively in operational wind turbines, and it is therefore necessary to determine whether the power in ocean currents is comparable to that of wind.

To first order, the power per unit area swept by a turbine's rotor (the power density) that can be extracted from such a flow depends on the rate at which the kinetic energy of the water flows past the rotor [9]. This means that the power density is proportional to the product of the water's density and the cube of its flow speed. If P is the power density, then:

$$P \ \alpha \ \tfrac{1}{2} \rho v^3 \quad (1)$$

where ρ is the density of the seawater and v is the current velocity.

Seawater is approximately 800 times denser than air, which means that an ocean current flowing at a tenth of the speed of an air current – wind – will provide almost the same power density as the wind does. Thus an 8 m s^{-1} wind (28.8 km h^{-1}) will deliver about the same power as a 1 m s^{-1} ocean current.

However, from drag-law considerations the forces on the rotor blades scale as the square of the flow speed times the fluid density, so the blades of a turbine in a 1 m s^{-1} current are subject to forces eight times greater than in a 10 m s^{-1} wind. Consequently, underwater systems generally have rotors much smaller than those of wind systems, while gearing also needs to be changed significantly because of the slower rotation rates.

It is clear from the decrease in current speed closer to the seabed that the optimum depth for current generation lies within the water column some distance from the seabed. It is therefore necessary that turbines be raised above the seabed, either through a structure mounted on the bed, or otherwise floating in the water column and attached by tether to the bed.

This latter situation is depicted in **Figure 8**, where an ocean current generator is suspended on a line from an anchor on the seabed. This concept of suspending two counter-rotating turbines to minimise the effects of torque has become an accepted model for such power generation from ocean currents [9]. Alternatively, large ocean current turbines can be deployed on tripod-like structures with bases situated on the seabed. The suspended turbines are generally lower maintenance but deliver less energy (typically 250 kW per turbine) than their larger seabed counterparts requiring more expensive maintenance, although capable of delivering more energy (typically 1.5 to 2 MW) per turbine.

To utilise economies of scale, it is envisaged that a number of ocean current turbines, as depicted in **Figure 8**, should be deployed. These could be connected to substation hubs located on the ocean floor and then power-cabled ashore. From there the power could then be connected to the existing electricity grid [24].

This will require substantial operational planning and coordination of optimal site identification, optimal OCT design and manufacture, and a number of other engineering contracts and agreements as well as financing and regulatory compliance determinations. Aspects such as materials, anchoring systems and maintenance will form part of these follow-up engineering assessments, confidential to the OCT manufacturers concerned.

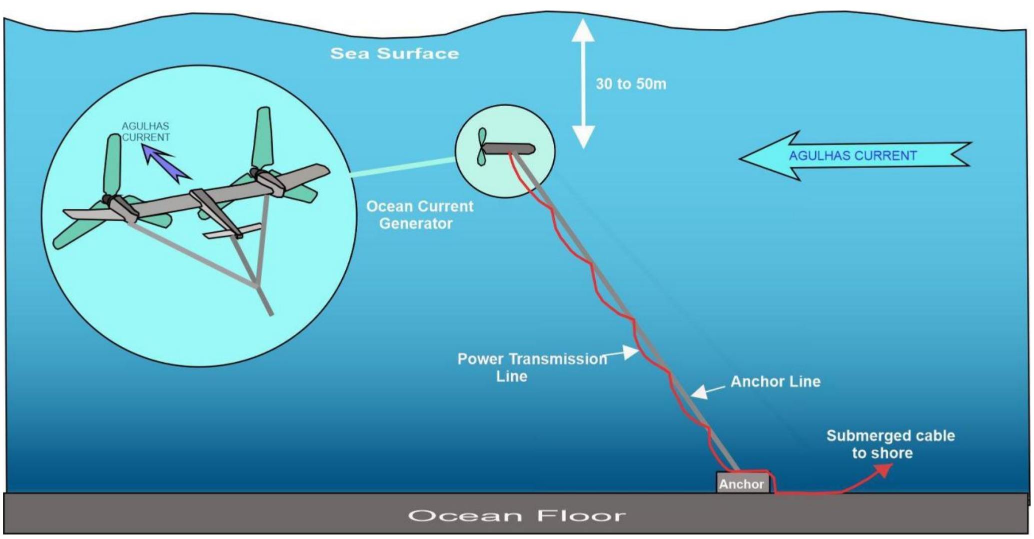

Figure 8. Proposed arrangement of an ocean current generator in the Agulhas Current.

The fact that the turbines are submerged at depth also provides two important advantages over surface-based deployments, namely minimising the effects of extreme weather events and that there is no surface signature. This obviates issues which could cause significant delays.

While it is clear that there are substantial opportunities for power generation in these western boundary currents, it is significant that, at present, there are no operating systems in these currents. Thus, Maksumic [35] states that, "According to FAU, currently, no operational ocean current test facilities exist worldwide."

This attests to the engineering challenges associated with power extraction, but work is progressing and there have been at least two reports of successful test deployments by companies of such turbines, for example in the Florida Current [36] and in the Kuroshio Current [37]. In the latter case it was stated that the company hopes to deploy full-scale commercial systems by 2030.

A further complication arises from the potential environmental impacts of deploying turbines in the water column, in particular the harm that could possibly be caused to fish and other sea life swimming into the blades. As already indicated, the turbine blade radii of OCTs are much less than

comparable wind-driven systems because of the greater drag effects of water compared to air; this means that the areal coverage perpendicular to the current flow will also be substantially less. Moreover, the slower rotation rate of the turbines will reduce the impact forces and therefore the potential harm.

It is known that substantial migrations take place along this section of coastline, with the most famous being the 'sardine run' [38]. This migration of large shoals of the sardine *Sardinops sagax* from the Agulhas Bank in the south reaches the southern KZN coast in late May/early June. Such migrations could be adversely impacted by arrays of turbines, however, the sardines prefer water temperatures less than 22 °C, and therefore stay close to the coast and out of the warm Agulhas Current; keeping to the coast also means they do not have to swim against the strong polewards Agulhas Current.

The annual northward migration of the Southern Hemisphere humpback whale also reaches its peak over June, July and August [39]. These whales have coastal migratory routes, which means that coastal observation stations off the KZN coast were deemed sufficient to assess numbers. With an offshore extent of not much more than 6 km, it means that these whales keep well inshore of the proposed turbine deployments.

The depth at which the turbines will be situated also excludes other biota, e.g., turtle hatchlings that get swept southwards from KZN by the Agulhas Current.

6. Conclusions

These results show the potential in the Agulhas Current of providing a substantial source of renewable energy. The extensive set of in-situ mooring measurements have provided detailed information on the structure and dynamics of the Current, highlighting possible areas where electrical power generation is feasible.

The data show that the Current maintains its strength and duration for sufficient periods to provide an effective electrical base load scenario. Furthermore, satellite data will enable reliable forecasts to be made of future slack or interrupted current conditions caused by features such as the Natal Pulse, allowing predictions of at least one or two days prior to reduced current strengths and/or direction changes. In the long term, the impact of such reversed flows can be offset by the deployment of along-coast ocean current turbine arrays, giving a consistent, reliable source of power.

Current structures in all three of the major western boundary currents, namely the Gulf Stream and Kuroshio in the northern hemisphere, and the Agulhas Current in the southern hemisphere, have been known for many years and are receiving increasing interest as a source of power. The deployment of turbines and connecting them to the national grid will be costly, so economies of scale are important in designs.

Such designs also need to minimise possible collisions with animals and vessels, to meet the requirements of "The Law of the Sea". In the long term there may also be consequences from potential changes in current flow dynamics.

Nonetheless, the advantages arising from (1) no need to acquire land to build the turbines, (2) no unsightly or intrusive surface structures, and (3) an environmentally-friendly sustainable baseload power all make the Agulhas Current a very attractive means of power generation in South Africa.

Author Contributions

Conceptualization and methodology, E.S. and M.R.; Software, E.S.; Validation, E.S., M.R. and M.B.; Formal analysis, E.S., M.R. and M.B.; Investigation, M.R.; Resources,

M.R. and M.B.; Data curation, M.R.; Writing—original draft preparation, E.S.; Writing—review and editing, E.S., M.R. and M.B; Visualization, E.S. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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