Surface drifter trajectories highlight flow pathways in the Mozambique Channel

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Abstract
The surface circulation in the Mozambique Channel is described from the tracks of 82 satellite-tracked SVP drifters between 2000 and 2010, and complementary satellite-derived altimetry. Overall, the tracks indicate that anticyclonic activity is mostly observed on the western side of the channel with cyclonic activity more prevalent in the east. A lack of eddy activity is noted in the southeast corner of the channel (i.e., SW of Madagascar). Drifter behaviour illustrated that (surface) water from the Comoros Basin, entrained into anticyclonic eddies during formation, can be retained and isolated for months whilst being transported southwards through the channel. However, during a strong wind event (tropical cyclone) a drifter was observed to switch between counter-rotating eddies indicating that horizontal mixing of the Ekman layer does occur. The drifters also illustrated and emphasised the flow field and transport between eddies (i.e., the interstitial flow) in the Mozambique Channel. That is, despite the dominance of southward propagating anticyclones, drifters were able to move northwards and southwards through the channel in the frontal flow field between eddies within periods of 51–207 days. Cross-channel transport in both directions between the Madagascan and Mozambique shelf regions was similarly observed with time spans of 19–30 days. Surprisingly, drifters from the southern limb of the East Madagascar Current found their way westward across the channel to the Mozambique shelf. This transport was similarly facilitated by the frontal flow field between eddies. It is hypothesised that the frontal zones between eddies and interstitial waters play an important role in distributing biota in the Mozambique Channel.

Keywords: Mozambique Channel, surface circulation, mesoscale eddies, surface drifters, frontal flow

1. Introduction

The concept of the Mozambique Current as a well-defined and continuous western boundary current has been under investigation for some time. Progress has been largely dependent on advances in measurement technologies.

Early work using only shipdrift observations presented by Saetre (1985) had suggested a non-continuous current off the coast of Mozambique. These data showed a general anticyclonic circulation in the channel with three areas of higher than average current speed and directional stability along the Mozambique coast: (1) north of the channel narrows, (2) along the Inhambane terrace and (3) south of Delagoa
Bight. Saetre (1985) also found seasonal differences, with the strongest currents during the northeast monsoon season (November to April).

The first hydrographic observations by Saetre and da Silva (1984) showed the existence of large anticyclonic gyres separated by smaller cyclonic eddies in the northern (Comoros Basin), central and southern parts of the Mozambique Channel, but no persistent current along the Mozambican shelf. Donguy and Piton (1991) also observed a large anticyclonic gyre in the Comoros Basin and strong but variable southward flow across the narrow part of the channel. The work of both Saetre and da Silva (1984) and Donguy and Piton (1991) showed a high level of variability in the circulation of the Mozambique Channel. More recent hydrographic observations by de Ruijter et al. (2002) confirmed the absence of a persistent current along the Mozambique shelf. Instead they observed a succession of anticyclonic mesoscale eddies that propagate poleward along the western boundary of the Mozambique Channel.

More recently, moored current meter measurements by Ridderinkhof and de Ruijter (2003) across the narrowest part of the Mozambique Channel (Figure 1a) showed large spatial and temporal variability in the current field and the dominance of strong current events during which anticyclonic eddies are formed. They found no seasonality in the current regime or in the formation of anticyclones in the channel narrows and estimated a net mean southward volume transport of 14 Sv through the channel over a period of one year, with substantial variations of between 20 Sv north and 60 Sv south. Updated calculations by Ridderinkhof et al. (2010) from the same current meter array for four years indicate a net mean transport of 16.7 Sv south, with seasonal variations of 4.1 Sv and inter-annual variability of 8.9 Sv. This large variability is attributed to fluctuations in the seasonal wind field over the Western Indian Ocean and inter-annual changes in the Indian Ocean Dipole index.

Due to the remoteness of the region and its complex circulation, satellite altimetry data are now commonly used to delineate circulation features in the Mozambique Channel. Satellite altimetry products also provide a synoptic view of the region which no other measurement method can achieve. In particular, Schouten et al. (2003) confirmed the dominance of anticyclonic eddies in the Mozambique Channel using five years of altimetry measurements. They found that on average, four anticyclones per year pass through the narrow part of the channel and then slowly propagate southwards, following the shelf bathymetry of the African continent. Apart from identifying mesoscale features, altimetry data has also been useful in determining the synoptic geostrophic current field, driven by mesoscale turbulence, in the Mozambique Channel. As an example Figure 1b depicts surface current vectors which illustrate the highly complex circulation associated with mesoscale eddies. The strong currents (> 1 m s\(^{-1}\)) generated by anticyclonic eddies, especially in the western part of the channel, underscore the dominance of geostrophy as a major driving force of the circulation in the Mozambique Channel.

Lately, Ternon et al. (this issue) investigated the circulation in the Mozambique Channel using S-ADCP data collected by ships between 2005 and 2010. These data included across- and mid-channel transects of the eddy field, as well as transects through targeted anticyclonic and cyclonic eddies. Results not only provided vertical and horizontal views of current structures associated with eddies, but also highlighted...
the fact that satellite-determined (geostrophic) currents were underrepresented by as much as 30%. Moreover, these data showed the importance of the a-geostrophic circulation component especially relevant in the south-eastern part of the channel adjacent to Madagascar. The high resolution of the S-ADCP in situ data identified narrow currents (jets) adjacent to Mozambique Island in the channel narrows, Inhambane in southern Mozambique and off the south-western coast of Madagascar — the latter apparently unrelated to the Sea Level Anomaly (SLA) field. Ternon et al. (this issue) calculated the contribution of wind driven Ekman currents in the channel, and found that these currents become dominant during the height of the monsoon in the northern region of the Mozambique Channel and during atmospheric cyclones experience between November and March.

However, the dominance of mesoscale eddies and their associated transient and complex geostrophic circulation patterns, as well as the super positioning of Ekman currents, all make it difficult to recognize pathways of near surface flow in the Mozambique Channel, and indeed whether any of these may be common. Questions relating to the isolation and retention of water in these eddies and in the channel itself also remain unresolved. Almost completely unstudied are the shelf currents off the coasts of Mozambique and western Madagascar, and their interaction with the channel circulation. Such knowledge is especially important to understand the distribution of biota and the connectivity between populations in the Mozambique Channel.

The objective of this paper therefore is to provide and analyse Lagrangian measurements, not previously done in large numbers, which highlight the integrated surface circulation of the Mozambique Channel. Surface drifters are used to track the passage and behaviour of mesoscale eddies, ground-truth geostrophic flow patterns and to visualise flow pathways. These enable potential transport routes for biota and avenues for connectivity between the open ocean and the Mozambican and Madagascan shelf regions to be identified.

2. Materials and methods

The surface drifters used in this study are manufactured according to design parameters established by the Global Drifter Program (GDP) (Sybrandy and Niiler 1992). These guidelines meet World Ocean Circulation Experiment (WOCE) standards that minimize downwind slip to less than 0.7 cm s$^{-1}$ in 10 m s$^{-1}$ winds (Niiler et al. 1995). The design consists of a small surface float that houses the electronics — including the satellite telemetry equipment and batteries. A subsurface drogue (centred at 10–15 m) dominates the surface area of the instrument and effectively anchors the surface float to a ‘parcel’ of water in the mixed surface layer of the ocean. The drogue is attached to the surface float with a thin wire tether to minimize drag.

Trajectories of 82 satellite-tracked drifters were used to describe the surface circulation in the Mozambique Channel. The dataset included 60 SVP (Surface Velocity Programme) drifters from the GDP that were either deployed in the Mozambique Channel or passed through the Channel between 2000 and 2010. In this study the Mozambique Channel is defined as the area between 12–27° S and 32–49° E (Figure 1a). GDP data were obtained from the Atlantic Oceanographic and Meteorology Laboratory’s (AOML) Drifter Data Assembly Centre (DAC)
DAC applies quality control and interpolates drifter positions to uniform six hour intervals, using an optimal interpolation procedure known as kriging (Hansen and Poulain 1996). In addition, 22 locally manufactured drifters with the same specifications were deployed on ACEP (2004, 2005, 2007), ASCLME (2008) and MESOBIO (2009) research cruises. These programmes were dedicated to studying the role of mesoscale turbulence in the Mozambique Channel ecosystem. The locally manufactured drifters transmitted a GPS position, date and time every four or eight hours via the Inmarsat array of satellites and were deployed across mesoscale eddy features (i.e., the boundary, centre and frontal zones) to compare the flow patterns, retention and dispersal potential in different parts of eddies.

Each of the 82 drifter trajectories was manually examined for the presence of mesoscale activity. Mesoscale eddies were defined by tracks that had closed clockwise (cyclonic) or anti-clockwise (anticyclonic) rotations with diameters > 50 km. The number of days the drifter remained in a particular eddy was recorded, as well as the average scalar velocity during that time and the number of rotations the drifter completed around the eddy.

Drifter positions were superimposed onto corresponding maps of weekly Delayed Time (DT) Mean Sea Level Anomaly (MSLA), gridded at 1/3 degree resolution, produced by Ssalto/Duacs and distributed by AVISO, with support of CNES (ftp://ftp.aviso.oceanobs.com/duacs/). This overlay contextualised drifter movement with respect to the mesoscale eddy field in the Mozambique Channel.

3. Results

3.1 Advection in mesoscale eddies

In total 81 individual mesoscale eddies were identified from the drifter dataset — 40 anticyclones and 41 cyclones (Figure 2) — and confirmed by altimetry data. Anticyclones were found to be present along the length of the Mozambique shelf, forming a distinct corridor along the western boundary of the Mozambique Channel. The region between 17 – 23° S and west of 40° E was characterised by well defined anticyclonic rotations with little cyclonic activity. Anticyclonic eddies were also found in the Comoros Basin and along the central Madagascan shelf, but these eddies were generally smaller and less defined than those near the Mozambican shelf.

The drifter tracks in Figure 2 highlight three distinct areas of cyclonic activity: (1) north of 17° S along the Madagascan shelf, (2) in the central part of the channel along the Madagascan shelf and (3) southwest of Madagascar extending towards the Mozambique coast. Cyclonic activity in the central part of the channel was generally confined to the region east of 40° E.

Retention time of drifters in cyclonic and anticyclonic eddies was similar with an average duration of 30 days and 28 days respectively. Maximum residence times were 124 and 82 days respectively with not one drifter being transported through the Mozambique Channel in a single eddy. In general drifter tracks in the anticyclonic eddies were associated with larger diameters and faster velocities than those in cyclonic eddies, i.e., the average anticyclonic velocity was 68.6 cm s⁻¹ compared to an average cyclonic velocity of 48.2 cm s⁻¹. Velocity of course is dependent on the
position of the drifter relative to the eddy centre where it is zero and the outer edge
where it is at a maximum.

Figure 3 shows a typical example of surface advection associated with a mesoscale
eddy as it propagates southward through the Mozambique Channel. In this case drifter
1 was entrained into the anti-clockwise flow of anticyclone (A) soon after deployment
off the northern Mozambique coast at ~ 13° S (Figure 3a — note the SLA map shown
is 2 months after drifter deployment and therefore does not portrait the initial
conditions of entrainment which was to the north in the channel narrows). The drifter
was gradually displaced southwards along the Mozambican shelf over a period 134
days within rotating eddy (Figure 3b). During this time the drifter made 15 anti-
clockwise rotations around anticyclone (A), moving at an average velocity of 87 cm s–1
(maximum of 195 cm s–1). Velocities > 100 cm s–1 were attained as the drifter moved
southward in the eddy adjacent to the Mozambican shelf, but diminished to < 100 cm
s–1 on the northward flowing side of the anticyclone (Figure 3c). Southward eddy
propagation of drifters slowed in the middle channel as also observed by Schouten et
al. (2003).

The satellite altimetry map on 10 December 2003 (Figure 3c) shows an enlarged
(merged) anticyclonic eddy (AB) centred at 19° S and 40° E, with a smaller elongated
cyclonic eddy (C) situated to the south, together forming a dipole. Drifter 1 was
observed to follow the frontal zone between these two counter-rotating vortices,
across the width of the channel. It then uncharacteristically entered the cyclonic
vortex of the dipole (AB-C) on 15 December 2003 (Figure 3d). Interestingly, this
cross-over occurred at the time when tropical cyclone (TC) Cela tracked southwards
through the Mozambique Channel (Figure 4), intersecting the trajectory of drifter 1 on
16 December. Between 14 and 16 December wind speeds increased from 35 to 65
knots and TC Cela reached peak intensity as a Category 1 storm on 16 December,
with sustained 1-minute average wind speeds of 65 knots and gusts of 80 knots.
Clearly, these winds gave rise to a significantly active Ekman layer which moved near
surface water between the vortices. On 20 December TC Cela rapidly weakened as it
moved southwards of 30° S.

Drifter 1 remained in the cyclonic eddy (C) for another 82 days (Figure 3d),
completing four clockwise rotations at an average velocity of 60 cm s–1 (maximum
velocity = 157 cm s–1). It is important to note that the trajectory of Drifter 1 was not
unique and is one of several examples that demonstrate horizontal mixing of surface
water between contra-rotating eddies in a dipole pair within the Mozambique
Channel.

3.2 Frontal zone transport

Importantly, drifters also moved around the Mozambique Channel in only the frontal
zones between eddies without becoming entrained into the eddies themselves. This
behaviour was typical for GDP drifters that were not purposely deployed in mesoscale
features, but rather entered the study area through the general ocean circulation of the
region. Such an example of frontal zone transport is shown in Figure 5 in which the
trajectory of drifter 71201 is superimposed onto a mosaic of two appropriate SLA
maps. This drifter entered the Mozambique Channel from north of 12° S on 6
December 2008, moving southwards relatively close to the north coast of
Mozambique. At this time the large anticyclone (D) seen in the sea level anomaly map
of 31 December 2008 at ~ 19° S was already present. The drifter moved into the frontal zone between anticyclone (D) and adjacent cyclone (E) for half a rotation reaching velocities between 150 – 200 cm s\(^{-1}\) (Figure 5b), but never became entrained into either vortex. Note that as expected, the drifter velocity is strongly linked to the frontal SLA gradient. For example a reduction in velocity near 12-13 December occurred when the frontal SLA gradient relaxed between the two seemingly minor negative SLA features adjacent to the Mozambique shelf. Drifter 71201 left the frontal zone of dipole (DE) and then moved south along another frontal zone created by eddy pair (EF) shown on the altimetry image of 31 December 2008 in Figure 5a. The drifter left the southern entrance of the channel on 26 January 2009, having travelled the entire length of the Mozambique Channel from north to south in 51 days — as opposed to drifters trapped in eddies which take on average 278 days to move through the channel (based on Schouten et al., 2003 where the average meridional translation speed of an anticyclone is 6 km/d).

3.3 Drifter pathways in the Mozambique Channel

A number of drifters moved from north to south through the Mozambique Channel (Figure 6a). Southward velocities > 150 cm s\(^{-1}\) were recorded along the length of the Mozambican shelf edge, as well as in the channel narrows. Southward velocities along the west Madagascan shelf were generally slower velocities between 100 and 150 cm s\(^{-1}\) restricted to the southwest Madagascan shelf edge between 21.5 °S and 24.5 °S. Drifter transit durations from north to south through the channel ranged from 51 to 150 days, with the fastest route along frontal zones created by dipole eddy pairs (example Figure 5).

Continuous northward transport was also seen in several drifter tracks, but was typically restricted to the eastern side of the Mozambique Channel, east of 40° E (Figure 6b). Northward drifter transit durations through the channel ranged between 55 and 207 days. The average northward drift velocity was 33 cm s\(^{-1}\) (maximum = 168 cm s\(^{-1}\)).

Three drifters stayed in the Mozambique Channel for more than 300 days (Figure 6c). Drifter 75232 (blue line) had the longest retention and remained in the channel for 535 days. It entered the Comoros Basin from the north at 45° E and became entrained in a cyclonic eddy off the northwest coast of Madagascar for 115 days before moving southward through the channel narrows. This location was found to be a common source of cyclonic eddies (Ternon et al., this issue). Drifter 75232 remained in the channel for another 420 days before drifting ashore in the Delagoa Bight.

Some drifters, however, remained in the Comoros Basin for extended periods without passing southward through the narrow part of the Mozambique Channel. This is demonstrated by the trajectories in Figure 6d where retention times spanned 65 to 284 days. These drifters either exited the Comoros Basin to the north (n = 4) or washed ashore on the northwest coast of Madagascar (n = 3).

3.4 Cross-channel connectivity

Cross-channel transport was seen in several drifter tracks, highlighting connectivity between the Mozambican and Madagascan shelf regions. Figures 6e and 6f respectively depict eastward and westward connectivity with transit durations between
15 and 113 days. Such connectivity was observed along the length of the Mozambique Channel.

Exchange of water between the Mozambican shelf (Sofala Bank) and the oceanic environment of the Mozambique Channel, as well the responsible mechanisms, was also established from the drifter data. For example, drifter 75252 moved between the open ocean and the Mozambican shelf region on two separate occasions. Note that in Figure 7 the trajectory of drifter 75252 is separated into two parts. In the first part (light blue) the drifter moved from mid-channel onto the Sofala Bank, following the periphery of a cyclonic eddy D (Figure 8a). It reached the shelf region on 7 March 2010 and drifted north-eastwards along the shelf edge for ~13 days before suddenly reversing direction to southwest on 21 March (Figures 7 and 8b). It is unclear if this change in drift direction from north-east to south-west was a caused by wind forcing or if it was a result of the geostrophic current generated by the adjacent anticyclone A (Figure 8c). Nonetheless, the drifter was pulled mid-channel in the frontal zone between anticyclone C and cyclone E on 5 April 2010 (Figure 8e).

In the second part of the trajectory (Figure 7, dark blue), drifter 75252 returned from mid-channel to the Sofala Bank on 19 August 2010, again following the periphery of a cyclonic eddy (not shown). The drifter stayed on the Sofala Bank for 82 days until 11 November 2010, drifting slowly (average speed = 17 cm s⁻¹) while alternating between north(east)ward and south(west)ward drift. Similarly, the drifter’s movement on the shelf was not clearly correlated with the mesoscale eddy field and at times it drifted in the opposite direction to the geotropically-driven slope current. The drifter was eventually pulled off the shelf in the frontal zone of a dipole eddy and passed through the southern mouth of the channel on 5 December.

Also of interest is the connectivity observed between the east coast of Madagascar and the central/southern Mozambican shelf which occurred with surprising frequency (Figure 9). Nine drifter tracks from the east coast of Madagascar (East Madagascar Current), rounded the southern tip of Madagascar and followed similar routes north-westwards across the channel towards the Mozambique coast. Again this pattern was associated with transport in the frontal zones of mesoscale eddies (Figure 10). Transport times differed markedly. For example, drifter 45966 covered a distance of more than 1500 km in only 41 days, while drifter 44647 took 219 days to make the crossing (Figure 9).

4. Discussion and conclusion

There is little doubt that the substantial variety of measurement methods previously used (see introduction) have highlighted in much detail the complex and highly variable circulation found in the Mozambique Channel. In almost all cases, the observed circulation has been the direct result of the high level of mesoscale turbulence found throughout this region, and consequently, the geostrophic response to the sea surface topography. Satellite altimetry, in providing synoptic maps, has been essential (Schouten et al. 2003), as have the long-term moored current meter measurements in establishing transport volumes and flow regimes in the channel narrows (Ridderinkhof and de Ruijter 2003; Ridderinkhof et al. 2010). Numerical models (Biastock and Krauss 1999, Penven et al. 2006, Backeberg and Reason 2010), have also played an important role in establishing the origins of eddies, with the in
situ S-ADCP measurements (Ternon et al., (this issue) providing not only ground-truthing of remotely sensed geostrophic measurements (actual velocities are underestimate by ~30%), but also vertical views of the eddy field and current maxima associated with the frontal zones between eddies. All have dispelled the notion of a permanent, continuous western boundary current along the Mozambique shelf which feeds into the Agulhas Current to the south.

However, despite the substantive number of observations and publications on the circulation, it remains difficult to recognize pathways of surface (and near surface) flow in the Mozambique Channel, and indeed whether any of these may be common. Such knowledge is especially important to understand the distribution of biota and the connectivity between populations in the Mozambique Channel. In particular, questions relating to the isolation and retention of water in eddies, and in the channel itself are unresolved, as are shelf–open ocean interactions. Earlier studies have created the impression that flow is southward in the channel and mainly in the form of mesoscale eddies with isolated water masses. Biota is therefore commonly perceived to be trapped and transported through the channel inside southward propagating vortices. This study, being the first to use a large number of Lagrangian measurements, has provided some new insights on the surface circulation in the Mozambique Channel.

The first of these pertains to the isolation of water in eddies. From the drifter trajectories, it is clear that surface water in the interior of eddies, originally sourced from the Comoros Basin, can remain isolated for extended periods (several weeks to months), and therefore is generally transported intact southward in the Mozambique Channel. It is however interesting that no drifter remained in the same eddy for the full duration of propagation through the channel. This could reflect eddy theory which stipulates that decaying free anticyclonic eddies become divergent in their surface waters (as opposed to convergence during spin up) which would facilitate ejection of a drifter (and surface water) into surrounding waters (Bakun, 2006). In contrast, decaying free cyclones should have convergent surface waters, which would promote drifter retention making it in principle possible for a drifter to remain in a cyclonic eddy during its passage through the channel.

It is important to note that in our study drifters were also observed to move out of eddies (switching between counter-rotating vortices) during strong wind events, clearly illustrating the dominance of the Ekman layer dynamics over that of the vertical eddy circulation (convergence and divergence) and geostrophic horizontal current and demonstrates that horizontal mixing of the near surface eddy field clearly occurs at times. Ternon et al. (this issue) similarly evaluated drifter displacement in terms of the geostrophic flow and Ekman transport, and also showed that moderate to strong wind events can significantly influence the surface current reducing the geostrophic dominance.

Secondly, the drifters further highlight the importance of the interlinked flows outside of prominent mesoscale eddies (i.e. the frontal zone jets and less vigorous “interstitial” waters) that have largely been ignored in previous studies. The increased sea level gradient between cyclonic (low) and anticyclonic (high) vortices of dipoles drive the strongest (frontal) jets in the eddy field, and consequently (depending on the eddy field configuration) can produce fast flow pathways (raceways) around the
A convergence zone is created on the side where water from the outer edge of the counter-rotating vortices enters the frontal zone jet with a divergence zone on the opposite (exit) side. Drifting objects, including plankton, will tend to concentrate in the convergence zone of frontal structures and be carried along the frontal zone. Accordingly, the majority of drifters that were not purposely deployed inside eddies, followed these frontal zones, highlighting pathways of flow through the eddy field. Given appropriate eddy field configurations it was found that drifters (and surface water) can move northwards through the channel against the southward migration eddy field in surprisingly quick periods of 55 days, and in the case of north–south movement, in 51 days. As indicated previously, transport in mesoscale eddies by comparison take on average some 278 days to move through the channel. Of importance is that few drifters became entrained in eddies.

Drifters also followed frontal currents zonally across the Mozambican Channel onto the Madagascan shelf and vice versa in as little as 15 days (Figure 6e and f). Moreover (and surprisingly), drifters deployed in the East Madagascan Current (EMC) crossed the channel and reached the Sofala Bank on the Mozambican shelf (Figure 9) in as little as 41 days. The EMC has been depicted at times to turn north-westwards into the Mozambique Channel upon rounding the southern tip of Madagascar (Di Marco et al. 2002; Quartly and Srokosz 2004). Figure 10 shows that the continuation of this flow towards the African mainland is in part in the form of frontal zone currents.

Thirdly, the drifter tracks have also given some insight into open ocean–shelf exchange and shelf retention. As already indicated, the presence of poleward propagating anticyclonic eddies along the western boundary of the Mozambique Channel is now well established, but their interaction with the shelf water is still poorly understood. Quartly and Srokosz (2004) used SeaWIFS satellite data to show that chlorophyll-rich filaments are at times pulled off the Mozambican shelf and wrapped around the edges of anticyclones, enriching the surface oceanic channel waters.

In our study drifters were not specifically deployed on the shelf region, but indeed the data demonstrate that exchange between the shelf and oceanic water does occur. As shown in Figure 7, drifters were moved onto the shelf along the periphery of mesoscale eddies and were retained on the Sofala Bank for extended periods (up to 2 months). It is not clear if the north–south movement of drifters on the shelf is wind driven or caused by smaller eddies moving along the shelf edge. Circulation studies on the shelf regions of the Mozambique Channel similarly remain to be done. It is important to note that drifters were typically pulled off the shelf in the frontal zones created between contra-rotating eddies (Figure 8). The same exchange between oceanic and shelf water was also observed on the Madagascan shelf (Figure 6e and f) with an area of increased drifter retention on the shelf between 18-21° S.

Also of interest from these drifter data is that the existence of an anticyclonic gyre in the Comoros Basin (Donguy and Piton 1991) could not be confirmed as flow was mostly in the form of mesoscale eddies (both cyclonic and anticyclonic) and showed a high level of retention in the Comoros Basin. Of particular interest is the strong cyclonic activity measured by drifter 75252 off the northwest coast of Madagascar (Figure 6c). This eddy was trapped here for ~90 days with its passage to the south.
blocked by an anticyclone positioned in the channel narrows. Both Roberts et al., (this issue) and Ternon et al., (this issue) similarly found the north-western coast of Madagascar to be a source of cyclones.

Clearly, circulation in the Mozambique Channel has important implications for connectivity between geographically separated areas. Eddies, whilst potentially favourable enrichment and concentration mechanisms for larval transport, may be too slow as effective larval transport vectors. Frontal zone–interstitial pathways identified by these drifters (although possibly lack the enrichment mechanisms), on the other hand, may be the more favoured (faster) mechanism for biological connectivity. Studies on regional Western Indian Ocean population genetics are extremely limited (Ridgway and Sampayo 2005), but possibly the best studied in terms of species specific genetic information, is the black tiger prawn *Penaeus monodon* — a commercially important species throughout the region. Forbes et al. (1999) showed no genetic difference among *Penaeus monodon* populations from South Africa, Mozambique and Madagascar, which supports good connectivity throughout this region. Given the findings of this study, we therefore hypothesise that the frontal zones between mesoscale eddies and associated interstitial waters of the turbulence field create pathways for biological distribution that link the shelf regions, islands and atolls of the Mozambique Channel.

Acknowledgements

We thank the officers and crews of the research vessels FRS Algoa, Antea and Fridtjof Nansen for their dedication towards the MESOBIO project. This work was sponsored by the African Coelacanth Ecosystem Project (ACEP) and the Western Indian Ocean Marine Science Association (WIOMSA).

5. References


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Fig. 1. Dominant circulation features in and around the Mozambique Channel. (a) Schematic highlighting the mesoscale eddy activity. A general anticlockwise circulation is commonly thought to prevail in the Comoros Basin. Anticyclonic eddies (AC) tend to propagate southwards along the Mozambican shelf usually accompanied by cyclones (C). At the southern entrance of the channel both cyclonic eddies and anticyclonic eddies travel from east to west towards the source region of the Agulhas Current. Important circulation features outside of the channel include the southeast Equatorial Current (SEEC), the northeast and southeast Madagascar Currents (NEMC, SEMC) and the east Madagascar retroflection (EMR). (b) Altimeter-derived geostrophic current vectors in the Mozambique Channel illustrate the complexity of the circulation as a result of this mesoscale activity.

Fig. 2. Positions of 41 cyclonic (blue) and 40 anticyclonic (red) eddies identified from surface drifter tracks (i.e. closed loops > 50 km diameter). Anticyclonic eddies mostly followed a distinct corridor along the Mozambican shelf edge. Cyclonic activity tended to be dominant off the northwest and central (east of 40 °E) coast of Madagascar and in the southern entrance of the Mozambique Channel. Note the lack of mesoscale activity off the southwest coast of Madagascar.

Fig. 3. A seven month trajectory of drifter 1, superimposed on corresponding maps of the weekly mean sea level anomaly (scale on RHS). (a) Soon after deployment on 24 July 2003 drifter 1 became entrained into anticyclone (A) and (b) made several anti-clockwise rotations as it moved southward along the Mozambican shelf. The drifter then (c) crossed the channel in a northerly direction along the frontal zone created by dipole (AB-C), before (d) moving into the cyclonic part of the dipole. The along-track speed and direction of drifter 1 is depicted in (e).

Fig. 4. The track of tropical cyclone Cela through the Mozambique Channel in December 2003. Wind speeds > 40 knots were recorded between 15 and 20 December, directly influencing the behaviour of drifter 1.

Fig. 5. (a): Trajectory of drifter 71201 overlaid on a mosaic of weekly sea level anomaly images (SLA). The drifter travelled southwards through the Mozambique Channel in 51 days and never became entrained in any of the mesoscale eddies but instead remained in their frontal zones. Labelled eddies are referred to in the text and the SLA height (cm) is shown in the scale bar on the RHS. (b) Shows the along-track velocity (cm s⁻¹) and direction of drifter 71201 for this period. As expected drifter velocity is strongly linked to the frontal SLA gradient with highest velocities occurring whilst moving around anticyclone D.

Fig. 6. Drifter trajectories show examples of (a) north to south transport (b) south to north transport (c) retention in the channel (d) retention in the Comoros Basin (e) east to west connectivity and (f) west to east connectivity across the Mozambique Channel. The duration of each drifter track is given in the table (insert) and is colour coded with the drifter trajectory. The numbers in brackets indicate the shelf-to-shelf duration of the track.

Fig. 7. Expanded block in Figure 6c. The trajectory of drifter 75252 illustrates exchange between the open channel waters and the Sofala Bank. The drifter moved onto the Mozambican shelf on two separate occasions indicated in brackets (inserted table) and the different colours. Arrows show the direction of drifter movement and the dots are daily ticks. In the case of the first visit (light blue), the drifter remained on the shelf edge following the 200 m depth contour. On the second visit (dark blue) the drifter penetrated the shelf proper off the Zambezi River and remained on the shelf for 2 months. Note the onshore-offshore tidal influence on the drifter track, particularly obvious off Beira where its velocity was very low.
Fig. 8. The trajectory of drifter 75252 (Figure 7 first visit) overlaid on weekly maps of the mean sea level anomaly highlights the influence of mesoscale eddies in the exchange of oceanic and shelf water in the Mozambique Channel. (a) In this case the drifter moved onto the Mozambican shelf within the geostrophic frontal zone current generated between eddies C and D, and then (b) continued drifting northward on the shelf edge (200 m contour) following the inshore boundary of cyclonic eddy D. Unexpectedly it then reversed direction to the south seemingly in opposition to the cyclonic (clockwise) circulation associated with D until (c) it was eventually was pulled into the channel again along the frontal zone of a dipole CE.

Fig. 9. Drifter trajectories demonstrate connectivity between the East Madagascar Current and the Mozambican shelf, previously not thought possible. The duration of each drifter track is given in the table (insert) and is colour coded according to drifter trajectory. Numbers in brackets give the duration of the track from origin (dot) to the Mozambican shelf.

Fig. 10: Mesoscale eddies provide the main mechanism for connectivity between the (south) east Madagascan shelf and the Mozambican shelf. For example here the trajectory of drifter 34160 has been superimposed on the mean sea level anomaly. The drifter entered the study area in the East Madagascar Current on 7 December 2004 (not shown) and washed up on Mozambican coast on 23 March 2005 (99 days later). This north-westward path across the Mozambique Channel was facilitated by frontal zone transport in the surface layer between mesoscale eddies. The SLA scale bar (cm) is shown on the RHS. The drifter entered the Mozambican shelf waters while moving around the frontal zone of the anticyclone.
Figure 1: Dominant circulation features in and around the Mozambique Channel. (a) Schematic highlighting the mesoscale eddy activity. A general anticlockwise circulation is commonly thought to prevail in the Comoros Basin. Anticyclonic eddies (AC) tend to propagate southwards along the Mozambican shelf usually accompanied by cyclones (C). At the southern entrance of the channel both cyclonic eddies and anticyclonic eddies travel from east to west towards the source region of the Agulhas Current. Important circulation features outside of the channel include the southeast Equatorial Current (SEEC), the northeast and southeast Madagascar Currents (NEMC, SEMC) and the east Madagascar retroflection (EMR). (b) Altimeter-derived geostrophic current vectors in the Mozambique Channel illustrate the complexity of the circulation as a result of this mesoscale activity.
Figure 2: Positions of 41 cyclonic (blue) and 40 anticyclonic (red) eddies identified from surface drifter tracks (i.e. closed loops > 50 km diameter). Anticyclonic eddies mostly followed a distinct corridor along the Mozambican shelf edge. Cyclonic activity tended to be dominant off the northwest and central (east of 40 °E) coast of Madagascar and in the southern entrance of the Mozambique Channel. Note the lack of mesoscale activity off the southwest coast of Madagascar.
Figure 3: A seven month trajectory of drifter 1, superimposed on corresponding maps of the weekly mean sea level anomaly (scale on RHS). (a) Soon after deployment on 24 July 2003 drifter 1 became entrained into anticyclone (A) and (b) made several anti-clockwise rotations as it moved southward along the Mozambican shelf. The drifter then (c) crossed the channel in a north easterly direction along the frontal zone created by dipole (AB-C), before (d) moving into the cyclonic part of the dipole. The along-track speed and direction of drifter 1 is depicted in (e).
Figure 4: The track of tropical cyclone *Cela* through the Mozambique Channel in December 2003. Wind speeds > 40 knots were recorded between 15 and 20 December, directly influencing the behaviour of drifter 1.
Figure 5: (a): Trajectory of drifter 71201 overlaid on a mosaic of weekly sea level anomaly images (SLA). The drifter travelled southwards through the Mozambique Channel in 51 days and never became entrained in any of the mesoscale eddies but instead remained in their frontal zones. Labelled eddies are referred to in the text and the SLA height (cm) is shown in the scale bar on the RHS. (b) Shows the along-track velocity (cm s\(^{-1}\)) and direction of drifter 71201 for this period. As expected drifter velocity is strongly linked to the frontal SLA gradient with highest velocities occurring whilst moving around anticyclone D.
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