Surface drift at the western edge of the Agulhas Bank

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The Agulhas Bank is a wide continental shelf that forms the southern tip of the African continent. On the eastern side of this shelf the flow of water is dominated by the adjacent Agulhas Current. On its western border, the movement is more complex. It is influenced by the Benguela Current, by the occasional presence of products from the Agulhas Current such as Agulhas rings, Agulhas filaments and by lee eddies. Understanding the flow on this western side of the Agulhas Bank is of considerable ecological importance because it has been assumed that a shelf edge jet carries immotile or weakly motile fish larvae and eggs from the spawning region on the bank to the biologically productive regions of the Benguela upwelling regime. We have used the tracks of a set of surface drifters to study the movement at the western edge of the bank, and show that on average the movement is indeed equatorward along this shelf edge, but that this movement is not persistent in direction or magnitude. Instead, this movement appears to be driven entirely by mesoscale turbulence created at the termination of the Agulhas Current.

Introduction

The ocean circulation directly south of the African continent is complex, but is shaped largely by the geomorphology of the wide continental shelf known as the Agulhas Bank (Fig. 1). On the eastern side of the bank the warm and swift Agulhas Current on average follows the shelf edge, but meanders considerably and in the process creates shear edge features such as cyclonic eddies and warm surface plumes.[1] The movement in the surface layers of the current may exceed 2 m s^{-1}, so that any organisms from the shelf waters caught up in it will be rapidly advected downstream.[2] Even marine turtles make use of this handy conveyor belt.[3,4] On the western side of the Agulhas Bank the water movement should in principle be dominated by a sluggish equatorward drift of the Benguela Current. Zonal hydrographic sections across the Agulhas Bank[5] do indicate such movement. However, this conceptual flow is complicated by a number of circulation features along this shelf edge that all have their origin in the Agulhas Current.

First, Agulhas rings that are shed at the Agulhas Current's retroflection[6] move off in a northwestward direction, but some of them seem to get quite close to the western edge of the Agulhas Bank.[7] This juxtaposition may cause an intense equatorward current along this shelf edge on such occasions. These rings do not necessarily remain here for long, but move off into the Cape Basin[8] and from there across the width of the South Atlantic Ocean.[9] So the equatorward flow induced by these passing rings at the Agulhas Bank edge may be intermittent at best. The Agulhas Current has furthermore been observed to drive a cyclonic eddy in the lee of the Agulhas Bank as it passes the tip of this shelf.[10,11] This eddy causes the water along part of the western side of the Agulhas Bank, in contrast to that induced by Agulhas rings, to move poleward. The presence of such lee eddies is also intermittent,[10] since they detach from the shelf edge at irregular intervals and then move westward. A new cyclone starts forming soon afterwards along this shelf break. These observations and results suggest that the flow along this shelf may be in either direction, but both for limited periods. What further evidence it there to elucidate the flow here?

Warm plumes that get detached from the Agulhas Current once they have passed the southern tip of the Agulhas Bank have been shown[12] to move as Agulhas filaments predominantly along the shelf edge and in a northerly direction, suggesting that this is the dominant flow here. Judiciously placed current measurements at this shelf edge would seem to have the potential to be the final arbiter of the flow. Regrettably, they have not succeeded in doing this as yet. Such observations[13] have indicated that at times there is indeed a strong flow, but that this is not persistent and that at other times there is no along-shelf flow.

The uncertainty about this flow is not just of academic interest. The pelagic fish of greatest economic importance to South African fisheries, anchovy[14] and sardine,[15–17] are known to spawn on the Agulhas Bank. The immotile eggs and weakly motile larvae are then thought[18,19] to be carried slowly westward by the average surface drift on the Agulhas Bank, to reach the western shelf edge, where they are carried by an intense and persistent jet[20,21] equatorward to the main upwelling regions along the west coast where they then spend the greater part of their adult life. The connecting role of this presumed shelf edge jet between the relatively quiescent spawning waters of the Agulhas Bank and the upwelling regime is therefore crucial to the life-cycles of these fish.[22–25]

In this regard, a distinction should be made between flow along the western edge of the Agulhas Bank and that which has been observed[26] at the thermal front of coastal upwelling[27] farther north. It has, for instance, been noted that anchovy eggs and larvae[28,29] and their main food supply such as microplankton[30] are concentrated at this upwelling front off the Cape Peninsula. Since the coastal upwelling starts at either Cape Point or, occasionally, at Cape Agulhas, depending on the reigning winds, this upwelling front is not found along the full length of the western edge of the Agulhas Bank. Although of great importance to the movement of organisms, the intensified flow at this upwelling front is not the same thing as the movement along the shelf edge of the Agulhas Bank.

Some new data have now become available that may give some further information on the dominant currents along this shelf edge.

Data and methods

Surface drifters are currently being placed all over the world ocean, mainly in order to give real-time input of surface drift to operational ocean models. Their positions and the data collected by their instruments are telemetered via satellite. A large number have been placed in the ocean regions adjacent to southern Africa. Fortuitously, some of these have been launched near the western edge of the Agulhas Bank (Fig. 1).

In total, 10 WOCE-GDP surface drifters were deployed on or near the western Agulhas Bank. Two of these did not survive very long. The remaining eight were used in our investigation (numbers 9379, 9394, 29494, 29495, 9525826, 9619407, 9619410 and 9619423). The transmissions from all of these lasted between six months and two years. The drifter data were acquired from the Data Assembly Center (DAC) at the Atlantic Oceanographic and Meteorology Laboratory (AOML) of NOAA (National

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Oceanic and Atmospheric Administration) in the United States. The DAC applies uniform quality control, edits and then interpolates the drifter data into 6-hour intervals. The drifters are in all cases drogued at a depth of 15 m. This makes them ideal trackers of the surface mixed layer, an important issue if one wants to simulate the movement of fish larvae by the trajectories of these drifters. Since they were all identical drifters and drogued at the same depth, this also presents a uniform data set, something that is not true of all such studies where sometimes tracks of drifters either undrogued or drogued at different depths are used.

Altimetry delayed-time data, merged from two satellites (TOPEX/Poseidon and ERS, or Jason-1 and Envisat) with the same ground tracks,[31] have also been used in this investigation. In these cases sea-surface height anomalies have been employed based on an average of many years and not on an accurate geoid. Previous experience in this particular region has shown[32,33] that this is entirely adequate for identifying and following the intense mesoscale features found in this part of the south-eastern Atlantic Ocean. For more detail on these respective data sets, the interested reader is referred to the websites indicated in the acknowledgement section below. Drift tracks that were singled out for analysis (Figs 2 and 3) were those that exhibited movement at the shelf edge in question for an appropriate lengthy time. Some other tracks were interrupted soon after launch and have been used only to contribute to a compendium of all the results (Fig. 4).

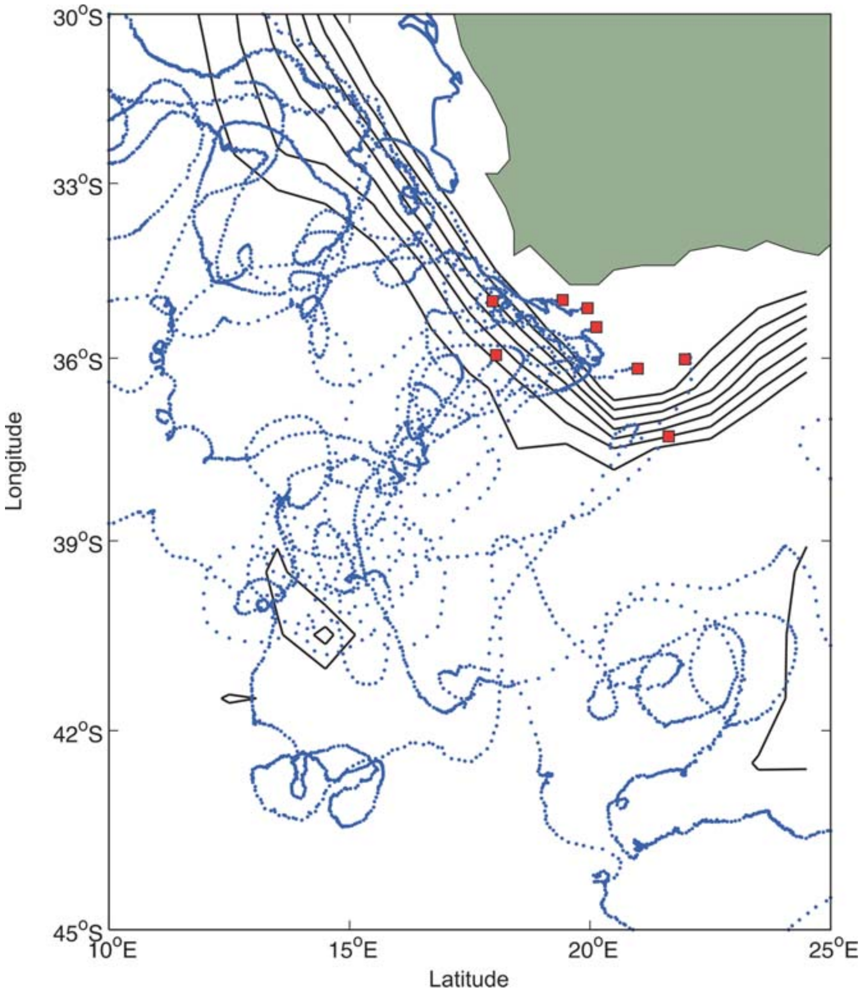

Fig. 1. Deployment positions (red dots) of eight drifters in the vicinity of the western Agulhas Bank during the period 1996 to 2001. The trajectories have been interpolated into 6-hour intervals and these positions are shown with smaller blue dots. The tracks are superimposed on the bathymetry that is given at 1000-m intervals. Note that all the motion is eventually away from the Agulhas Bank.

Those parts of the drifter tracks that were at the shelf edge have been colour coded (Figs 2 and 3) for the period corresponding to the sea-surface height field on which the tracks have been superimposed. These fields are averaged for a five-day period that is indicated in the figure captions by the middle day of the period. Although mesoscale features in this region are known[8] to shift position relatively rapidly, during a period of five days there should be negligible movement on the spatial scales of interest to this investigation.

Results and discussion

The movement of eight drifters subsequent to being launched near the western edge of the Agulhas Bank shows a wide range of movement covering an extensive ocean region (Fig. 1). Only those parts of the tracks that were in the Cape Basin are shown here. Some moved far into the South Indian Ocean in the Agulhas Return Current, but this information is not pertinent here.

First, two drifters, one placed on the eastern side of the Agulhas Bank, the other just south of the bank, were both carried off rapidly by the Agulhas Current and never came near the western edge of the Agulhas Bank (Fig. 1). The first may for a short while have been in an incipient lee cyclone on the southern point of the bank. These two drifter tracks therefore give no useful information on the movement along the western shelf edge of the bank but do illustrate the strong influence of the Agulhas Current on the surface drift on the eastern side of the shelf.

Four drifters placed on the bank itself slowly moved in a westward direction. Once off the shelf, they were caught up in complex patterns of circulation in the Cape Basin while some were eventually carried off by the Agulhas Current and the Agulhas Return Current. With one exception, all drifters eventually moved offshore. Only one moved onto the broad shelf region of the west coast. This confirms that surface water from the Agulhas Bank is not constrained to remain on the continental shelf.

In Fig. 2, the tracks of two drifters are given that are representative for those that have followed a route along the shelf edge. The drifter for which the track is shown in Fig. 2a was placed well offshore of the shelf edge. It moved farther offshore and subsequently went through six gyrations in a cyclone that in the figure lies to the west of the tracks shown. This cyclone had moved there before the period of the sea-surface height portrayal of Fig. 2a. The drifter then went through an anti-cyclonic motion, part of which is shown by the elongated red area at about 16° E, being returned to the shelf edge. Judging by the sea-surface height of this anti-cyclonic feature,[8] that exceeded 60 cm, it was an Agulhas ring. Having arrived back at the shelf edge this drifter then moved in a straight line along the edge of the Agulhas ring before being caught up in a cyclone forming a characteristic part of the southern upwelling regime.[34] This cyclonic movement caused it to drift onto the shelf, where it stayed in cold, shelf waters. It is evident that during the latter

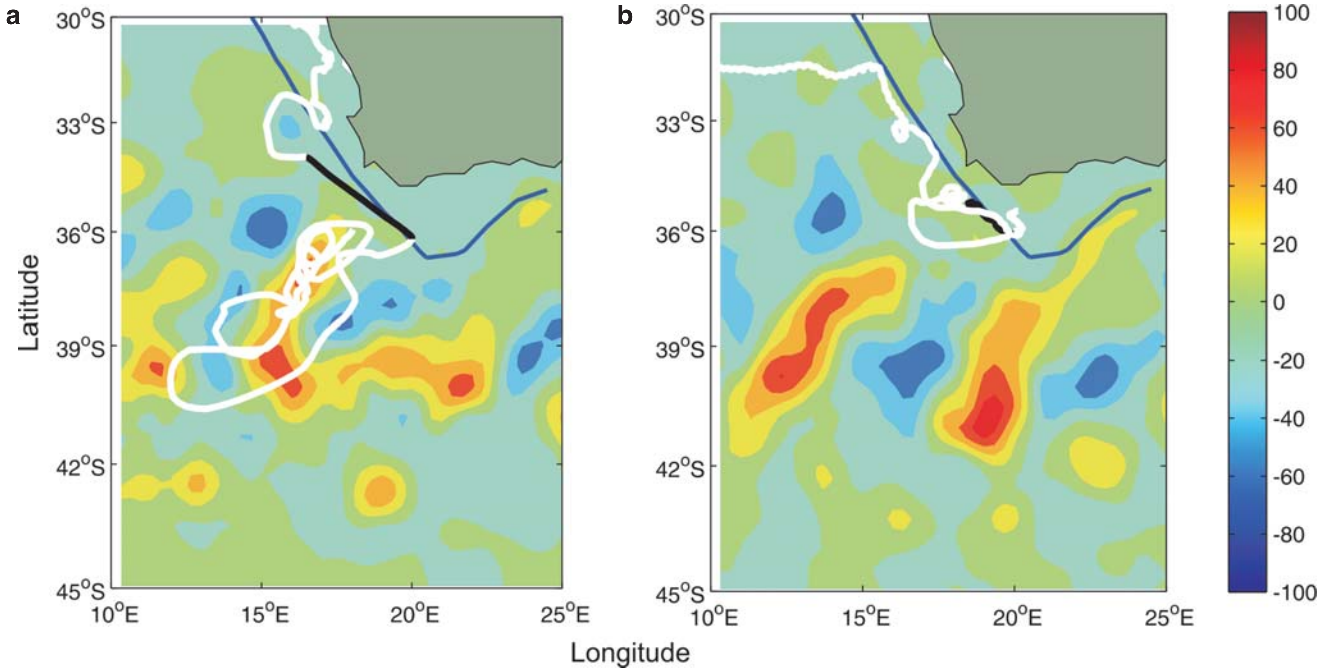

Fig. 2. Two examples of drifter tracks, overlaid on sea-surface height anomalies (in cm), that show an equatorward trajectory over the western edge of the Agulhas Bank. (**a**) Track of drifter 9379 overlaid on the 5-day averaged sea-surface height anomaly field for 26 April 2000. (**b**) Track of drifter 29495 overlaid on the same field but for 28 November 2001. Drifter positions shown with black lines correspond to the 5 days for which the sea-surface field has been averaged; the given dates are for the middle day of each 5-day period. Colours towards the red end of the spectrum denote anti-cyclonic motion; conversely, blue/green colours indicate cyclonic movement. The 1000-m isobath, circumscribing the shelf edge, is demarcated by a solid blue line. Correspondence between the drift tracks and the altimetry is strong.

part of this period there was a clearly demarcated equatorward movement along the western edge of the Agulhas Bank, driven by the adjacent Agulhas ring and that it caused water along the shelf edge eventually to land up in the upwelling waters off the west coast.

The trajectory of the drifter shown in Fig. 2b is different in many respects from that of the one in Fig. 2a. Launched on the Agulhas Bank, once it had left the shelf this drifter moved slowly along the shelf edge (black lines in Fig. 2b), clearly driven by a weakish anti-cyclone lying next to the shelf. This anti-cyclone had a maximum sea surface height of only 20 cm. It is therefore unlikely that this was a fully fledged Agulhas ring. It could, however, have been one of the break-up products of such a ring that have been observed here in previous investigations.[35] After this along-shelf movement, the drifter carried out an anti-cyclonic trajectory (centred at 35°S, 18°E) around the eddy, and

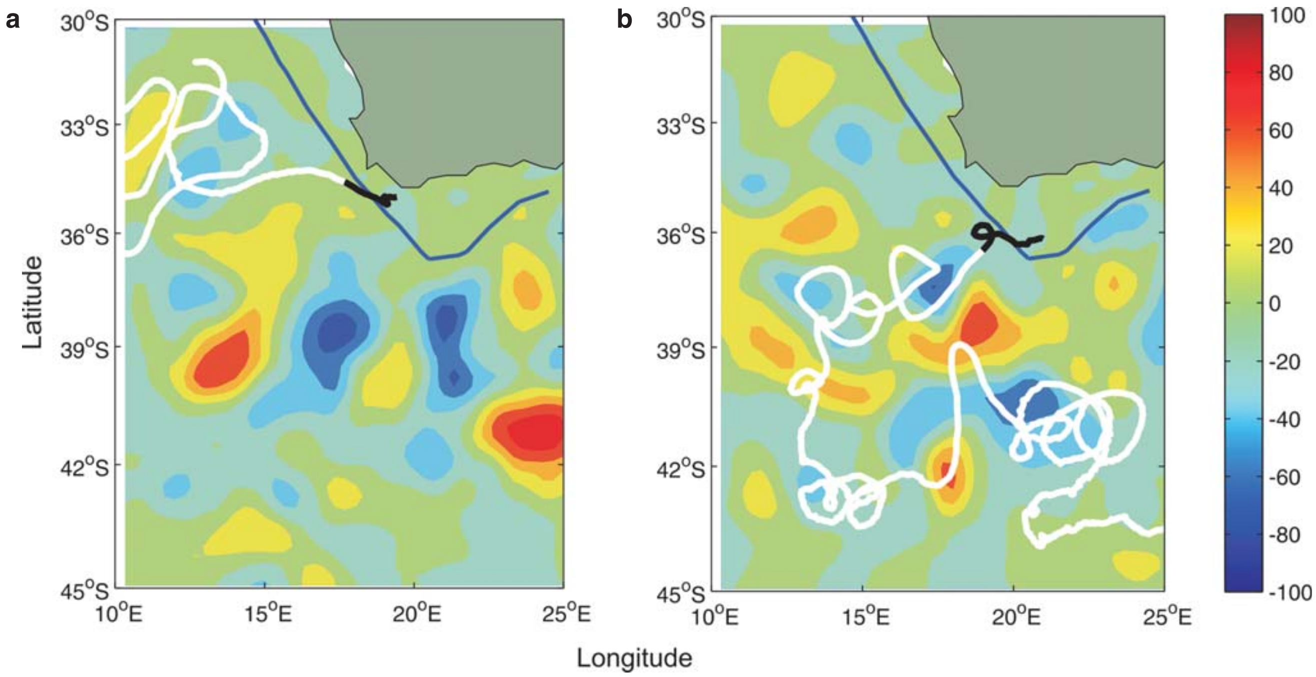

Fig. 3. Two examples of drifter tracks, overlaid on a field of sea-surface height anomalies (in cm), that show non-equatorward trajectories over the western edge of the Agulhas Bank. (**a**) Track of drifter 9394 overlain on the 5-day averaged sea-surface height anomaly field for 20 December 2000. (**b**) Track of drifter 9619423 overlain on the 5-day averaged sea-surface height anomaly field for 9 May 1997. Drifter positions shown with black dots correspond to the 5 days for which the sea-surface field has been averaged; the given dates are for the middle day of the 5-day periods. Colours towards the red end of the spectrum denote anti-cyclonic motion; blue/green colours indicate cyclonic movement. The 1000-m isobath, circumscribing the shelf edge, is demarcated by a solid blue line. The drifters clearly follow the altimetry.

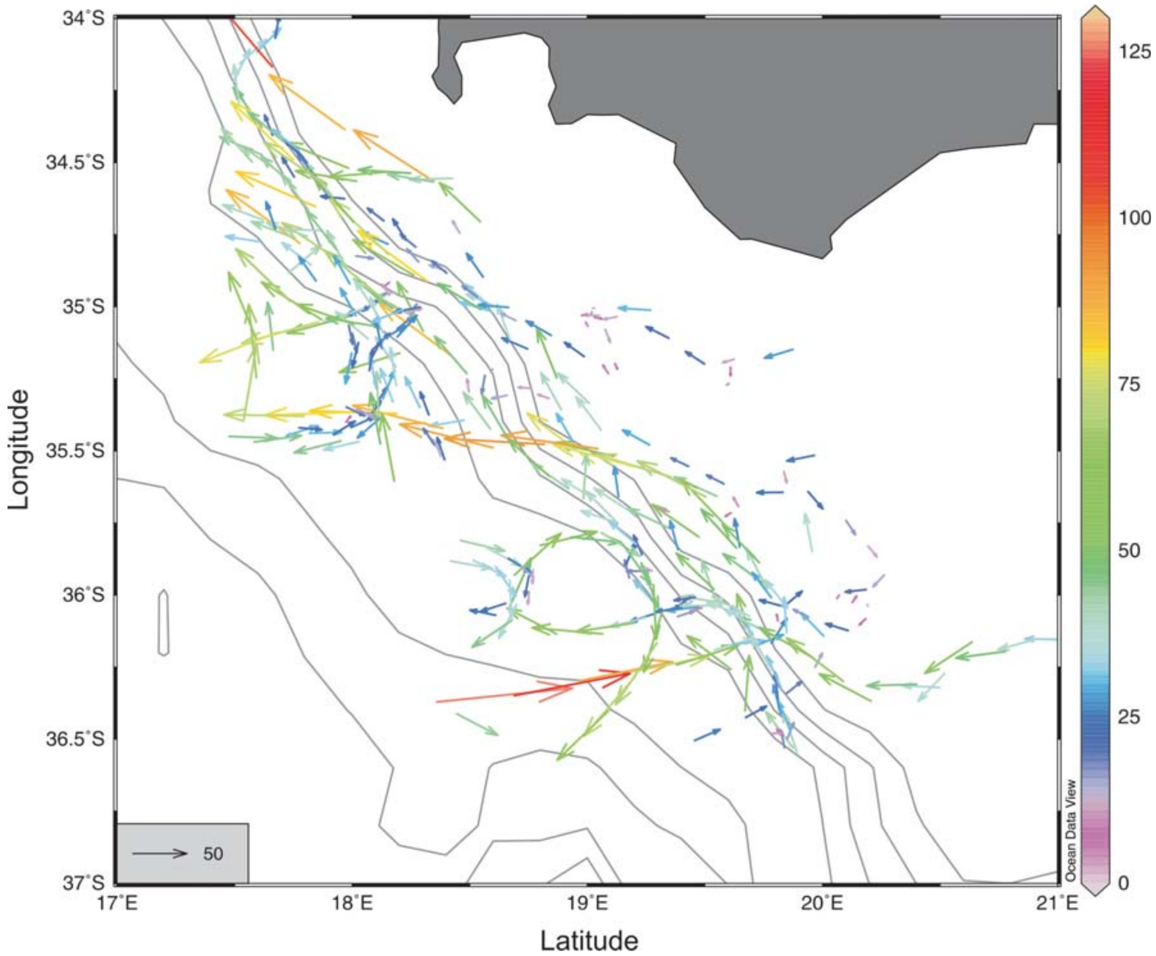

Fig. 4. Velocity vectors (in cm/s) derived from surface drifters' motion taken at 24-hour intervals near the western shelf edge of the Agulhas Bank. Colour coding as well as arrow size represents the speeds of the drifters. Bathymetry less than 4000 m is shown in intervals of 1000 m. An average northwestward trajectory of drifters at the western edge of the Agulhas Bank is evident, but with a number of anomalous circulation patterns that evidently do not fit this general motion.

passed along the shelf edge once again. It then hugged the shelf edge for a while in moving equatorwards, under the influence of more anti-cyclonic features to the north, until it abruptly left the shelf edge at about 32°E. The drifter motions presented in Fig. 3 were, by contrast, fundamentally different.

The track portrayed in Fig. 3a shows a drifter moving off the Agulhas Bank under the influence of an extension of an Agulhas ring (with a centre of 60 cm maximum elevation, farther to the southwest). It followed the edge of this anti-cyclone closely until about 500 km offshore, where it encountered some large cyclones that determined its subsequent motion. Such cyclones have been observed to be shed from this coastline[8] and to move westward. There is no evidence here that this drifter showed a tendency to move in a shelf edge jet. Its motion seems entirely predicated by the presence of the anti-cyclone. This is even clearer for the motion of drifter 9619423 (Fig. 3b).

This drifter moved off the shelf, carried out a small anti-cyclonic gyration and was then caught up in an offshore cyclone. Judging by the location of this cyclone it is more than likely that this was a lee eddy[10] spun up along the southwestern edge of the Agulhas Bank and this is confirmed by altimetric observations for previous periods (not shown here). It can be postulated that had this drifter been launched somewhat earlier, it would have moved south-eastward along the shelf edge under the influence of this cyclone.

The four drift tracks given in Figs 2 and 3 may be characteristic, but are from a comparatively small data base. The chances of having this data base expanded significantly during the next few years are small. If one combines all the drift tracks currently available, what result does one get? This is shown in Fig. 4, where the speeds for each day for all currently available drifter motion in the region are given. A number of patterns are clear.

First, the surface motion of the water on the Agulhas Bank hardly ever exceeds a speed of 20 cm s^{-1}. Second, the speeds at the shelf edge are on the whole considerably higher and, with a few notable exceptions, all roughly in an equatorward direction. However, the individual speeds vary over a range of about 25 cm s^{-1} to 80 cm s^{-1}. A considerable number of tracks show a distinct offshore tendency. It is also clear that only two of the drifters placed on the Agulhas Bank eventually made their way to the Benguela upwelling region, so that a stable and unwavering advection pattern is unlikely. This has implications for the assumed movements of fish eggs and larvae here. In these drift velocities (Fig. 4), there is no evidence for a highly localized, enduring current jet of great speed.

Conclusions

The number of drifters available for this investigation regrettably was relatively small and not all were optimally placed to study the purported shelf edge jet on the western side of the Agulhas Bank. However, comparing their tracks with anomalies in sea-surface height indicates a very high degree of correspondence between these two independent data sets. This gives us considerable confidence that the movement of the upper ocean layers in this region is well-represented by altimetric information.

Based on these measurements, one can therefore conclude that the movement along this shelf edge on average is considerably faster than on the Agulhas Bank itself. Although in general equatorward, it at times may be poleward, particularly along the southern part of this shelf edge. Of greatest importance is the conclusion that intensification of current speeds along this shelf edge is driven almost entirely by circulation products of the Agulhas Current. The presence of anti-cyclonic Agulhas rings will increase flow speeds equatorward; the presence of a cyclonic lee eddy will—by contrast—induce flow poleward. If neither of the above is present, there seems to be no current speed enhancement at this shelf edge. This implies that the flow here can be monitored using observations of sea-surface height alone, possibly presenting at least one method to help predict the spawning success of the year class of pelagic fish.[22]

The drifter data used in this study are made available by the DAC of the AOML of NOAA at http://www.aoml.noaa.gov/phod/dac/dactata.html. Altimetry data were obtained via ftp from the SSALTO/DUACS at ftp://ftp.cls.fr/pub/oceano/AVISO/SSH/duacs/ global/dt/ref/msla/merged/h/. Analyses were carried out using the free software made available by R. Schlitzer (Ocean Data View, http://www.awi-bremerhaven.de/GEO/ODV). This research was supported by the National Research Foundation. We thank the University of Cape Town for a postgraduate bursary for J.V.D.

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