

Satellite drifter observations on South Africa's Agulhas Bank and their relevance to the dispersion of chokka squid (*Loligo vulgaris reynaudii*) paralarvae — summer 2002/3

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Four satellite drifters were released on the eastern Agulhas Bank to investigate chokka squid paralarvae transport. Two drifters with drogues to 8 m (near-surface) were released directly above a bottom-mounted ADCP (36 m) on the inshore spawning grounds 1.5 km from the Tsitsikamma coast. The other two were released on the mid shelf where squid eggs had previously been found (120 m). One of these was tethered to a drogue at 70 m to monitor flow in the bottom layer. This mid shelf position was also used to release “virtual paralarvae” in a preceding IBM experiment which showed substantial losses from the shelf. Comparison between the ADCP and drifter data showed the drifters to accurately reflect current velocity and direction in the near-surface layer when wind was $< 4 \text{ m s}^{-1}$. Inshore transport projections (progressive vector plots) based on the ADCP data were found to be reliably accurate for distances of $\sim 50 \text{ km}$ on this straight coastline. Both inshore drifters were transported 70 km eastwards in the Tsitsikamma counter current to Tsitsikamma Point. One beached here, the other left the shelf after 20 days. The surface drifter on the mid shelf was transported westward across the central and western Agulhas Bank (550 km) to leave the shelf after 58 days just south of the Cape Peninsula. The deeper drifter also travelled westward, but after 40 days was found well inshore 100 km from the release position. During the study period satellite SST and ocean colour imagery indicated frequent leakage of shelf water near the southern tip of the Agulhas Bank, as well as an intrusion of oceanic water onto the western Bank. The latter caused an anti-cyclonic circulation which led to further leakage of shelf water from the inner central Agulhas Bank. The combination of drifters and satellite imagery used here demonstrated that the retention of chokka squid paralarvae in the Agulhas Bank ecosystem is not guaranteed, even for the inshore spawning grounds. The risk would be less if paralarvae were found near the bottom, but so far sampling indicates they occupy the surface layer.

Key words: satellite drifters, chokka squid, *Loligo vulgaris reynaudii*, transport, Agulhas Bank, shelf water leakage, cold ridge

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Introduction

The Agulhas Bank at the southern tip of Africa is the largest expanse of shelf on the continent spanning 800 km from east to west and 300 km from north to south at its widest point (21° E , see Figure 1a). The shelf break is at 200 m giving the shelf an average depth of $\sim 100 \text{ m}$. The Bank is bordered in the east by the fast ($\sim 200 \text{ cm s}^{-1}$) and warm ($24\text{--}25^\circ \text{C}$) Agulhas Current which flows poleward along the continental slope, diverging from the coast as the shelf widens between 26° and 21° E . This powerful western boundary current typically forms an 80 km wide barrier between the shelf water and the Indian Ocean. South of the Bank, the Agulhas Current undergoes a number of final fates which range between continuing north-west along the slope of the western Agulhas Bank, generating anticyclonic eddies which move into the Atlantic Ocean, and retroflexion to the south with final flow eastwards along the Subtropical Convergence. Numerous configurations exist between these extremes some of which can be seen in Figure 9. The Benguela Current is less defined, mainly because it is the eastern component of the South Atlantic gyre, and has lower velocities ($\sim 40 \text{ cm s}^{-1}$). A strong but small jet (Benguela Jet) is often formed along the Cape Peninsula. This leaves the western Bank less confined than the central and eastern regions. More detailed regional overviews of the

oceanography are given in Boyd and Shillington (1994), Roberts (2005), Lutjeharms (2001) and Roberts and van den Berg (2002).

The Agulhas Bank plays a major role in the early life histories of many species including but not least, clupeids, sciaenids, sparids, merluccids, carangids, and squid (Augustyn *et al.*, 1994; Hutchings, 1994; Japp *et al.*, 1994; Roel *et al.*, 1994; Barrange *et al.*, 1998; Hutchings *et al.*, 2002). In particular, the western and central Banks are the main spawning ground for sardine (*Sardinops sagax*) and anchovy (*Engraulis capensis*) with the latter often spawning between the cold ridge and the Agulhas Current (see Figure 1a and Roel *et al.*, 1994). Several modelling studies based on ADCP ship-borne data (Shannon *et al.*, 1996), averaged winds and geostrophy (Skogen, 1999), and more recently a Regional Ocean Modelling System (ROMS) coupled to an Individual Based Model (IBM) (Mullon *et al.*, 2003; Parada, 2003), have demonstrated that sardine and anchovy eggs and larvae are largely transported westwards towards the Cape Peninsula where they are typically moved by the Benguela Jet onto the west coast feeding grounds. Hutchings *et al.* (2002) identified the outer shelf of the central Agulhas Bank as playing a critical role in the retention of eggs and larvae.

Chokka squid (*Loligo vulgaris reynaudii*), another commercially important species, spawn on the eastern Agulhas Bank depositing their egg capsules on the seabed both inshore and on the mid shelf regions (Augustyn *et al.*, 1994). In contrast to the sardine and anchovy, Roberts and van den Berg (2002) suggested that the paralarvae are at risk by currents on the Agulhas Bank and at times could be lost from the ecosystem through the leakage of shelf water into the greater ocean (see their Figs. 9, 10). This incorporated work by Roberts and van den Berg (in press) who concluded that squid paralarvae on the inshore spawning grounds (< 60 m) in the vicinity of the Tsitsikamma coast are predominantly transported eastwards in the surface layer with potential distances of ~ 200 km. This was based on data collected by a single ADCP bottom-mounted current meter and the use of progressive vector plots (i.e. projected trajectories). Potentially such transport places paralarvae at risk because *in situ* data collected by Goschen and Schumann (1988) and ROMS model results by Penven (2000) demonstrated offshore advection near Algoa Bay.

To test for mid shelf losses, a first version of an IBM for squid paralarvae was also developed in which hatchlings were treated as Lagrangian particles with an assumed 40 day pelagic phase i.e. no swimming ability. Dispersion simulations were performed for paralarvae in the bottom layer at a depth of 120 m (Roberts and Mullon, in prep.). This was considered a worst case scenario relative to higher in the water column where currents are stronger (CSIR report, 1986). The IBM was driven by the output from a hydrodynamic ocean model based on the Regional Ocean Modelling System (ROMS) numerical code (see Haidvogel *et al.*, 2000) which has been adapted to the Agulhas Bank and west coast (Penven, 2000; Penven *et al.*, 2001). This was used in the sardine and anchovy IBM studies cited above (Mullon *et al.*, 2003; Parada, 2003). Results from the squid ROMS–IBM showed the majority of hatchlings to be transported eastwards on the shelf and then swept offshore in the vicinity of St Francis where they were displaced westwards in the Agulhas Current and finally lost. This result was surprising because flow on the mid shelf is thought to be mainly westward. In its present form the ROMS–IBM is not reliable in the shallower coastal region and hence can not be used to validate the results of Roberts and van den Berg (in press) already mentioned.

Understanding egg and larval transport in the ocean is not trivial and no one method appears to be definitive. In this paper satellite tracked drifters were employed as a complementary method in an attempt to: (1) validate the results of the squid ROMS–IBM simulations on the mid shelf spawning grounds and (2) determine the potential fate of paralarvae in the Tsitsikamma counter current (and validate the use of progressive vector plots as a means of estimating potential egg and larvae transport). Lagrangian measurements have been used in numerous experiments to study surface currents and larvae dispersion e.g. Pepin and Helbig (1997) and Kasai *et al.* (2002).

Methods

Four satellite tracked surface drifter buoys were used in this experiment, each tethered to a standard 6.4 m long “holey sock” drogue. This is a well used design and has been deployed extensively in the Surface Velocity Program (SVP) of the World Ocean Circulation Experiment (WOCE) (Sybrandt and Niiler, 1991).

Two drifters (referred to as 1 and 2) were simultaneously released on the mid shelf of the eastern Agulhas Bank on the 10 November 2002 (16:45) at the same position used in the ROMS–IBM experiment to release virtual particles ($34^{\circ} 29.53$ S; $23^{\circ} 20.06$ E; Figure 1a). Drifter 1 monitored movement of the upper mixed layer with the drogue hanging 2 m below the float. Drifter 2 monitored the bottom mixed layer with the drogue hanging 70 m below the float. The depth here is 120 m and the thermocline in summer is typically at 30 m (Largier and Swart, 1987). All drifters transmitted their positions (GPS) hourly. The remaining drifters (Drifters 3 and 4) were released at different times on the inshore squid spawning grounds off the Tsitsikamma coast directly above a permanently bottom-mounted ADCP on Middlebank in 36 m ($34^{\circ} 02.64$ S; $23^{\circ} 52.58$ E; Figure 1a). Drifter 3 was released on 11 November at 10:50 and Drifter 4 a week later on the 19 November at 11:26. Drogues on both drifters hung 2 m below the float. The intention was to monitor the drifters for 40 days, the same period used to track virtual particles in the IBM experiment.

Other data required were wind, current meter and satellite imagery. Wind data shown in Figure 3, measured 15 m above sea level, were obtained from a dial-in automatic weather station (AWS) located at Storms River (see Figure 1a). AWS measurements were made hourly. This location is not ideal because the coastline topography is exceptionally steep and rises to a coastal plain at an altitude of 180–220 m. In addition, the small embayment at Storms River mouth introduces an inflection in the otherwise linear coastal topography. This may influence measurements made at this site so that these data do not accurately represent the wind field farther offshore i.e. velocities offshore are probably greater. However, for this study this data are adequate because the main wind directions are parallel to the coast i.e. east–west. A New Hampshire Lanczos filter (UNH), with 71 weights and a power point of 36 h was used to remove land breeze effects in the analysis.

The current meter data used to compare inshore drifter trajectories were collected at Middlebank (coordinates give above) using an *RDI Sentinal Worhorse* 300 kHz ADCP configured to measure every 30 minutes with 2 m bins (see Roberts and van den Berg, in press, for details). The data did not require filtering to remove noise. Currents shown in Figure 2 were made prior to Drifter 1 and 2 deployments using a hull mounted *RDI Ocean Surveyor I* 150 kHz ADCP aboard the *FRS Algoa*. Four meter sample bins were used. SeaWiFS ocean colour satellite imagery (chlorophyll *a*) was used to distinguish Agulhas Bank water from that of the surrounding ocean. SST AVHRR imagery was obtained from NOAA.

Results

Drifter release conditions

An ADCP survey undertaken by the “FRS Algoa” immediately prior to drifter deployment showed the upper and bottom mixed layers of the water column to be westward flowing on the mid shelf between Plettenberg Bay (23° E) and St. Francis (25° E) including the inshore region along the Tsitsikamma coast. The Plettenberg Bay transect data are shown in Figure 2. Near-surface velocities ranged between $20\text{--}30\text{ cm s}^{-1}$. The westward inshore current was confirmed by ADCP data collected at Middlebank (see Figure 6). Wind at the time (10 November) was light to moderate ($3\text{--}4\text{ m s}^{-1}$) easterly (Figure 3). Clearly the strong south-westerly wind on 8 and 9 November had little lasting effect on the westward shelf current.

Drifter tracks

An overview of all four drifters is shown in Figure 1a. Selected time frames of these are shown in Figure 4. Drifter 2 (deep mid shelf) had fewer positional data than the other drifters seemingly caused by the inability of the float with its long tether to ride on the surface of large wind waves and successfully transmit. For example on 19–20 November (see Figure 4) a strong south-westerly wind of $> 6 \text{ m s}^{-1}$ blew (Figure 3) and no data were received for this period. Note that linear interpolations have been used to fill data gaps in Figure 4. Drifter 3 lost communication with the satellite between 26 November 2002 and 21 January 2003, a period of 57 days. Interestingly, data loss in this region has also been experienced with three other drifters released into the Agulhas Current subsequent to this experiment.

Drifter 3

Initially Drifter 3 was observed to move westwards with the rest of the shelf water under the 3–4 m s^{-1} north-easterly wind reported above (Figure 5a), but then reversed course to eastwards late on 12 November (Day 2) coincident with a wind change to strong south-westerly (6 m s^{-1}). The drogue continued eastwards to Tsitsikamma Point (see Figures 4, 5a) with a velocity of $\sim 43 \text{ cm s}^{-1}$ despite a further change in wind to light north-easterly ($2\text{--}3 \text{ m s}^{-1}$) on 14 and 15 November (Days 4 and 5). On 15 November Drifter 3 turned offshore onto the mid shelf and completed two clockwise gyrations in the same place with the drogue revisiting the inshore counter current before disappearing altogether on 26 November (Day 16). When communication was re-established on 21 January (Day 71), Drifter 3 was found directly south of Algoa Bay some 400 km from the shelf edge in the vicinity of the Agulhas Plateau and the Subtropical Convergence (26° E ; 38° S ; see Figure 1a). From here it travelled further south to reach 41° S before turning eastwards to 42° E where communication finally failed on 26 March 2003 (Day 137).

Drifter 4

On the first day after release Drifter 4 moved offshore for 10 km (Figure 5b). This was opposite in direction to Drifter 3 only 30 km away which was moving inshore during a clockwise gyration and similarly was 10 km from the coast (see Figures 5a, b). By Day 2 Drifter 4 had moved back towards the coast under a strong south-westerly wind and continued to move steadily eastwards with a similar velocity as experienced by Drifter 3. On 23 November (Day 5) under a strong north-easterly wind (6 m s^{-1}) it floundered at Tsitsikamma Point. The cause of the initial temporary offshore excursion is not obvious. The ADCP data collected at Middlebank (Figure 6) also measured an offshore flow with similar displacement. Previously, Roberts and van den Berg (in press) demonstrated that coastal upwelling events cause offshore flow on the Tsitsikamma coast, but in this case, no coastal upwelling was evident from data collected by a thermistor array on Middlebank (data not shown), nor in SST imagery. Another possible cause could be an offshore land breeze, but then a similar event was not caused by the much stronger offshore breeze on 21 November which temporally stalled the drifter (see Figure 5b). A connection with an onshore event a few days previous could imply Coastal Trapped Wave (CTW) forcing.

Drifters 1 and 2

The tracks of the surface (Drifter 1) and deep (Drifter 2) drifters on the mid shelf initially showed westward movement under the moderate north-easterly wind on 11 November and followed the southward curvature of the shelf edge with velocities of about 31 cm s^{-1} and 30 cm s^{-1} respectively (Figures 1a, 4), strongly suggesting barotropic conditions. This initial trajectory supports the general westward flow observed in the ship-borne ADCP data (Figure 2). The drifters then underwent a number of north-eastward reversals of varying distances, the longest being 43 km between 19 and 23 November (Days 9 and 13).

Closer examination shows these track reversals corresponded with strong south-westerly wind events measured by the AWS on the Tsitsikamma coast (see Figure 3). For instance on 19 November (Day 9) the wind was light and variable. Drifter 1 was travelling directly westward across the shelf and no longer followed the south-west curved bathymetry of the shelf edge. Drifter 2 at the time was semi stationary. Late on 19 and then 20 November a strong ($\sim 6 \text{ m s}^{-1}$) south-westerly wind began to blow. Both the surface and

deep drifters responded by moving eastwards for some 20 km. Wind on 21 November returned to light conditions with the drifters semi stationary. Similar eastward movement of the drifters was again observed when the next strong south-westerly followed on 22 and 23 November. This time the bottom drifter moved the furthest by some 20 km. Such response is understandable for the near-surface layer but not for the deeper layers of the water column, and raises concern about the influence of wind on the floats. Of course it is possible that this is evidence of the bottom layer responding to an atmospheric pressure change at sea level (i.e. cold front approaching), which in turn could change the water pressure gradient and hence background current.

The effect of these track reversals was a net northward encroachment towards the coast (see Figure 4, 24 November). Overall the deep and surface drifters tended to move in tandem but the latter track was usually more exaggerated than the bottom as a result of the greater velocities. By 24 November (Day 14) both drifters were close to the 100 m isobath between Knysna and Mossel Bay and about 80 km apart, well away from the shelf edge. This is the usual position of the cold ridge (see Figure 1a; Largier and Swart, 1987; Shillington and Boyd, 1994; Roberts, 2005). Between 24 and 26 November a strong easterly wind blew ($\sim 6 \text{ m s}^{-1}$; the strongest in November) which moved the drifters westwards until the wind changed on 27 November yielding a distance of 92 km for the surface drifter and a velocity of about 30 cm s^{-1} . The bottom drifter moved 55 km with a lower velocity of about 20 cm s^{-1} . These trajectories are of interest because the south-west flow of water here is what Roberts (2005) suggested was required for the formation of the cold ridge which he described as an upwelling filament.

Between 28 November and 11 December (Days 18 and 31) both drifters continued to edge their way westwards. The deep drifter reached a position 22 km off Ystervarkpunt (21.7°E ; see Figure 4, 11 December for location) after which it turned eastward and headed back towards Mossel Bay and was picked up by a fishing vessel on 20 December (Day 40) having moved a straight distance of about 100 km from the place of release. It is noteworthy that Drifter 2 moved eastwards between Ystervarkpunt and Mossel Bay. This is where averaged ADCP ship data collected by Boyd and Oberholster (1994) showed a short eastward current, which later Roberts (2005) speculated would move squid paralarvae, hatched in this area, towards the cold ridge where food abundance is generally highest on the Agulhas Bank. The change in direction of the deep drifter to eastward travel was initially coincident with a $3\text{--}4 \text{ m s}^{-1}$ south-westerly wind but the remainder of the eastward track took place under light and variable winds (see Figure 3). Wind during this period was clearly not a factor in this drifter track reversal.

On 11 December (Day 31; Figure 4), the surface drifter (Drifter 1) had reached a position in the middle of the central Bank having followed approximately the 100 m isobath. Here it became thwarted in its steady westward progression and instead moved directly inshore for 55 km between 14 and 18 December (Days 34 and 38). On Day 40 the drifter was still in this vicinity and remained here until 25 December (Day 45) where after it followed a direct route westwards across the inshore region of the western Bank to leave the shelf edge at 35°S . It continued into the Atlantic Ocean on a northward curved course to reach a position 132 km directly west of Cape Point on 15 January 2003 (Day 67). Later communication showed the drifter to have moved up the west coast.

High frequency drifter motions

Although not obvious in Figure 1a, a closer look at the data reveals at times small anticlockwise circular trajectories in both mid shelf drifter tracks (Drifters 1 and 2). The best example of these is found in the track of Drifter 1 whilst on the inner central Bank (indicated by the box). Figure 1b shows an enlargement of this area. The oscillations became obvious late on the 21 December and lasted until the 25 December. This period corresponded with a 5 m s^{-1} south-westerly wind which peaked in wind velocity on the 23 December (Figure 3). (Note that this peak occurred on the 24 December in the Tsitsikamma AWS record but it takes a day to reach Storms River from the central Bank). The emergence of the two distinct anticlockwise oscillations later

on the 23 December (Figure 1b), after the peak wind speed, suggests that these motions were inertial. Certainly their period, i.e. ~ 23 h, corresponds with the inertial period for this latitude $\tau \approx 21$ h.

Largier and Boyd (2001) found similar high frequency motions in a comparable drifter study on the west coast during the winter of 1999. These were observed sporadically along the entire shelf and also last for 3–5 days. The authors undertook an analysis of drifter velocity and found near-diurnal cycles characteristic of inertial motions in the southern hemisphere at these latitudes. They suggested that these followed distinct increases or decreases in wind force, advocated in text books such as Dietrich *et al.* (1980).

Alternatively, the motions in Figure 1b could be turbulence induced created by the intrusion of oceanic water onto the western Bank (see Figure 8), although similar oscillatory motions observed on the 18 November on the eastern Bank in the tracks of Drifter 1, 2 and 3 (see Drifter 3 in Figure 5a) suggest otherwise.

Discussion

Performance of drifters

Of fundamental importance in this experiment is whether the satellite drifters truly reflected the currents to which they were “anchored” and hence provide Lagrangian measurements of transport. Conversely, the reliability of using progressive vector projections for displacement (transport) based on moored current meter measurements also needs to be determined (Roberts and van den Berg, in press).

Accuracy and ADCP progressive vector projections

On several occasions the performance of the inshore drifters could be assessed by making comparisons with the ADCP deployed at Middlebank.

For instance on 11 November Drifter 3 was released directly above the ADCP mooring under a light to moderate 3 m s^{-1} easterly wind. The first hourly measurement made by the ADCP indicated a westward current of 37 cm s^{-1} at a depth of 5 m. This was mid depth of the attached holey sock drogue which had an average velocity of 35 cm s^{-1} over the first 2 h. Three days later on 14 November under an easterly $2\text{--}3 \text{ m s}^{-1}$ wind, Drifter 3 back-tracked over the ADCP mooring travelling in an eastward direction with an average 24 h velocity of 48 cm s^{-1} . The average velocity for the same period measured by the ADCP at 5 m was 49 cm s^{-1} . The progressive vector plot based on the ADCP measurements for this 24 h period yielded a displacement of 36.6 km. The distance travelled by Drifter 3 was 35.9 km with the difference in direction being about 6° over this distance.

Drifter 4 could also be used for performance assessment. It was released on 19 November similarly under light ($1\text{--}2 \text{ m s}^{-1}$) easterly wind conditions which became strong SW'ly after mid day. At deployment, a two hour average velocity of 14 cm s^{-1} was measured by the ADCP at 5 m. Drifter 4 for the same period showed an average of 13 cm s^{-1} . On the fourth day after release (22 November) Drifter 4 was some 30 km east of the ADCP. Wind at the time was 4 m s^{-1} south-westerly. The 24 h ADCP average velocity was 37.5 cm s^{-1} compared to the drogue average of 32 cm s^{-1} .

From a technology view point it was found that wind and sea state had an influence on drifter communication. For example on 11 November Drifter 3 was released in a moderate north-easterly wind and a westward current. Regular positional data were received under these conditions (see Figure 5a). However later on 14 November the same drifter was travelling eastwards along the Tsitsikamma coast with a swift velocity of 48 cm s^{-1} against a moderate easterly wind which had started in the morning. Transmission from the drifter ceased at 08:03 only to regain communication at 21:03 that evening when the wind strength had decreased. It would appear that a breaking sea, enhanced by opposing current and wind, caused the drifter float to become frequently submerged and hence prevented signal transmission to the satellite.

Overall these comparative results are very encouraging and provide the assurance that under light to moderate wind conditions, both with the current in sympathy with wind and opposed, drifters of the holey-

sock design provide reliable measurements of the near-surface current. Also, progressive vector plots used to project displacement from a current meter can be used to simulate transport but are limited to straight coast lines and understandable become inaccurate the greater the time span.

Mid shelf

The surface drifter on the mid shelf indicated unquestionably that the net flow during November 2002 was westward despite the wind regime for this month being dominated by south-westerly winds. But the size of both the surface and deep drifter track reversals suggests substantial current reversals which include at least the upper portion of the bottom layer assuming a thermocline at a depth of ~ 30 m. Such large track reversals were not seen in the inshore tracks although strong opposing winds ($> 6 \text{ m s}^{-1}$) were not experienced during their coastal zone occupation. Without current meter measurements beneath the mid shelf drifters, it is impossible to verify that these reversals were indicative of actual currents. Instead, we have to use theory.

There are a number of theoretical mechanisms through which wind can impact flow in the surface layer of the ocean. Two of the more important are Ekman drift (Ekman, 1905) and Stokes drift (1847).

Stokes drift is caused by wind induced waves and the associated incomplete closure of the vertical orbital paths of water particles in the surface layer. This results in a near-surface current moving in the direction of wave propagation. Application of Coriolis wave stress theory, however, eliminates Stokes drift as a mechanism to explain the track reversals because it drives a current that oscillates at the inertial period but has a mean flow that exactly mirrors the Stokes drift (Ursell, 1950; Pollard, 1970; Hasselmann, 1970). Therefore, the total wave-averaged current regime, after including the Stokes drift, is one that oscillates at the inertial period but with no net transport i.e. Stokes drift is exactly cancelled by its mirror image generated by the Coriolis wave stress.

In the case of Ekman drift, wind in the southern hemisphere sets up in the upper layer a left rotating current spiral which exponentially decreases in velocity with depth to the bottom of the Ekman layer (D_E). The direction of the current at the surface is given to be 45° to the left of the down wind direction (southern hemisphere) and its velocity by:

$$V_0 = \frac{0.0127}{\sqrt{\sin|\phi|}} U_{10}$$

Where ϕ is the latitude and U_{10} the velocity of the wind measured 10 m above sea level. The depth of the Ekman layer (D_E) is found using:

$$D_E = \frac{7.6}{\sqrt{\sin|\phi|}} U_{10}$$

Substituting a wind speed of 6 m s^{-1} , $V_0 = 0.10 \text{ m s}^{-1}$ and $D_E = 60 \text{ m}$ for the latitude of 35° S (approximate latitude of drifters). At an increased wind speed of 10 m s^{-1} , $V_0 = 0.17 \text{ m s}^{-1}$ and $D_E = 100 \text{ m}$.

A number of *in situ* experiments have attempted to verify Ekman theory. Examples include Davis *et al.* (1981) who measured currents between 2–175 m using 19 vector-measuring current meters deployed from a mooring for 19 days in 1977 in the northeast Pacific. Weller and Plueddmann (1996) measured currents between 2–132 m using 14 vector-measuring current meters deployed from the Floating Instrument Platform FLIP in 1990 some 500 km off California. Ralph and Niiler (2000) tracked 1503 drifters with drogues at 15 m in the Pacific between 1987 and 1994. Results indicated that inertial currents are the largest component of the flow and that the flow is nearly independent of depth within the mixed layer for periods near the inertial period, i.e. the mixed layer moves like a slab at the inertial period. Current shear is concentrated at the top of the thermocline. The flow averaged over many inertial periods is almost exactly that calculated from Ekman's theory. The shear of the Ekman currents extend through the averaged mixed layer and into the thermocline. In particular, Ralph and Niiler (2000) adjusted the above equations to fit their observations by decreasing the

numerators to 0.0068 and 7.12, respectively. This meant that the Ekman layer depth D_E is almost exactly that proposed by Ekman (above equation) but the surface current V_0 is half his value. Moreover, transport is 90° to the right of the wind in the northern hemisphere, which agrees well with Ekman's theory.

Application of the modified equations finds that $V_0 = 0.09 \text{ m s}^{-1}$ and $D_E = 94 \text{ m}$ for a 10 m s^{-1} wind on the Agulhas Bank. This indicates that even with a 10 m s^{-1} wind, we should still observe a westward going current in the presence of an unchanged pressure gradient (background current) i.e. a near-surface velocity of $\sim 31 \text{ cm s}^{-1}$ would be reduced to $\sim 21 \text{ cm s}^{-1}$, but Ekman mass transport would induce a north-westerly drifter track (acts at 90° to the down wind direction). For the deeper drifter the reduction in westward current would be less, especially considering that a component of the Ekman current, theoretically, would reinforce the pressure gradient current. This is not observed in the surface and bottom drifter tracks in this study and must mean that either the pressure gradient reversed causing the track reversals or that the drifters were dragged in a breaking sea. This argument can be strengthened considering the large track reversals are not seen in December when south-westerly winds were less frequent and their wind speeds much lower.

In conclusion, it is likely that strong winds ($c. > 6 \text{ m s}^{-1}$) on the mid shelf with large breaking seas tended to drag the drifters downwind, particularly obvious between 19 and 24 November, resulting in the observed drifter track reversals. Conversely in the case of the strong north-easterly wind between 24 and 26 November (cold ridge area), drifter track velocities were probably exaggerated by the wind drag given that the pressure gradient remained to the west. The similar behaviour of the surface and deeper drifters in November suggests that the drogue of the latter was pulled higher into the water column during these times and therefore not indicative of the bottom current. However, the obvious separation of the two drifters means that at other times the deeper drifter was definitely influenced by subsurface flow.

Larval transport in coastal waters (inshore spawning grounds)

Roberts and van den Berg (in press) attempted to estimate squid larval transport along the Tsitsikamma coast using measurements from the bottom-mounted ADCP deployed on Middlebank. They portrayed the data as progressive vector plots as a means of estimating displacement, and assumed squid paralarvae to be passive, neutrally buoyant for 30 days, and to mainly occupy the upper layer of the water column. This suggested transport was mainly eastward with potential distances ranging up to 550 km from Middlebank. Literally interpreted this meant squid paralarvae could be transported as far east as Port Alfred and East London (Figure 1a) where in fact a few paralarvae have been sampled in a survey (see Roberts and van den Berg, 2002; their Figure 1). But coastal upwelling was also shown to temporally influence the eastward counter current causing offshore flow. From the ADCP data, potential offshore displacement of 40 km was estimated. Eastward flow was found to return to the coastal current with relaxation of the upwelling process (onset of westerly winds), suggesting that squid paralarvae may well be transported offshore onto the mid shelf and returned into the eastward coastal counter current up stream i.e. they are carried in a clockwise circle. This supported earlier work by Tilney *et al.* (1996) who postulated that such “current-closure scenarios” existed on this coast. Regrettably, it was not possible to use the squid paralarvae ROMS-IBM (Roberts and Mullon, in prep.) to verify these results because of inadequate resolving abilities (?) at the model boundaries.

The use of drifters however, has made it possible to test the transport scenarios near the coast. The results confirmed the existence of a coastal counter current off the Tsitsikamma coast, and for short distances of up to 50–60 km, the use of progressive vector projections to gauge transport can be appropriate but become unrealistic beyond these dimensions. Certainly, as demonstrated by Drifter 3, the progressive vector displacements in Roberts and van den Berg (in press) were unable to contend with the realities of bathymetry such as Tsitsikamma Point and the offshore movement of water there. The complexity of this offshore flow is seen in Figure 7b where a cyclonic swirl is evidently responsible for the circular track of Drifter 3. (Satellite altimetry data also indicated a localised lower SSH here at the same time.) Whether this is a common phenomenon, and hence, the usual end of the Tsitsikamma counter current has yet to be established. The

swirl, it would appear from Figure 7c, existed for more than 10 days and remained stationary suggesting it could be a lee eddy created by the westward shelf flow moving past Seal Point (Figure 7c).

Alternatively as noted above, coastal upwelling could have caused the offshore movement of Drifter 3. For example Roberts and van den Berg (in press) showed in their Figure 9a (SST imagery) the emergence of a westward curved plume of cold water extending 10–15 km offshore from Tsitsikamma Point. This is expected to produce a similar trajectory as seen in Figure 5a, although the upwelling event would need to be much larger to account for the dimension of this track. Upwelling as the mechanism for offshore movement was plausible because a light north-easterly wind was blowing at the time. But examination of temperature records from an Underwater Temperature Recorder (UTR) at Middlebank (data not shown) and SST imagery in Figure 7b, showed no signs of coastal upwelling on the 14 and 15th leaving the swirl as the accountable mechanism.

The fact that Drifter 3 left the inshore squid spawning grounds near Tsitsikamma Point and went so far south is perhaps the most significant but also surprising result from this experiment. Spawning on the inshore shelf of the Agulhas Bank has been seen by many as being retentive for fish eggs and larvae (Tilney *et al.* 1996). The possibility of paralarvae being lost from the inshore chokka squid spawning grounds had been suggested by Roberts and van den Berg (2002) but this was thought to happen further east in the vicinity of Algoa Bay and beyond where the Agulhas Current is closer to the coast (Goshen and Schumann, 1988). Mechanisms responsible for loss of shelf water and squid paralarvae are discussed latter.

Larval transport on mid shelf (ROMS–IBM model validation)

In the absence of behavioural information on chokka squid paralarvae, the first ROMS–IBM dispersion experiment treated hatchlings as virtual particles of neutral buoyancy lasting 40 days (Roberts and Mullon, in prep.). Five thousand were released every second day for 12 “model” months in the bottom layer (~120 m) at three single point locations on the mid shelf. Results overall indicated the potential for considerable loss of paralarvae from the Agulhas Bank ecosystem through three routes: (1) mid way on the western Bank between the southern tip of the Agulhas Bank and Cape Point, (2) south of Cape Point, and (3) off the eastern Bank by the Agulhas Bight cyclonic eddy. The central Bank was found to have better retention since most of the virtual particles moved onshore and entered the coastal region of the central and eastern Bank providing good retention in the ecosystem.

Also absent in the ROMS-IBM was north-west advection along the narrowing outer western Bank, as was suggested by Robert and van den Berg (2002) who based their assessment on current meter data collected by Largier *et al.* (1992). Further supported with data collected by the CSIR¹ on the outer central Bank (CSIR report, 1986), these authors anticipated the westward current on the eastern Bank to continue into the north-west flow on the western Bank, suggesting that squid paralarvae too would be swept from the mid shelf spawning grounds westwards around the inner central Bank and onto the western Bank. This flow pattern is also thought to exist by others e.g. Shannon *et al.* (1996), Boyd and Oberholster (1994), and Hutchings *et al.* (2002). But Robert and van den Berg (2002) did note that larval loss was occasionally possible on the eastern Bank through offshore directed filaments of shelf water observed in satellite imagery (see their Figures 9, 10). Nonetheless, it still came as a surprise to observe the majority of virtual particles released on the eastern Bank being advected eastwards to the model perimeter at 25°E, and then offshore into the boundary zone of the Agulhas Current.

At first glance the results from this drifter study seem to contradict those of the ROMS–IBM, and instead strengthen the claim of westward transport on the mid shelf of the eastern Bank. The ADCP ship data collected during drifter deployment also add support in that this flow is seen to be barotropic (Figure 2), as is also indicated to some degree by the deep drifter despite the influence of strong south-westerly winds on drifter performance. This meant in terms of the “40 day drifter–IBM comparison” that the mid shelf drifters

¹ Council for Industrial Research.

did not leave the shelf and instead moved inshore. That is by Day 40 the deep drifter was off Mossel Bay in less than 100 m and its surface counterpart in the middle of the central Agulhas Bank similarly in 100 m. While it is acknowledged that a drifter of such proportions is far from an impersonation of a squid paralarvae 3 mm in length, these devices have demonstrated that paralarvae in the upper water column, hatched in the vicinity of the release position, would have been retained on the Agulhas Bank during November/December 2002. This judgment is strengthened when considering that the chosen time span of 40 days for paralarval passive dispersion is possibly too long and could in reality be as short as 20 days.

The drifters also demonstrated that squid paralarvae hatched near the 10th November would have been transported to the position of the cold ridge. This supports the “westward transport hypothesis” proposed by Roberts (2005), which states that chokka squid spawning relies on the westward drift on the eastern Agulhas Bank to transport new hatchlings to the cold ridge region where food is more abundant (Huggett and Richardson, 2000). Although in this case (November and December 2002), neither SST imagery nor *insitu* SST data showed any hint of cooler surface water here, usually indicative of the cold ridge. This is understandable since wind data in Figure 3 shows very little easterly winds which are required to drive coastal upwelling.

The apparent conflict of results from the drifter experiment and the IBM i.e. westward transport with retention vs. eastward transport with shelf loss, however, can be resolved to a large extent by closer examination. Inspection of the ROMS output indicated the presence of a large cyclonic eddy in the Agulhas Bight which also occupied most of the shelf edge of the eastern Bank in the model domain i.e. up to ~24°E. Lutjeharms *et al.* (xxxx) had also noted this feature in the model and showed that it escaped down stream from time to time. Superimposing the release positions of Drifters 1 and 2 on the same day SST image (Figure 7a) revealed that they were deployed only 1–2 km from the edge of a large Agulhas Current cyclonic eddy located in the Agulhas Bight, as simulated in ROMS. The SST imagery showed the eddy influencing a considerable portion of the outer shelf including some of the mid shelf. Should the drifters have been deployed a little further south, then it is highly probable that they would have been advected eastwards in this cyclonic eddy and yielded very similar results as the ROMS–IBM. This implies that the cyclonic eddy in ROMS is exaggerated and encroaches too far onto the mid shelf compared with the reality.

Beyond 40 days (shelf water leakage)

Drifter 3

A large data gap exists for inshore Drifter 3 between the last mid shelf position on Day 16 (26th November) and the next reported position some 400 km south of the continent on Day 71 (21st December) near the Subtropical Convergence. This is unfortunate because the route off the shelf and the time of exit are unknown, and hence important information leading to an understanding of shelf water leakage has been lost. Nonetheless, some insight into the mechanisms responsible for the drifter’s removal from the Agulhas Bank can be provided by satellite imagery, and it appears there are two.

The first involves leakage of shelf water from the Agulhas Bank via filaments which extend southwards off the shelf edge mainly in the vicinity of 21° E (tip of the Agulhas Bank). Daily SeaWiFS ocean colour images for January 2003, examples of which are depicted in Figure 8, showed the existence of chlorophyll filaments which extended from the typical cold ridge position on the mid shelf, distances of 100–300 km south of the shelf edge (see Roberts (2005) for details of the cold ridge). These filaments were stretched along the north-western boundary of the Agulhas Current. In all four images depicted in Figure 8, elevated chlorophyll streaks can be seen on the shelf indicating the existence of the cold ridge. From their south-westward, at times curved orientation, it is clear that biologically active shelf water was at the time being drawn off the shelf to form these filaments.

It is appropriate here to recall the work by Roberts (2005) in which he demonstrated that the cold ridge was a cold water filament that originated at the coast as a result of wind driven coastal upwelling. He suggested that this water was transported onto the mid shelf by the westward bound flow coming from the

eastern Bank (Roberts and van den Berg, 2002). This he argued, explained the “classic” diagonally aligned (SW–NE), at times curved shape, of the cold ridge. He noted in his data (Figs. 10a, 11), however, the existence of the Agulhas Bight cyclonic eddy at the time, and its possible interplay with the cold ridge. In this satellite analysis we note the eddy’s presence again, suggesting its movement of water onto the shelf, seen clearly in Figure 8d, plays a role in the formation the classic cold ridge filament shape i.e. this eddy could be facilitating the offshore movement of shelf water on the eastern Bank.

The offshore chlorophyll filaments at the time of this drifter experiment appeared in the imagery around the 30th November (Day 21) and lasted in various forms such as those depicted in Figure 8 until about the 21st January. Given the last known position of Drifter 3 on the 26 November, and the appearance of these features, it is possible that Drifter 3 was swept westwards in the eastern Bank flow along with the chlorophyll enriched shelf water and then southwards off the shelf into one of these filaments. Once in the boundary zone of the Agulhas Current, it could be carried around the retroflexion, if it existed at the time, and then eastwards along the Subtropical Convergence. It must be pointed out that some caution needs to be exercised here because upwelling is known to occur in filaments (reference) and therefore not all the chlorophyll maybe from the Agulhas Bank.

Analysis of SST imagery showed that the Agulhas Current began to turn due south around the same time the chlorophyll filaments appeared in the SeaWiFS data. By the 5th December (Day 26) the current was in full reflection mode (see Figure 9a) and stayed in this configuration until about the 21st December (Day 40), where after, the retroflexion began to retreat and the core flow (warmest water) instead moved westward towards the Atlantic. In the process, the end trajectory of the current “doubled backed” eastwards on its northern side creating cyclonic flow (see Figure 9b). This configuration corresponded with the chlorophyll filament leading off the shelf depicted in Figure 8b, and existed between the 29th December and 4th January 2003. The “double-back” then moved away in a north-west direction expanding the configuration but also unfolding itself. On the 11th January, the Agulhas Bight semi-permanent cyclonic eddy was well formed with another “double back” cyclonic feature further down stream just west of the tip of the Agulhas Bank (Figure 9c,d). This similarly appeared to be the cause of the offshore chlorophyll filament seen in Figure 8c recorded on the 12th January. In contrast to the previous occasion, this “double back” formed a cyclonic eddy a few days later on the 24th January, which corresponded to the cessation of chlorophyll filaments off the Agulhas Bank.

This is not the first mention of shelf water leakage on the eastern Agulhas Bank. Roberts and van den Berg (2002), also using SeaWiFS ocean colour imagery, noted that an unusual eastward position of the Agulhas Current retroflexion off Algoa Bay in April 1999 caused a spectacular chlorophyll filament to stretch southwards along the current’s western boundary for some 200 km (see their Figures 9a, b). A second offshore chlorophyll extension in the vicinity of the ones cited in this paper was also evident.

In the case of Drifter 3, it is unlikely that it was pulled off the shelf by the “double back” features, as these would have transported it into the Atlantic Ocean. Rather, it must have happened during the retroflexion mode in the first three weeks of December (Days 25–40). A simple trajectory calculation around the retroflexion to the Subtropical Convergence at an average speed of 80 cm s⁻¹ (which maybe too slow) suggests the drifter left the shelf about the 11th January which is not possible given there was no retroflexion then and the existence of the “double back” features. It is also unlikely that the drifter would have crossed the main core of the Agulhas Current. This means that the drifter must have spend at least 30 days caught up in eddies and boundary like phenomena whilst being transported south.

Of course, given that offshore leakage occurs, the question is how often does this happen? Here SeaWiFS GAC (4 x 4 km) ocean colour data is useful. A monthly composite for the month of January 2003 which includes images discussed above (i.e. Figure 8b–d) produced a distinct plume of chlorophyll extending off the Agulhas Bank due to the persistence of these filaments during this period (Figure 8e). Although not a rigorous analysis, a search for similar patterns in a monthly GAC composite time-series between September 1997 and October 2004 (not depicted here) showed that this pattern is common, suggesting that shelf water leakage is frequent near the tip of the Agulhas Bank.

While the offshore filament mechanism is a probable contender to explain the removal of Drifter 3 from the eastern Bank, there is another mechanism equally likely. This involves the drifter being drawn from the mid shelf into either the semi-permanent cyclonic eddy observed spinning in the Agulhas Bight (Figures 8c, 9a) or another cyclonic border eddy moving eastwards along the shoreward boundary of the Agulhas Current. Lutjeharms *et al.* (1989) has provided a good description of these phenomena and has shown that these features exist almost all the time when the current is against the shelf. At times, as many as three eddies can be observed between the Agulhas Bight and Algoa Bay. As seen in the example in Figure 8d, shelf water (chlorophyll) is entrained into these features. While this route might mean that the drifter would move around the eddy for a while, ultimately it would be carried away when the eddy escapes the bight, as demonstrated by Penvin *et al.* (2000) (is this correct reference?) using the ROMS developed for this region. Given that the Agulhas Current in this case was in a retroflexion mode, the result would be transportation of the drifter to the Subtropical Convergence.

Given the above, it is a wonder that Drifters 1 and 2 were not pulled off the shelf by these filaments. Inspection of the tracks, however, shows that these two drifters by 30th November had moved westwards and well inshore away from the south-westward arching offshore flow of shelf water.

Drifter 1

Another unexpected result in this experiment was the westward traverse of Drifter 1 across the central and western Agulhas Bank and its exit on 6th January 2003 (Day 58) from the shelf south of Cape Point. Its last reported position shown in Figure 1a was 132 km west of Cape Point on 15th January 2003 (Day 67). The exit position is of interest because this is a shelf leakage point identified in the ROMS (Penvin 2000; Roberts and van den Berg 2002, see their Figure 10) and the coupled IBM (Roberts and Mullon, *in prep.*), and verifies the model's performance in this respect. The traverse is unexpected because it crosses the distinct inner central Bank where water flow is thought to be subdued as indicated by the low bottom dissolved oxygen levels experienced during the summer months and the net low current velocities (Eagle and Orren, 1985; Chapman and Shannon, 1987, Roberts, 2005). As already mentioned, typically it is thought that eastern Bank water flows around the inner central Bank (outside of the 100 m contour) and onto the western Bank (Largier *et al.*, 1992; Boyd *et al.*, 1992; Boyd and Oberholster, 1994; and Roberts, 2005). So why did Drifter 1's track not follow this conventional flow model?

Again SeaWIFS satellite imagery is useful here and in this case is more informative than SST. The imagery showed that around mid December a distinct body of water with low chlorophyll levels occupied the entire western Bank as far east as ~ 22° E (see Figure 8b). This body was easily distinguishable from the water on the eastern Bank at the time and was likely of oceanic origin. At the time the Agulhas Current was in retroflexion mode (noted above) with chlorophyll filaments leaking southwards off the shelf (see Figure 8a). Around the 29th December, new oceanic water identified by extremely low chlorophyll levels, was observed moving into this same area from the west leaving a narrow band of coastal water (higher chlorophyll levels) along the coast between Cape Point and Struis Bay (see Figure 8b,c,d). This was especially evident around the 11th January when the second Agulhas Current “double back” was forming (see Figure 9c,d). The oceanic body of water appeared to reinforce the southward funnelling of eastern Bank water into the leakage filaments described earlier, and resided on the western Bank until about 27th January. This is also observed in the monthly GAC ocean colour composite (Figure 8e).

On the 14th December (Day 29), Drifter 1 located at 21.5° E was seen to move abruptly northwards, no doubt pushed by the first intrusion of oceanic water (low chlorophyll levels) onto the western Bank. By the 20th December the drifter was well on its way westwards across the western Bank moving along the interface between the oceanic and shelf waters and indicating anticyclonic circulation in this region (this is confirmed by a deepening of the thermocline on the western Bank, not shown here). The departure of Drifter 1 from the shelf just south of Cape Point clearly demonstrated the return of this water to the Atlantic Ocean.

Conclusions

Satellite drifters are clearly poor imitations of squid paralarvae but they do provide insight into the Lagrangian behaviour of passively drifting material such as eggs and early larvae in the upper layers of the water column. As was established in this study, drifter drag in rough seas can misrepresent advection, and so some caution needs to be exercised when using these devices. In this experiment, this occurred twice in November with a minor event in December. If anything, the inshore movement caused by drifter drag added extra “refuge” on the shelf. Despite this, the tracked drifters visibly demonstrated that retention on the Agulhas Bank is not guaranteed, as did the ROMS-IBM experiment undertaken by Roberts and Mullon, (in prep), although the latter was for bottom “hatched” particles. These results also confirm the suspicions of Roberts and van den Berg (in press) and Roberts and van den berg (2002) who raised the issue that currents on the Agulhas Bank could pose a threat to successful recruitment of chokka squid by removal of paralarvae from the ecosystem.

The mid shelf drifters released in this study showed that paralarvae hatched on the eastern Bank would likely be transported westwards and retained in the ecosystem near the cold ridge. This supports the “western transport hypothesis” proposed by Roberts (2005). Paradoxically, those paralarvae hatched on the inshore spawning grounds off the Tsitsikamma coast, according to the drifter would have been lost due to a propitious coupling of a cyclonic swirl found off Tsitsikamma Point at the end of the eastward counter current and shelf water leakage. The latter via either an off-shelf directed filament which appear to be common or entrained into the semi-permanent cyclonic eddy in the Agulhas Bight. How often this combination occurs is unknown but clearly its persistence will have a negative impact on recruitment. Squid hatchlings on the inner central Bank, at times used by some squid as a peripheral spawning ground and thought to be a good retention area, would also have been advected off the shelf in this instance as a result of an intrusion of oceanic water onto the western Bank.

Overall the results from this drifter experiment are profound as they begin to challenge the commonly held perception that water on the mid eastern Bank flows westwards around the inner central Bank and then northwards up the narrowing western Bank to join the west coast. This perception intuitively implies that retention on the Agulhas Bank is good, especially at the southern tip where eggs and larvae of sardine need to move westwards from the spawning grounds and into the Benguela Jet to get to the nursery grounds on the west coast. Moreover, it is interesting that large offshore chlorophyll filaments were observed in SeaWiFS imagery in 2000 during a time when the Agulhas Current retroflected east of its usual position (usually happens south of the Bight), and that in 2001 the squid fishery almost collapsed with an annual catch around 2500 t against the average of 7000 t.

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Figures

Figure 1. (a) Overview of tracks for all four satellite drifters (see legend). Drifters 1 and 2 were released on the mid shelf on 10th November 2002. Drifter 3 was released 1.5 km from the coast at Middlebank (Storms River) on the 11th November and Drifter 4 on the 19th November. Drifter 4's track is masked by that of Drifter 3 (Expanded view given in Figure 5). The last recorded position of Drifter 1 is 132 km west of the Cape Peninsula, and that of Drifter 3 about 450 km south of the continent near the Agulhas Plateau. Drifter 4's last position on the shelf was the 26th November 2002. (b) Expanded view of the box for showing anticyclonic inertial motions in the track of Drifter 1.

Figure 2. ADCP measured currents across the eastern Agulhas Bank between the coast (Plettenberg Bay) and the release position of Drifters 1 and 2. (a) near-surface (10 m) vector field depicting westward flow. (b) Vertical profile (4 m depth bins) showing westward flow throughout the water column.

Figure 3. Winds measured at Storms River on the Tsitsikamma coast for November and December 2002 (see Figure 1a for location). Middlebank is 1.5 km offshore from here. The filter (see methods) used on the data eliminates vectors for the first and last days of the month and has a tendency to decrease wind velocity a little.

Figure 4. Selected time frames for all four satellite drifter tracks. Note data gaps in the tracks have been filled using linear interpolations.

Figure 5. Expanded view of the inshore drifter tracks on the Tsitsikamma coast. The “+” indicates the release position for both drifters which is directly above a bottom-mounted ADCP (36 m). Dates in November 2002 are indicated. (a) Drifter 3 first travelled westwards to return directly over the ADCP mooring and then parallel along the Tsitsikamma. It turned offshore on the 15th November at Tsitsikamma Point and completed two clockwise gyrations before leaving the shelf. Inertial motions were observed on the 19th and 20th. The data gap (dashed circle) was caused by opposed wind and current. (b) Drifter 4 also moved parallel along the coast but ran aground at Tsitsikamma Point on the 23rd November. The small direction reversal on the 21st November was coincident with a strong breeze. Interestingly, this was not observed in the ADCP data i.e. stick vectors (Figure 6b).

Figure 6. ADCP data collected at Middlebank (see Figure 5a for position). (a) ADCP data between 10th and 25th November presented as a progressive vector plot. Note true north is towards the top of the page and the origin of the plot coincides with the position of the ADCP mooring. Initial flow was westward but became eastward on 12th November and parallel with coast. Drifter 3 was released at the beginning of this data set with the release of Drifter 4 midway. (b) The same ADCP time-series as in (a) but presented as stick vectors. Note the orientation of the plot is such that eastward flow is to the top of the page.

Figure 7. Selected daily AVHRR SST images of the eastern Agulhas Bank. The Agulhas Current (> 23° C) is seen clearly flowing along the shelf break with the shelf water ranging 18–20° C. (a) 11th November, the Agulhas Bight cyclonic eddy is seen sweeping onto the shelf with Drifters 1 and 2 only a few kilometres north of the thermal front. Drifter 3 is travelling westwards close to the Tsitsikamma coast. (b) 15th November, Drifter 1 and 2 are moving westwards on the mid shelf and Drifter 3 leaving the coast at Tsitsikamma Point under the influence of a meso-scale cyclonic swirl. (c) 26th November, the cyclonic swirl still exists 11 days later with Drifter 3 completing 1½ gyrations shortly before communications failed. Drifters 1 and 2 have moved well inshore. (d) 4th December, Day 25 for the mid shelf drifters which are now separated by 170 km and well away from the Agulhas Bight eddy.

Figure 8. SeaWiFS ocean colour images. (a) Long filaments of chlorophyll (shelf water origin) were observed to lead southwards off the shelf from the 30th November. These stretched along the westward boundary of the Agulhas Current (deep blue). (b) a filament being drawn off the southern tip of the Agulhas bank by the first current trajectory “double back” (see Figure 9b). (c) Agulhas Bight cyclonic eddy drawing in shelf water (high in chlorophyll) and the closure and disappearance of the first double back filament. (d) Another chlorophyll filament being drawn off the south tip of the Agulhas Bank into the second “double back”. Mechanisms by which Drifter 3 could have left the shelf are illustrated by the red arrows. (e) Composite of low resolution SeaWiFS GAC data for January 2003 highlights the semi-presence of chlorophyll filaments trailing southwards off the shelf (yellow in Figure).

Figure 9. Selected daily AVHRR SST images from NOAA showing the Agulhas Current with a number of final flow configurations south of the Agulhas Bank. (a) full retroflexion mode with warm water flowing along the northern boundary of the subtropical convergence. (b) retroflexion has retreated and the core flow (warmest water) instead has moved westward towards the Atlantic, in the process creating a “doubled back” in the current trajectory on its northern side. This feature is seen to correspond with the chlorophyll filament leading off the shelf depicted in Figure 8b and black arrow. (c and d) A second “double-back trajectory forming and drawing in a chlorophyll filament shown in Figure 8d.

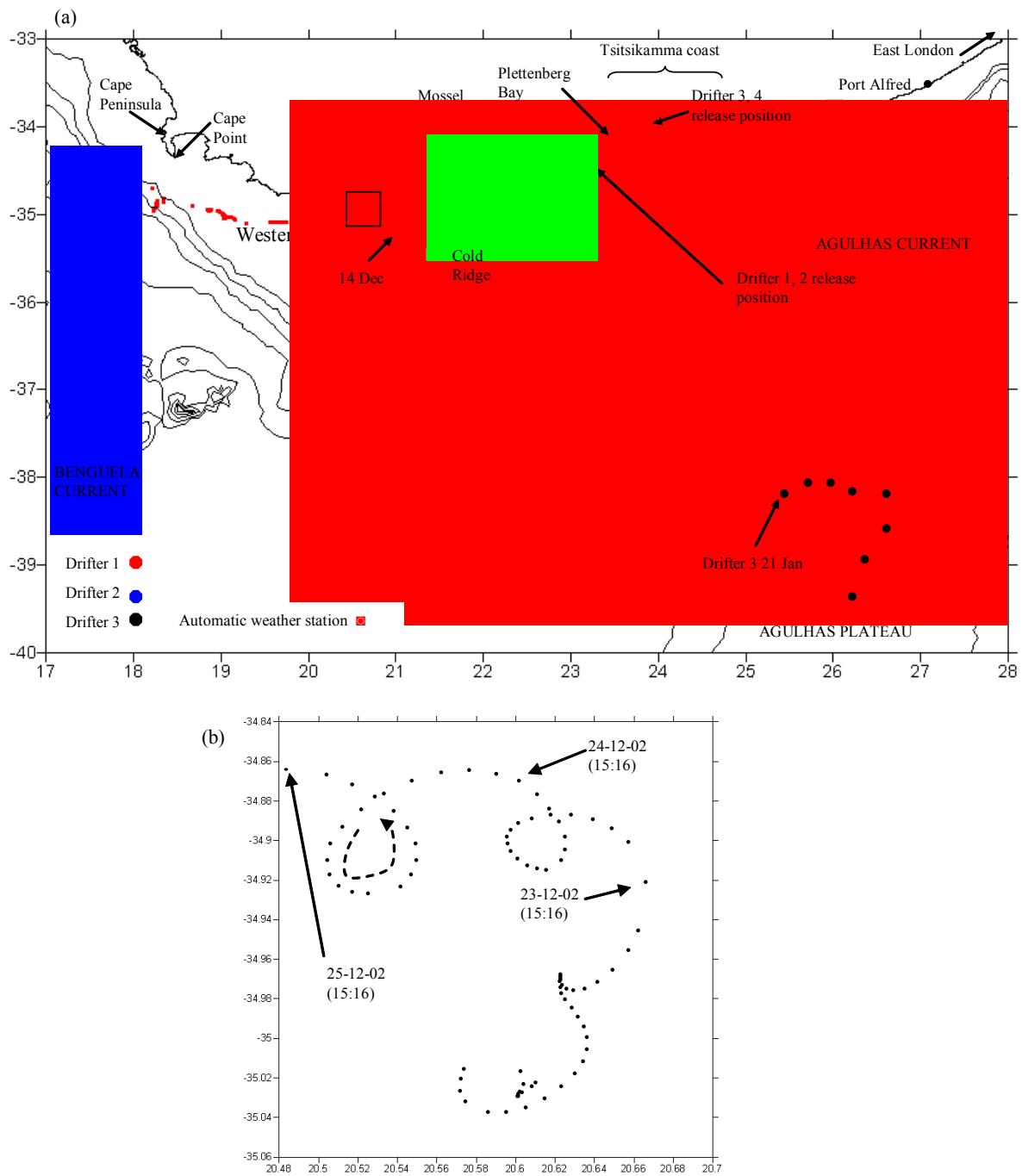
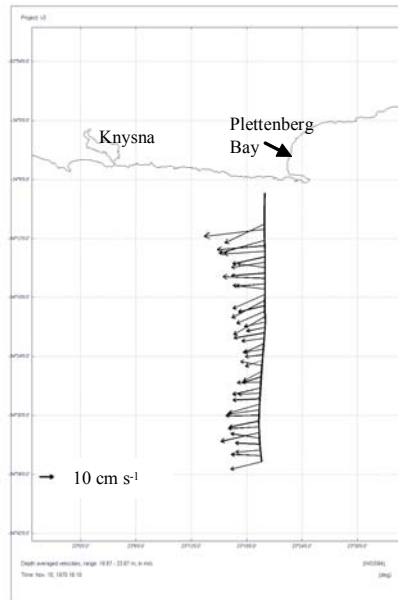


Fig. 1

a)



b)

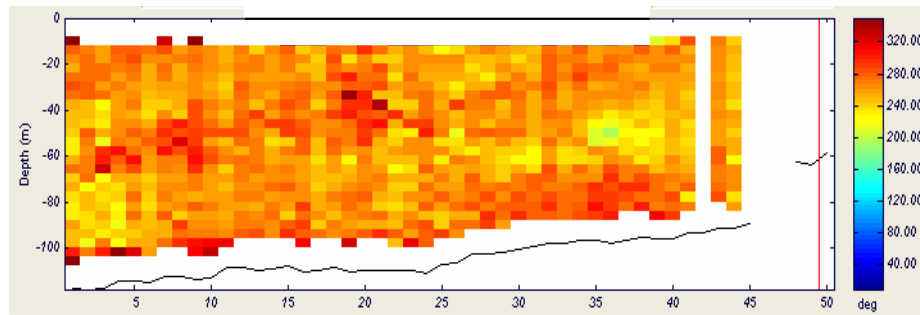


Fig. 2

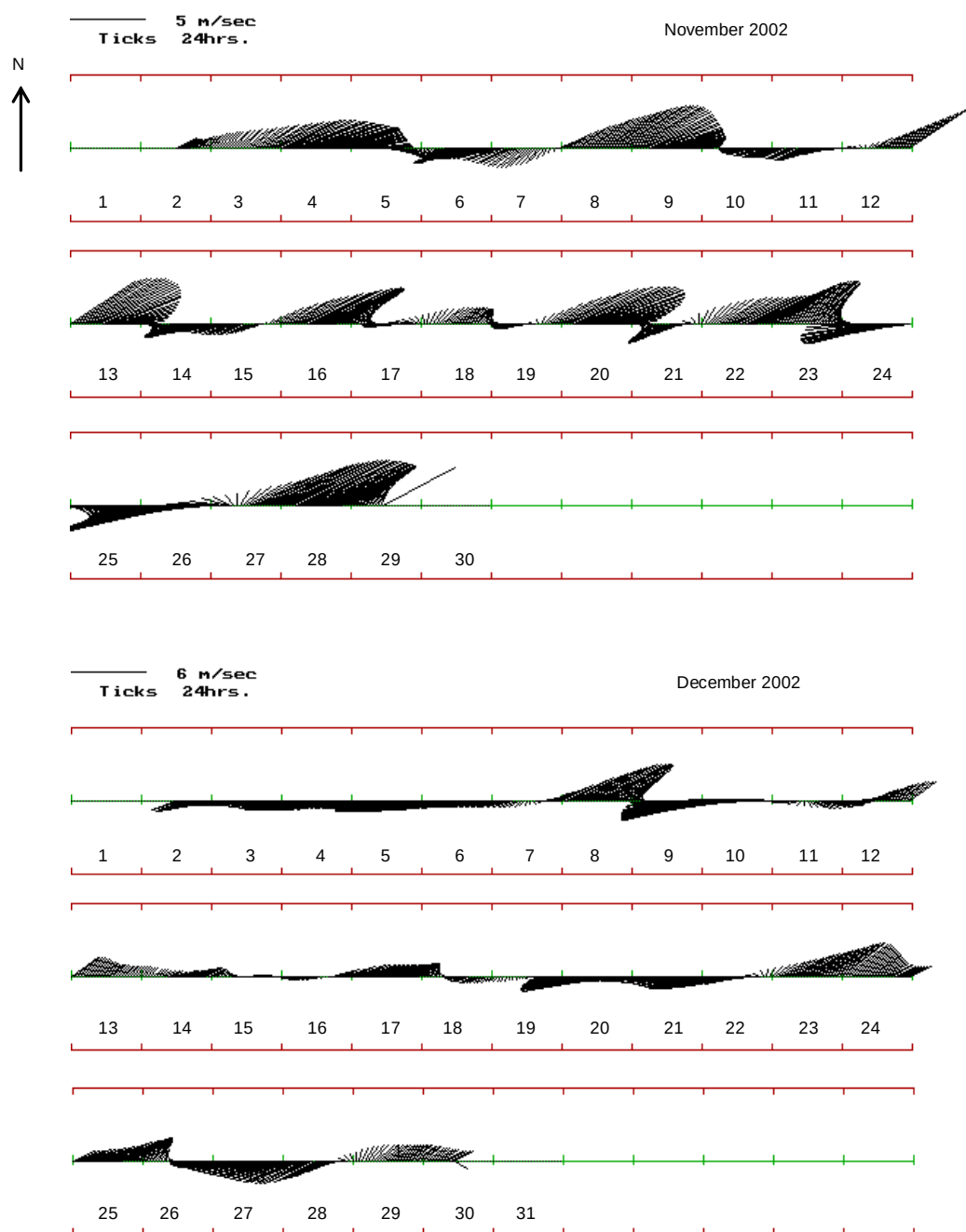


Fig. 3

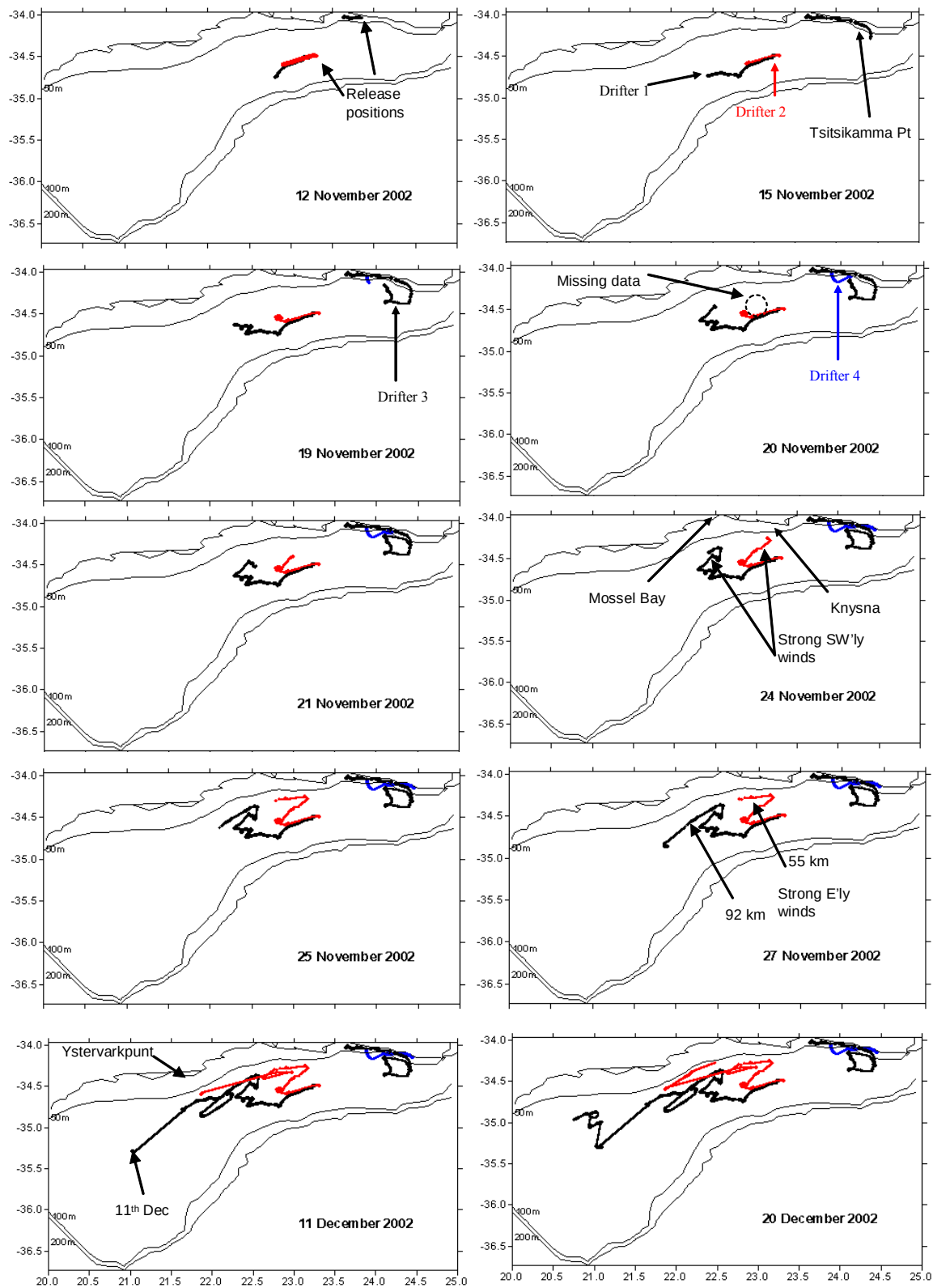


Fig. 4

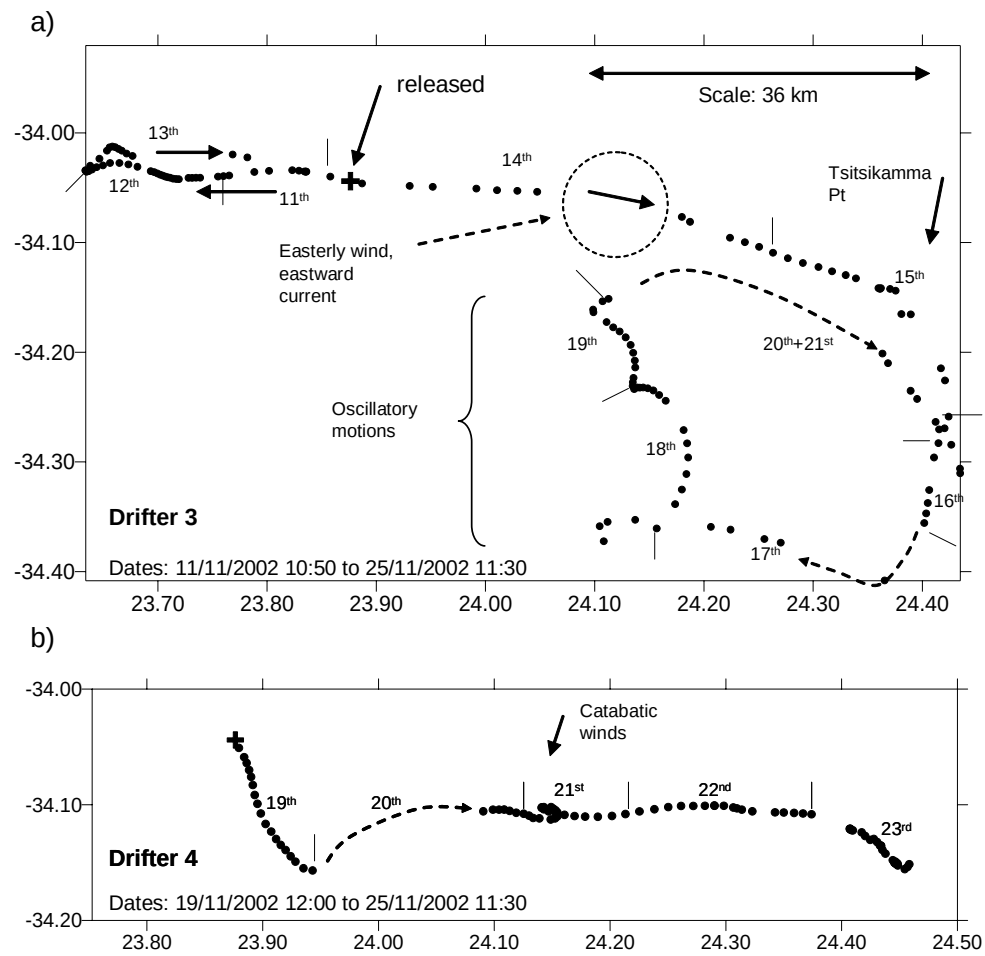


Fig. 5

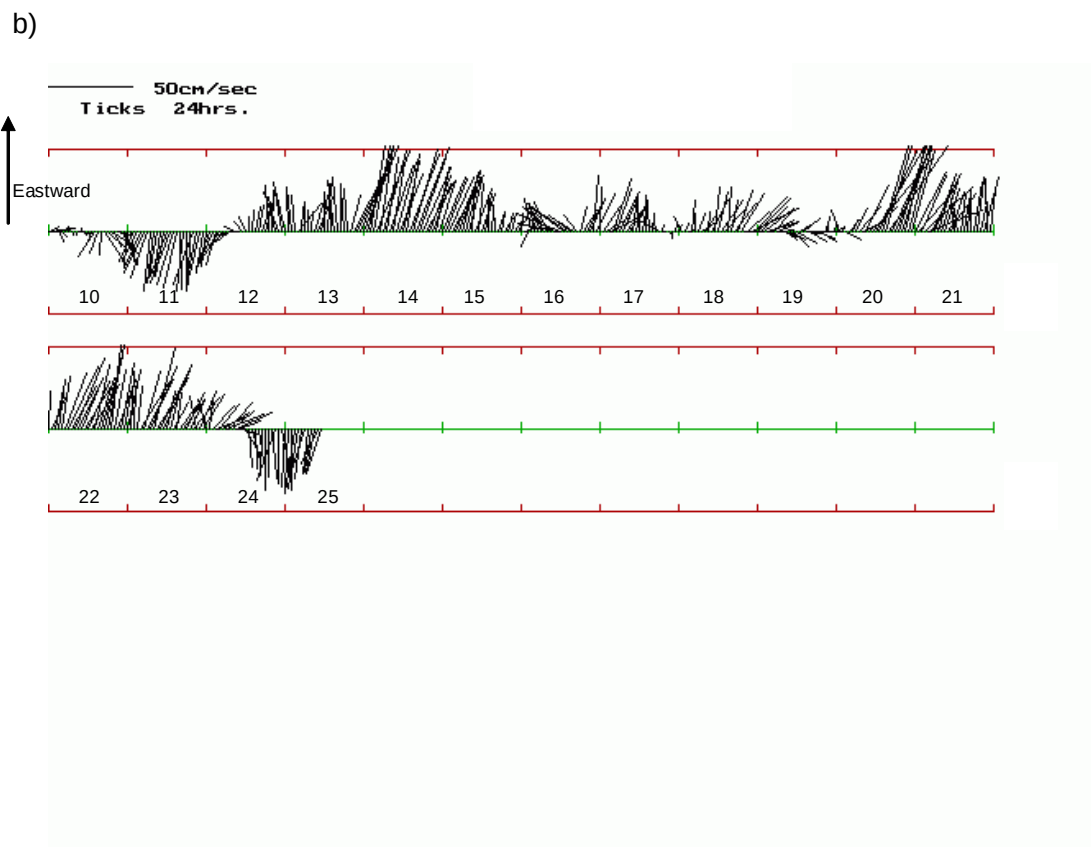
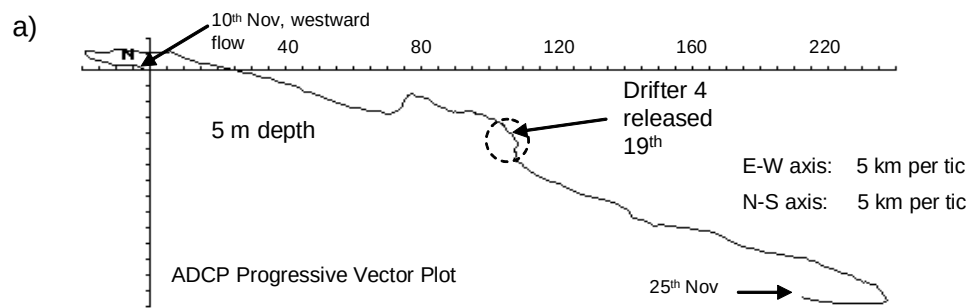


Fig. 6

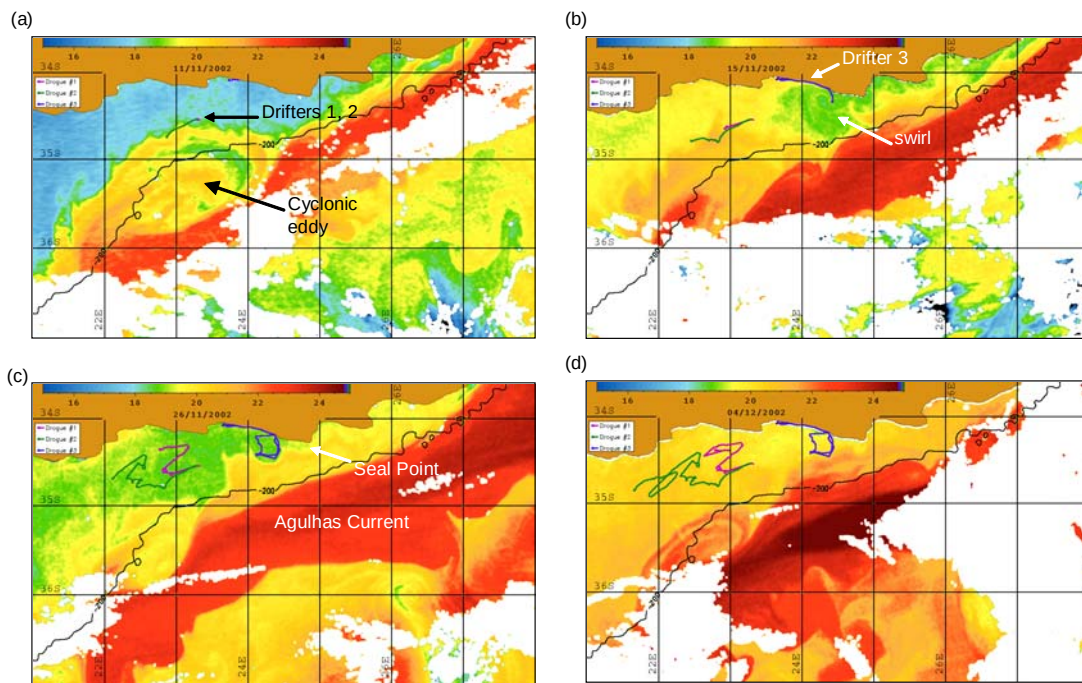


Fig. 7

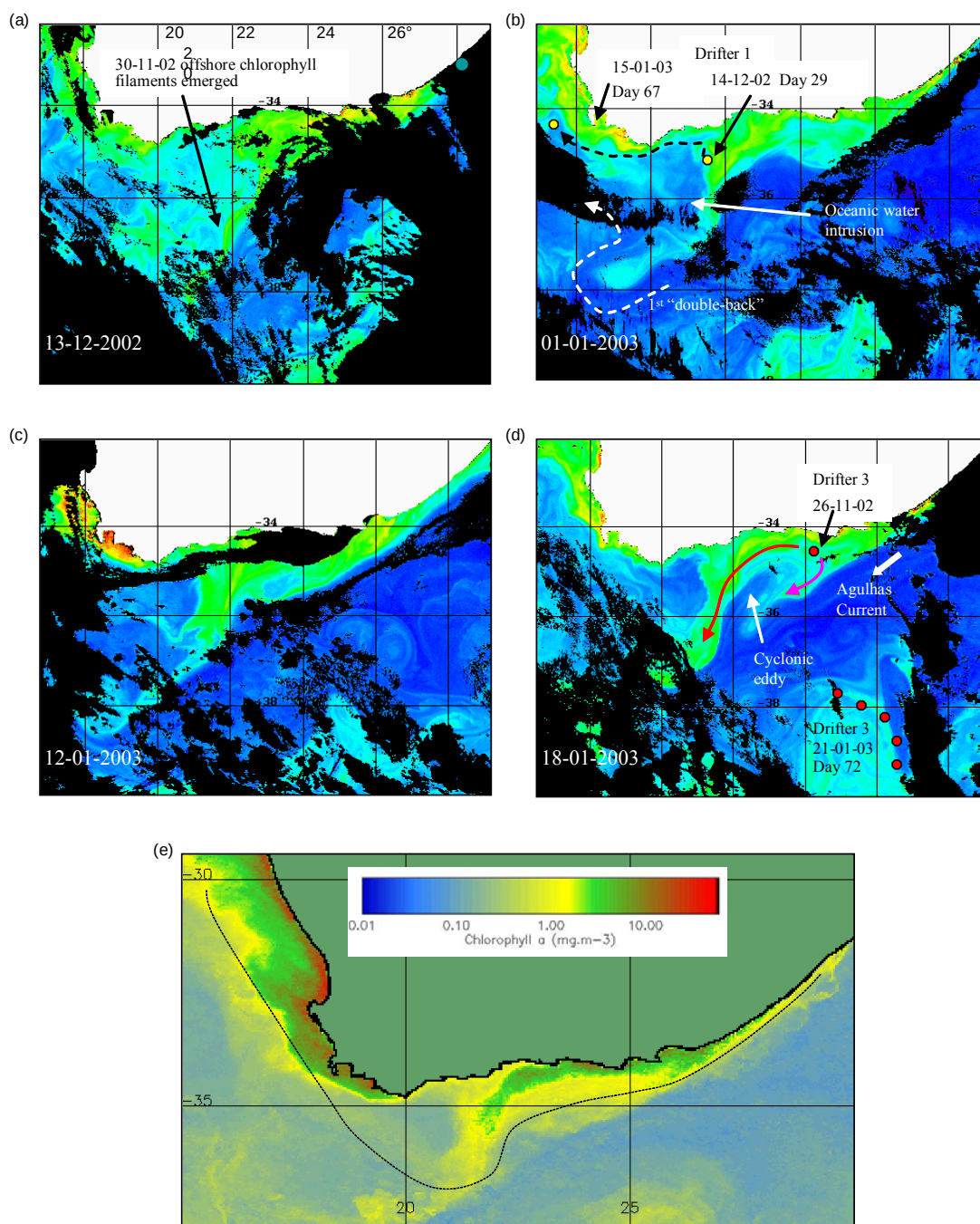


Fig. 8

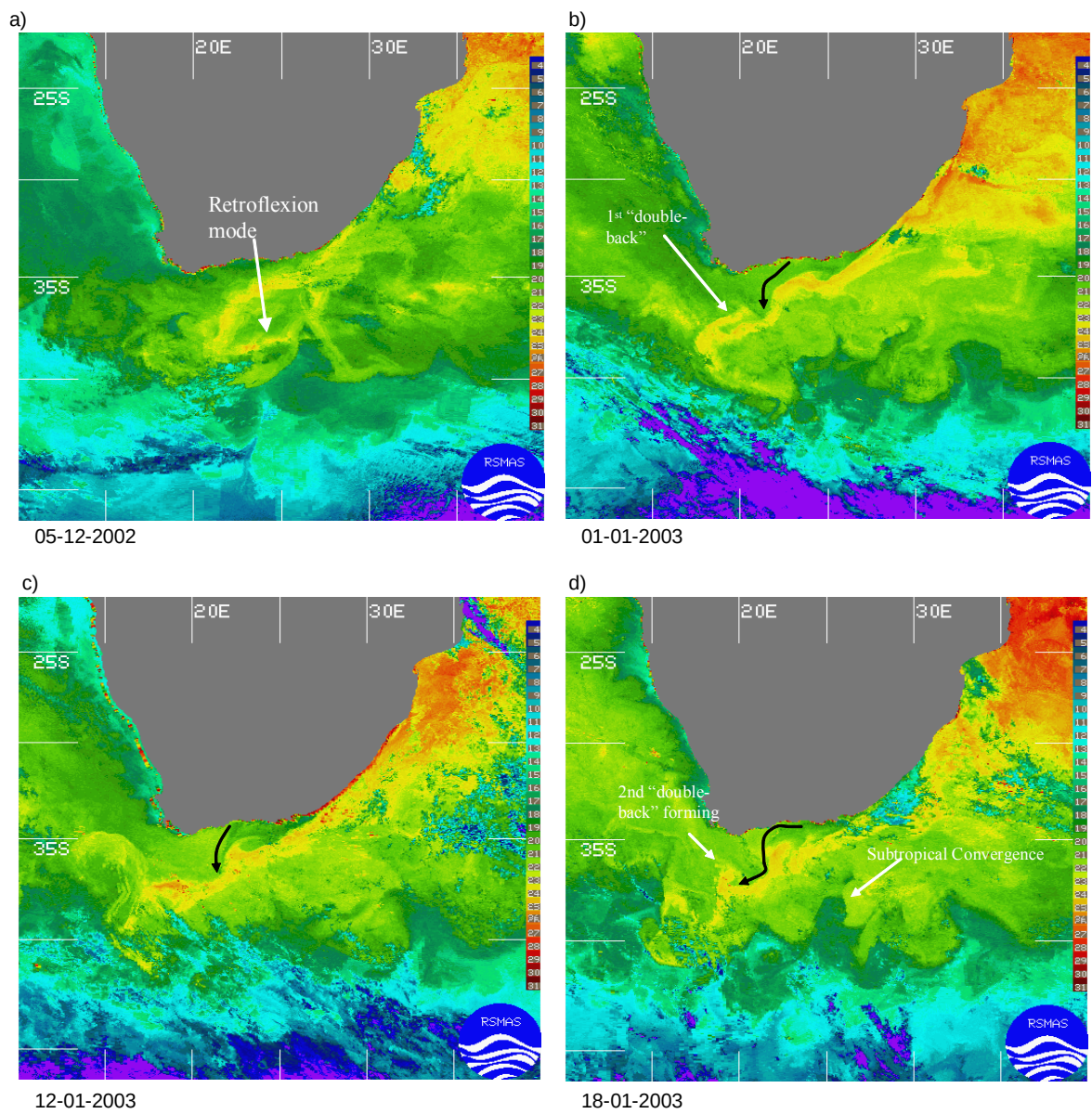


Fig. 9