In situ measured current structures of the eddy field in the Mozambique Channel

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Abstract

Circulation and the related biological production have been studied during five cruises conducted in the Mozambique Channel (MZC) between 2005 and 2010. The circulation in the MZC is known to be highly turbulent, favouring both enhanced primary production due to the mesoscale eddy dynamics and connectivity throughout the channel due to the variable currents associated with migrating eddies. This paper presents the results of in-situ measurements that characterize the horizontal and vertical current distribution in the surface and subsurface layers (0 to 500m). The in-situ data are analysed together with the geostrophic eddy field observed from satellite altimeter measurements. Different circulation regimes were sampled, including the “classical” anticyclonic eddy generated at the channel narrows (16°S), the enhancement of southward migrating eddies by merging with structures (both cyclonic and anticyclonic) formed in the east of the channel, and the presence of a fully developed cyclonic eddy at the channel narrows. Comparison between in situ measurements (S-ADCP and velocities derived from surface drifters) and the geostrophic current derived from sea surface height measurements indicate the latter to provide a reliable, quantitative description of the eddy-driven circulation in the MZC with the exception that these currents are weaker by as much 30%. It is also suggested from in-situ observation (drifters) that the departure from geostrophy of the surface circulation might be linked to strong wind conditions. Finally, our observations highlight that a-geostrophic currents need to be considered in future research to facilitate a more comprehensive description of the circulation in this area.

Keywords: Mozambique Channel, mesoscale eddies, geostrophic currents, S-ADCP measurements, wind driven circulation,
1. Introduction

Due to its location between Madagascar and the coast of Africa, the ocean circulation in the Mozambique Channel (MZC) is turbulent and complex (Penven et al., 2006). The contribution of the southward flow through the MZC to the Agulhas Current system (Biastoch et al., 1999; Beal et al., 2011) makes the understanding of its source, nature and variability of major interest. Extensive reviews of research conducted since the 1950’s have been outlined in DiMarco et al. (2002), Schouten et al. (2003), and Lutjeharms (2006), and have highlighted important questions such as the permanent presence of a southward flow along the African coast (i.e. the Mozambique Current - MC) and the sources of variability observed at seasonal or inter-annual scales.

At first, analyses of ship drift data (e.g. Særte, 1985; Lutjeharms et al., 2000) and data from hydrographic cruises (e.g. Særte and Jorge da Silva, 1984; Donguy and Piton, 1991) suggested that a southward flow along the African coast did indeed exist. However, its persistence throughout the year could not be demonstrated. It has long been suspected that the seasonality of the MZC circulation is linked to the South Asian Monsoon system, at least in the northern part of the channel. Særte and Jorge da Silva (1984) proposed two different circulation patterns corresponding respectively to the southern hemisphere summer (northeast monsoon, from November to April) and winter (southwest monsoon, May to October) (Figure 1). A remarkable feature of their circulation schematics was the presence of rotating cells, both in the northern and southern part of the Channel. They identified three anticyclonic gyres as major components of the circulation, two of them merging in winter. Interestingly, Harris (1972), who also used ship drift, had already proposed a similar schematic but with eddies of varying sizes and at different locations, all of which indicated high levels of variability in the MZC (Biastoch and Krauss, 1999). Særte and Jorge da Silva (1984) mentioned cyclonic cells of smaller size within the Channel, some of them being quasi permanent (Figure 1). They also depicted a north-eastward coastal flow along the Sofala Bank at both seasons (Figure 1). Accordingly, the semi-permanent cyclonic circulation near Anoche at 15°S (Lutjeharms, 2006) and in the Delagoa Bight (Quartly and Srokosz, 2004) appears to lead to a northward coastal flow. Donguy and Piton (1991), from the analysis of tide gauge records and hydrographic data, described a persistent anticyclonic gyre in the Comoran Basin (north of the channel narrows around 16°S – see location in Figure 1c), with seasonal and inter-annual variability in its intensity. However, they found that a strong southward flow exists across the narrows around 16°S within the 0-500m upper layer.

Mesoscale eddies have also been identified in the southern MZC, using surface drifter and hydrographic cruise data. Gründlingh (1989) hypothesised these features form locally near Madagascar and propagate westward, eventually reaching the Agulhas Current system (de Ruijter et
al., 2004). Few observations have focused on the eastern side of the MZC. According to the circulation schematics of Særte and Jorge da Silva (1984), the mean flow in the eastern MZC is southward (Figure 1) but Særte (1985) indicated that the few observations available make this result questionable.

Modern cruises with high precision CTD and S-ADCP (Shipborne-Acoustic Doppler Current Profiler) instrumentation, as well as drifter deployments, have been conducted in this region since the mid-90’s (e.g. DiMarco et al., 2003; Chapman et al., 2003; De Ruijter et al., 2004; Swart et al, 2010). These technologies have allowed for a better description of the MZC circulation and confirmed that (1) the circulation in the MZC is highly variable (turbulent) and (mesoscale) eddy driven, and (2) the variability of this circulation is remotely constrained by the basin-scale variability within the Indian Ocean. Moreover, the mesoscale dynamics in the channel are forced by the South Equatorial Current (SEC) that splits upon reaching the east coast of Madagascar around 12°S: The northern branch (North Madagascar Current - NMC) flows equatorwards and past the northern tip of Madagascar (Cap d’Ambre, 12°S) while the East Madagascar Current (EMC) flows southwards towards Cape Ste Marie (25°S) at the southern tip of Madagascar (e.g. Schouten et al., 2003 – see Figure 1c). After passing Cap d’Ambre, the NMC flows westward, and upon reaching the African coast, splits into a northward branch (East African Coastal Current – EACC) and a southward branch that flows into the northern MZC. This flow through the channel narrows was thought to become the Mozambique Current (MC).

From the trajectories of subsurface (900m) ALACE floats, DiMarco et al. (2002) argued that, due the presence of the Comoro Islands, the flow at intermediate depths originating from the northern latitudes circulates eastward rather than entering directly into the northern part of the channel. Indeed, northern waters at intermediate depths join the westward NMC flow and enter the MZC in passing Cap d’Ambre at 12°S (DiMarco et al., 2002). Similarly, in the south, the EMC flows westwards after passing Cap Sainte Marie and plays a significant role in the formation of eddies (or pairs of eddies) near the southern tip of Madagascar which then drift westwards or south-westwards until they eventually reach the Agulhas Current (de Ruijter et al., 2004; Quartly and Srokosz, 2004).

Undoubtedly, remote sensing in the form of altimetry has greatly improved our understanding of the circulation in the MZC. Schouten et al. (2003) using altimetry, tracked 25 anticyclonic eddies between 1995 and 2000, and showed that these features propagated preferentially southward along the coast of Mozambique with a frequency varying from 7 eddies per year in the north to 4 per year in the south of the channel. The SSH anomaly of these eddies was shown to vary along their trajectory with maximum eddy amplitude reached in the middle of the Channel around 20-24°S. Quartly and Srokosz (2004) successfully used sea surface colour from SeaWiFs (1998-2003) to distinguish cyclonic and anticyclonic eddies moving from Cap Sainte Marie along the west coast of Madagascar to 23°S.
An array of current-meters deployed in 2000 to depths of 2000 m across the narrows of the channel around 16°S allowed for a long term study of the flow through the MZC (De Ruijter et al., 2002; Ridderinkhof and de Ruijter, 2003). Using the data recorded during the first 2 years of measurements (2001-2), Ridderinkhof and De Ruijter (2003) showed that there is no continuous MC along the coast of Mozambique, but rather strong current events occur on the western side of the mooring array, corresponding to the passage of anticyclonic eddies. These eddies occur at a frequency (9 events over a 2 years period) and is compatible with that proposed by Schouten et al. (2003). The net flow across the channel narrows was found to be southwards throughout the year. The eddies crossing the mooring array were shown to be essentially barotropic, with both the southward and northward flow component of the eddy extending down to 2000 m (Ridderinkhof and de Ruijter, 2003).

The current-meter array was re-deployed in 2003 and has been regularly serviced since then (LOCO programme, De Ruijter et al., 2006). A robust cyclic mechanism for the generation of anticyclonic eddies at the channel narrows has been proposed by Harlander et al. (2009). The start of the cycle is associated with the appearance of a strong southward current at the eastern edge of the mooring array. Once generated, eddies interact with anticyclonic (cyclonic) structures from the east of the Channel (Palastanga et al., 2006). These control the growth (decay) of the eddy during its southward displacement along the Mozambican coast. The authors related the resulting variability in the eddy field to the large scale variability in the Indian Ocean basin especially the Indian Ocean Dipole – IOD (Saji et al., 1999). A positive (negative) IOD index has been related to a decrease (increase) in the strength of the SEC and to a subsequent decrease (increase) of the southward transport through the channel narrows in the MZC. This occurs with a time lag around one year (Ridderinkhof et al., 2010). Harlander et al. (2009) proposed that internal Rossby normal modes could be triggered by the large scale oscillations and be the local control of the eddy dynamic variability.

Advances in modelling have more lately contributed to understanding spatial and temporal variability of the circulation in the MZC. In particular, analyses of model outputs have suggested possible mechanisms for the generation of eddies (Biastoch and Krauss, 1999; Backeberg and Reason, 2010), their distribution and evolution within the MZC (Halo et al., this issue). These model studies similarly indicate that the eddy turbulence in the MZC is driven by remote, basin-scale, forces as suggested by the in-situ observation.

In this paper, we present new current measurements obtained from cruises in different sectors and at different seasons in the MZC between 2005 and 2010. These data, together with those in Roberts et al. (this issue) not only provide in-situ observations of the physical oceanography but also support the sampling and analysis of biological observations intent on understanding the role of mesoscale turbulence in the MZC ecosystem (Ternon et al., this issue; see also the different papers in this Special
Ocean current estimates were derived from S-ADCP measurements along the ship track. The near-surface circulation during the cruises is interpreted together with Sea Level Anomaly (SLA) data and surface drifters deployed during the cruises (Hancke et al., this issue). These data with others are described in Section 2 of this paper. Circulation patterns at the time of the cruises are presented in Section 3, with emphasis on both horizontal and vertical distributions. In-situ observations are compared to the current field observed from satellite altimetry, and the potential importance of the ageostrophic circulation (including an Ekman component) in the MZC is assessed in Section 4.

2. Material and Method

Data used in this study include S-ADCP current measurements obtained during oceanic cruises in the MZC between 2005 and 2010, satellite-derived altimetry data with geostrophic current estimates, and wind estimates from satellite-borne scatterometers for the same time period. These data were analysed together with satellite-tracked surface drifters released in the MZC between 2000 and 2010.

Current measurements

Underway current profiles (S-ADCP) were undertaken using three different ships over a number of cruises: the R/V Algoa (ACEP MC05 and MC07 cruises using a 75 kHz RDI Ocean Surveyor II with a time average of 3 min per ensemble.), the R/V Fridtjof Nansen (ASCLME MC08A cruise using a 150 kHz RDI Oceano Surveyor I with a time average of 3 min. per ensemble) and the R/V Antea (MESOP MC10A cruise using a 75 kHz RDI Ocean Surveyor II using a time average of 2 min.). The entire S-ADCP dataset was processed using the CASCADE software (released by IFREMER, France) which allows “flagging” of the data according to statistical and threshold analysis, as well as horizontal and vertical filtering. Standard settings used included (1) a reference layer for profile validation selected between cells 3 and 5 (e.g. 16 to 48 m), (2) a maximum horizontal velocity set at 200 cm s\(^{-1}\), and (3) an error threshold on the vertical velocity set at 10 cm s\(^{-1}\). Vertical profiles extended in to between 300 to 500m depending on the frequency of the instrument used (i.e. cruise). Finally, the profiles were averaged over 5 km (1/12 degree) intervals for plotting and further calculation.

Onboard the ANTEA (MC09B and MC10A cruises), currents were also measured at each CTD station using a lowered ADCP profiler (L-ADCP) (RDI WHM 300 kHz). This allowed vertical profiles to a depth of 500 or 1000m (depending on the cruise). Both S-ADCP and L-ADCP data were available for the MC10A cruise. In general, there is good agreement between the currents measured by the L-ADCP and those by the S-ADCP upon approaching and departing from a CTD station.

Surface drifters

During the ACEP, ASCLME and MESOP cruises, 22 satellite-tracked surface drifters (drogued at 10m depth) were deployed in the Mozambique Channel between 2004 and 2009. These were deployed...
on the edge or near the centre of the selected eddies (details given in Hancke et al., this issue). The u
and v components of velocity for each drifter were calculated from the 6-hourly position reports. Daily
averaged velocities were calculated and attributed to the mid-point (median) position for that day.

In addition to the 22 drifters mentioned above, 60 drifters from the Global Drifter Program (GDP; http://www.aoml.noaa.gov/phod/daac/) tracked in the Mozambique Channel between 2000 and 2010 have been used (Hancke et al, this issue). The GDP data includes both u and v components and the magnitude of the velocity at six-hourly intervals. The same methodology was applied to calculate a daily mean velocity at the mid-position for that day and for each drifter.

Altimetry data

To describe the MZC eddy field sampled during the cruises, we used the weekly “Updated Delayed Time” (DT) mapped Sea Level Anomaly (MSLA) gridded at 1/3 degree resolution, produced by Ssalto/Duacs and distributed by AVISO and CNES (ftp://ftp.aviso.oceanobs.com/duacs/). The Sea Level Anomaly (SLA) was chosen as it is better suited for the identification of transient mesoscale features. The merged, multi-satellite products were used which provide improved accuracy for studies of mesoscale variability (Le Traon and Dibarboure, 1999; Pascual et al, 2006).

For the quantitative comparison between (altimetry-derived) geostrophic velocity, S-ADCP velocities and the velocities derived from surface drifters, the Absolute Dynamic Topography (MADT) was used instead of SLA. The DT (Delayed Time) daily MADT product, with a horizontal resolution of 1/3 degree, was used. This product combines sea level anomaly observations with the Rio09 mean dynamic topography (Rio et al, 2011), using data from up to four satellites at a given time.

Wind data and Ekman surface current

For the period 2003–2009 which corresponds with the drifter deployments in this study, we used the Mean Wind Field (MWF) wind data. This is a daily product with a spatial resolution of 1/2 degree (55 km) from the QuikSCAT/SEAWINDS scatterometer (http://podaac.jpl.nasa.gov), which is distributed by CERSAT (Centre for Satellite Exploitation and Research)/IFREMER. QuikSCAT failed in November 2009. For 2010, wind data were obtained from the Advanced Scatterometer (METOP-A/ASCAT, daily product, which has a spatial resolution 1/4 degree. Only the QuikSCAT data were used to calculate the Ekman component of the surface circulation (2003-2009) for comparison with the altimetry-derived geostrophic velocity and drifter velocity. The Ekman surface current was calculated using the satellite wind speed at a height of 10 m following the classical method by Stewart (2004).

A global analysis of the wind field has also been performed over a grid of the MZC composed of four latitudinal bands (4° width) divided in boxes of about 4° longitude (see Table 1). Within each of the 10
boxes, the percentage of wind speed within speed classes (0-4 m s\(^{-1}\), 4-8 m s\(^{-1}\), 8-12 m s\(^{-1}\), 12-16 m s\(^{-1}\) and 16-20 m s\(^{-1}\)) have been calculated on a yearly base, for the 8 years of satellite wind data (2003-2010). A mean distribution of the yearly mean wind speed classification has been calculated over the whole period (2003-2010). The same analysis has been performed for periods corresponding to the peak influence of both NE and SW monsoon (November to February and May to September, respectively) in order to investigate the monsoon influence over the whole MZC (wind speed and direction). An empirical relationship has been used to estimate the corresponding Ekman current speed classes (Pond and Pickard, 1983):

\[
V_0 = W \left(\frac{\Phi}{100}\right)^{0.0327} (1)
\]

where \(V_0\) is the Ekman surface current speed (m s\(^{-1}\)), \(W\) is the wind speed (m s\(^{-1}\)) and \(\Phi\) is latitude (20°S for our estimate).

**Altimetry versus in-situ velocity comparison (ADCP and drifter derived)**

The comparison was done using the S-ADCP data for cruises 2007 and 2008. The comparison gave similar results for the two cruises. For the S-ADCP/altimetry comparison, longitude, latitude and the corresponding u and v component of the in-situ velocity were extracted at 5 km resolution. No daily mean was calculated for the S-ADCP velocity as the ship might cross an entire eddy within one day. Instead, altimetry data were interpolated to all the S-ADCP positions for each successive day. The interpolation was done using the “nearest neighbour” method (e.g. Murat Yilmaz, 2007).

For the drifter/altimetry/velocity comparison, the daily mean position and u and v components for each drifter were determined. Altimetry data of each corresponding date were interpolated to the mean drifter position using the “nearest neighbour” method.

**Ekman velocity versus altimetry geostrophic current**

Daily wind and altimetry products were used for the comparison between geostrophic and wind driven surface velocities in the MZC. Interpolation (“nearest neighbour” method) was used to match the altimetry data (1/3 degree) to each wind data location (1/2 degree resolution).

The comparison between geostrophy, wind and drifter velocities was done at the daily mean position of the drifters for the period 2003-2009 (QuikSCAT/SEAWINDS data set). Interpolation of the Ekman surface current calculated from QuikSCAT wind data to the daily drifter position was also done using the nearest neighbour method. For each position, we thus obtained in-situ surface velocities (drifter), geostrophic (altimetry) and Ekman (wind data) components of the velocity.
3. Results

3.1 Eddy sampling and wind conditions during MESOBIO cruises

Five multidisciplinary cruises were undertaken between 2005-2010 (Figure 2) covering an area which ranged from the channel narrows (14°S) to Delagoa Bight (26°S) – (see Figure 1-c). The western and central MZC were surveyed more intensively with the exception of the 2010 cruise (MC10A) where some stations were done between 20-23°S. Cross channel transects were undertaken in the southern and northern regions of the MZC in 2007. Along track S-ADCP measurements were undertaken during all cruises except for 2009 (MC09B), while lowered L-ADCP data were available for the cruises in 2009 and 2010 (MC09B and MC10A). The current measurements are presented in this paper.

Where possible the cruises targeted well defined dipoles, i.e. 2005 (MC05), 2007 (MC07) and 2009 (MC09B) or otherwise surveyed a more extensive eddy field comprising several cyclones and anticyclones, i.e. 2008 and 2010. In the case of 2008 (MC08A), the ship track successively sampled a weak cyclone in the northern basin, a newly formed anticyclone in the channel narrows (16°S), and then cyclones and anticyclones distributed along the western side of the MZC to 23°S.

Generally, anticyclones were more developed and more stable than the cyclonic structures. In 2010 (MC10A) however, a cyclonic cell remained roughly at the latitude of the narrows (around 16°S) during most of the cruise while the anticyclone sampled at the beginning of the cruise rapidly shifted south-westwards halfway through the cruise and merged with a smaller anticyclone located further south. Convergence areas, to the west of eddy dipole structures, with an anticyclone to the north and a cyclone to the south, were sampled in 2005 (MC05), 2007 (MC07), 2008 (MC08A) and 2009 (MC09A). Divergence areas, to the east of the above eddy dipole structures were sampled in 2007 (MC07), 2008 (MC08A) and 2009 (MC09A). Cross dipole tracks were undertaken in 2007 (MC07), 2008 (MC08A) and 2010 (MC10A).

Two seasons (September-December – austral summer – and April-May – austral autumn) were sampled during MESOBIO. The time periods were not in phase with the monsoon but, at these latitudes, the monsoon influence is known to be weak (Sætæ and Jorge da Silva, 1984; Lutjeharms, 2006) except in the north of the channel (Bigg, 1992). According to Sete et al. (2002), NE winds dominate along the northern coast of Mozambique (e.g. Pemba, at 13°S).
in the austral summer (during the northeast monsoon) and SW winds dominate during the austral winter (period of the southwest monsoon). Along the central and southern Mozambique coasts, SE trades dominate all year long, the southerly winds being guided locally by the channel shape (Bigg, 1992).

The satellite wind data are in agreement with these general trends. The analysis of the 2003-2010 time series in the sectors previously defined (Table 1) clearly highlighted (1) the repeatability of the trends in each sector from year to year, (2) the occurrence of the NE monsoon winds in the northern sectors only (zones 1 to 4) mainly from November to February, (3) the generally higher wind speed south of 20°S (especially for wind entering the channel south of Madagascar – zones 9 and 10) and (4) the high variability in the direction of the westerlies reaching the coast of Mozambique (zone 7, sampled during cruises MC07 and MC09B). Malauene et al. (this issue) also noted the two wind regimes related to the monsoon winds offshore Anoche (16°S), the SW winds being generally stronger than the NE ones.

Superimposed to these seasonal trends, considerable short time scale (daily) variability in the wind conditions were experienced during the MESOBIO cruises, especially in the south-west of the prospected area. Episodes of winds stronger than 10 m s⁻¹ (20 knots) occurred in September 2007 (MC07) and November 2009 (MC09B). Cruises in 2008 and 2010 (MC08A and MC10A) experienced weak to moderate winds, with high daily variability.

3.2 – Eddy field during MESOBIO
The dipole sampled off Inhambane in April 2005 (MC05) resulted from the merging of four anticyclones formed in the northern and eastern MZC several weeks before the cruise. The first anticyclone was tracked since November 2004 when it formed in the narrows before merging with three other anticyclones, two of which formed in the eastern MZC. The cyclonic component of the dipole remained closely associated with the anticyclone for two months prior to the cruise. Contrary to the 2005 dipole, the anticyclonic part of the dipole sampled in November 2009 resulted from the merging of only two anticyclones originating from the northern MZC. The dipole formed about two months before the cruise and drifted to the location where it was sampled at the beginning of this cruise. It remained stable for the duration of the cruise.
In 2007 (MC07) and 2008 (MC08A), the eddy field in the MZC consisted of suites of anticyclones formed in the northern basin and in the channel narrows, and cyclones that evolved in response to the dynamics of the anticyclones. A cyclone that formed west of Madagascar in August 2007 developed along 40°E while the anticyclone sampled during the cruise shifted westward toward the Sofala Bank at 20°S (see Figure 1-c). In 2008, an anticyclone formed west of Madagascar at 21°S and merged two months after with the anticyclone originating from the north that was sampled at 39°E.

The eddy field in 2010 (MC10A) had two specific characteristics not seen in the other sampled eddy fields: (1) a strong eastern component as both an anticyclone and two cyclones were part of the structures sampled during the cruise and (2) the presence of a well developed cyclone at the latitude of the channel narrows instead of the usually observed anticyclone in this location. This resulted in an atypical eddy distribution in early May 2010 when the central MZC was dominated by a strong cyclone located between 15° and 18°S and a large anticylonic cell in the west between 17° and 22°S (and a weak cyclonic structure in the east of the basin at these latitudes).

It should be noted that prior to or during most of the cruises (2007, 2008, 2009 and - to a lesser extent, 2010), a small cyclonic cell was observed in the eastern part of the northern MZC basin. This cyclone was sampled (S-ADCP) in 2007 when the ship sailed to Nosy-Be at the end of the cruise MC07. Such a feature was also suspected to be present during a cruise along the western coast of Madagascar in September 2009 (see Pripp et al., this issue).

3.3 – In-situ observation of the velocity field

3.3.1 – Zonal transects across the MZC (September 2007, MC07)
A zonal transect crossed the channel at 24.5°S from west to east (Figure 3). West of 40°E, satellite altimetry showed that the ship track crossed an anticyclone (centred at 23.5°S/36.5°E) then a cyclone (centred at 24.5°S/37.75°E). The anticyclone was associated with a strong south-westward flow (ADCP mean speed up to 1.2 m s⁻¹ in the 0-50 m surface layer). This current contributed to the southward flow along the coast of Mozambique. The cyclonic cell was also clearly evident in the ADCP data, with speeds up to 0.60 m s⁻¹ at its edge. East of 40°E, ADCP measurements were consistent with an anticyclonic flow between 40.5°E and 41.5°E then a cyclonic cell associated with strong south-eastward flow around 43°E. The
currents along the section were most pronounced in the upper 200 m and remained apparent to depths of 600 m, which is also the maximum penetration depth of the ADCP. Of interest is a strong south-eastward coastal current (up to 0.50 m s⁻¹) evident between 23.5°-24°S off Madagascar, which remained disconnected from the south-eastward branch of the easternmost cyclone (Figure 3).

A second transect across the channel was undertaken from 15°S/41.5°E (Mozambique) to 13.5°S/47°5°S (Madagascar) - (Figure 4, southern leg). This sampled a dipole with its anticyclonic core centred at 14°5°S/43°E and the cyclonic core centred at 14°S/46°E. The surface (0-50m) currents measured using the ADCP closely agree with the position of the two eddies observed from satellite altimetry (Figure 4-b). Flow in the western section contributed towards a general anticyclonic gyre circulation in the northern basin of the MZC (see northern transect). In the east, a consistent south-eastward current flowed between the edge of the cyclone and the coast of Madagascar. According to the altimetry, this cyclone remained stable in the northern basin from mid-July until early November 2007. Such a circulation pattern has also been observed during a cruise in September 2009 (Pripp et al., this issue). West of the anticyclone, south-eastward surface currents reached up to 2.0 m s⁻¹ with those east of the cyclone reaching 0.55m s⁻¹. On the eastern side of the anticyclone the northward current component reached 1.1 m s⁻¹, with up to 0.75 m s⁻¹ observed on the western limb of the cyclone. These currents extended down to 600m on the western boundary of the dipole (maximum depth of the S-ADCP) and around 200 m elsewhere in.

The third cross-channel transect also shown in Figure 4 spanned the northern MZC basin (Comoran basin) between the Madagascar continental shelf (Nosy-Be) and the African coast (southern Tanzania) north of the above mentioned dipole. This cut through the islands of the Comoros archipelago. North of the Comoros, another elongated anticyclonic cell was fully developed with a SLA of > 20cm. In this case, the surface currents (0-50m) do not agree closely with the observations from satellite altimetry. Rather, the currents seem to be constrained by the islands of the Comoros archipelago. The flow was predominantly south-westward east of Grande Comore (43.25°E), and as mentioned above, suggests an anticyclonic circulation in the Comoran Basin. Unfortunately the section was too far to the south to capture the westward flow passing the northern tip of Madagascar. However, the south-westward flow east of Grande Comore may be part of this westward flow entering the northern MZC.
3.3.2 – Cross-dipole transects

Horizontal surface (0-50m) currents measured by the S-ADCP across and around the 2007 dipole are shown in Figure 5. The anticyclonic and cyclonic eddies had comparable SLA amplitudes of around ±0.40 m. The anticyclone was larger than the cyclone with a SW-NE diameter of 280 km versus 170 km for the cyclone. The dynamical characteristic of the two eddies were significantly different (Table 2) with the anticyclone being more “energetic” than the cyclone. The velocities up to 1.60 m s⁻¹ in the surface layer between 0-50 m were measured on the western edge of the anticyclonic eddy not far from the Mozambique shelf edge. They are possibly indicative of an acceleration of the current near the coast. By contrast, the surface current was only 0.65 m s⁻¹ on the western edge of the cyclone. Velocities of around 1.30 m s⁻¹ were measured at the boundary between the two eddies.

Vertical distribution of the current is shown the east-west dipole sampled during the MC08A cruise at 18-19°S / 37-42°E (Figure 6). As in 2007, the anticyclone was more “energetic” than the cyclone. The SLA in the cyclone was only 0.15 m (negative) while it reached 0.30 m (positive) for the anticyclone. Maximum surface velocity (1.80 m s⁻¹) was measured at the western edge of the anticyclone (Table 3). At 150 m depth, velocity was still 1.00 m s⁻¹ at the edge of the eddy (point A on Figure 6-a and 6-b) while almost zero velocities were found in the centre of the eddy. Maximum surface velocity at the boundary of cyclone was less than 0.50 m s⁻¹, and the width of the current core was limited to 0.25 m s⁻¹ at 75 m depth (section E-F). The end of the transect (point G) reached the edge of a neighbouring anti-cyclone to the south of the cyclone.

3.3.3 – Central versus eastern MZC circulation (cruise MC10A, April 2010)

The eddy field during the MC10A cruise included a stable and well developed cyclonic eddy between 15°S and 17°S in the western part of the channel narrows and a well-defined anticyclone around 19°S during leg 1 (Figure 7). The later rapidly propagated to the west one week later. A weak and elongated cyclonic structure (~21°S) was sampled in the middle/eastern side of the channel at the end of the cruise (i.e. leg 2). Maximum velocities of 1.65 m s⁻¹ (south-eastward current) were measured during leg 1 at the edge of the cyclone (point A in Figure 7-a). The eddy signature was clearly visible to depths of 300 m (the maximum depth of the S-ADCP measurement), with velocities up to 0.50 m s⁻¹ to a depth of at least 200 m (points A and B in Figure 7 a-b and points H and I in Figure 7 c-d). The
velocity at the edge of the anticyclone (points D and F in Figure 7 a-b) reached \(1.10 \text{ m s}^{-1}\) at the surface during leg 1, with the eddy structure clearly visible to depths of 200 m.

Near the African continent, a coastal south-westward current was evident during leg 2. This narrow current was opposite to the predominantly north-eastward flow at the edge of the cyclone (Figure 8). Speed up to \(1 \text{ m s}^{-1}\) was found within the core of this very narrow (20 km wide) boundary current. It should be noted that a significant decrease in the temperature was recorded during the same period at 18 m depth on Mozambique Island (http://www.cfoo.co.za/utr/utr.php?ID=118). The coastal current is consistent with the development of upwelling resulting in lowered sea surface temperatures - see also Malauene et al. (this issue) for coastal upwelling in this area.

The circulation was much weaker south of 21°S. The southern-most cyclone (from 20° to 21.5°S) displayed velocities up to 0.45 cm s\(^{-1}\) and a limited vertical extent of about 100 m (depth of the 0.25 cm s\(^{-1}\) isoline - point K in Figure 7 c-d). Weak and reversing surface currents were measured along the south-east coast of Madagascar. The vertical structure of the currents no longer appeared to be structured by the eddy field. These observations suggest that the circulation in this area was not strongly associated with eddies, in agreement with the MC07 cruise data (zonal transect at 24.5°S – see paragraph 3.3.1)

3.4 ADCP / SLA comparison

Comparison between along-track S-ADCP surface velocity and geostrophic velocity from altimetry is shown for two cruises (MC07 and MC08A) in Figure 9. Straight ship tracks favourable for such comparisons were selected. The relationship between ADCP measured currents and geostrophic velocities shows a similar trend for both cruises, despite a greater spread of data in 2007. This could be due to the steeper gradients in the sea surface topography observed during this cruise, which corresponded to higher velocities (Figure 9-b) that are potentially smoothed by the low spatial resolution of the altimetry data set. During both cruises the altimetry observations underestimated the velocities observed from the ADCP measurements by about 30% (linear coefficient was 1.27 in 2007 and 1.30 in 2008). This result is attributed to the smoothing of the more dynamical structures resulting from the lower spatial and temporal resolution of the remote sensing data, and to potentially fast eddy displacements in the MZC causing a shift between the structures sampled during the cruises versus the interpolated satellite measurements. The a-geostrophic component (e.g. locally
wind driven component) of the circulation in the MZC may also contribute to the difference
between the altimetry and ADCP velocities (see section 3.6 below). The poor correlation
between both velocity data sets ($R^2 = 0.2$ to 0.4) is mainly attributed to their very different
resolution, namely the interpolated SLA derived geostrophic velocities versus
instantaneous in-situ measurements.

3.5 Surface drifter trajectories / SLA comparison

In a complementary paper by Hancke et al. (this issue), the surface circulation in the MZC has
been investigated using 67 satellite drifters released in the MZC since 2003. Despite good
general agreement between surface velocities derived from the drifter trajectories and those
for the gridded geostrophic currents, some differences are noticeable. An example is shown in
Figure 10 where velocity and direction of both current estimates are compared along a 5.5
month drifter track. Of note are the sporadic peaks in the magnitude of drifter velocity (Figure
10-b), as well as differences in the direction of the current (Figures 10-a and 10–c). Also,
when following the actual track of each drifter, it becomes apparent that the direction of the
drifter-derived current is the better of the two estimates. This corroborates the hypothesis of
an a-geostrophic, wind driven component of the surface circulation in the MZC. The
comparison between the daily mean surface currents estimated from the full drifter data set
and the geostrophic current derived from altimetry indicates that the geostrophic velocities are
some 21% lower than those of the drifter. This observation is consistent with the
underestimates of the geostrophic surface current compared with the ADCP measurements
where the latter provides a more direct measure of the currents compared to the drifters. On
the other hand, the integrated value provided by the drifter might be more relevant to assess
the potential migration of drifting (biological) material driven by the eddy circulation in the
MZC (Hancke et al., this issue).

3.6 Wind component of the circulation in the MZC

Comparison between the Ekman surface currents derived from the daily 1/2 degree wind
(QuikSCAT scatterometer) and the altimetry-derived geostrophic currents for the time series
from 2003 to 2009, shows that in most cases, the geostrophic component is at least one order
of magnitude higher (not shown). In some instances, however, strong wind events are
observed to drive an Ekman surface current of the same order of magnitude in a different
direction. Such an event is noted in Hancke et al. (this issue) where a surface drifter was
moved out of an anticyclone into an adjacent cyclone. This illustrates the potential of the wind
driven surface circulation in the MZC to drive the transport of passive (eventually biological) material close to the surface even in a context of ubiquitous mesoscale features.

The analysis of the satellite wind velocity (2003-2010 time series) informed on the occurrence of strong wind events in each zone of the 4°×4° gridding defined for the MZC (Table 1). For each box, the percentage of wind speed within velocity ranges has calculated on a yearly base and averaged over the full time series (Figure 11). Low to medium (0-4 and 4-8 m s\(^{-1}\)) velocities are dominant over the whole MZC excepted in the two south-east zones (9 and 10) in the south and south east of Madagascar. Wind velocities in the range 8-12 m s\(^{-1}\) (corresponding to surface Ekman velocities from 0.15 to 0.25 m s\(^{-1}\)) occurred at frequencies 10-15% in the boxes north of 20°S (zones 1 to 4) and 20 to 40% south of this latitude (zones 5 to 10). The faster wind velocity class (12-16 m s\(^{-1}\), corresponding to Ekman velocities from 0.25 to 0.35 m s\(^{-1}\)) represented only 1% of the occurrences north of 20°S, 3.5% of the occurrences between 20 and 24°S (zones 5 and 6) and up to 9% in the south-east MZC (zones 9 and 10). Only a few wind events occurred in the class 16-20 m s\(^{-1}\), corresponding probably to the passage of atmospheric cyclones in the area. The same analysis on a seasonal basis (monsoon cycle – not shown) confirmed the lower velocities north of 20°S during the period of NE monsoon wind (November to February) but didn’t show significant changes in the southern MZC. This analysis demonstrates and quantifies the potential of wind driven circulation to exceed the geostrophic component in specific circumstances.

4. Discussion

4.1 Dipole history and eddy traceability.

The generation processes of anticyclones in the channel narrows (around 16°S) has been described from satellite observations (Schouten et al., 2003), \textit{in-situ} measurements with the mooring line deployed at 16°S (Harlander et al., 2009; Ridderhinkhof et al., 2010) and numerical models (Backeberg and Reason, 2010; Halo et al., this issue). Harlander et al. (2009) clearly showed the different steps leading to the formation an anticyclonic cell (their Figure 7), which is triggered by strong southward flow in the east of the channel narrows. Using a high resolution regional circulation model, Backeberg and Reason (2010) showed that this process is connected to the transport variability of the SEC north of Madagascar. Positive (anticyclonic) vorticity is generated at the inshore edge of the SEC as it flows westward past the northern tip of Madagascar and propagates into the northern basin of the
MZC where eventually an anticyclonic eddy is formed. Such scenarios correspond with the
“classical” scheme (or normal situation) of eddy formation in the MZC resulting in the
propagation of anticyclones along the western side of the MZC (e.g. Schouten et al, 2003).
This was presumably the situation for most of the cruises in this study (MC05, MC07,
MC08A, MC09B).

From a statistical analysis of sea level height (SSH), Palastanga et al. (2006) highlighted the
intermittent presence of positive SSH anomalies in the eastern MZC. During our study,
anticyclones in the central part of the channel were shown to increase in strength when they
merged with these positive anomalies, as already suggested by Schouten et al. (2003). This
was clearly the case in 2005 (MC05 cruise) and in 2010 (MC10A cruise). In 2008 (MC08A
cruise), there was no positive SSH anomaly near the west coast of Madagascar, but an
isolated anticyclone formed in the east during September and subsequently merged with a
south-westward moving anticyclonic structure. On the contrary, no eastward contribution to
the eddy migrating southward in the western basin was evident in 2007 during MC07 and in
2009 during MC09B.

While the formation of anticyclones at the channel narrows is the most common and most
effective process, the analysis of SLA confirmed that areas of anticyclonic eddy generation
exist elsewhere in the channel. As mentioned above, anticyclones might originate from positive
SSH anomalies periodically observed in the eastern MZC. Alternatively, anticyclones formed
at the southern tip of Madagascar may enter the channel from the south and merge with other
anticyclonic eddies propagating southwards. These different generation sites are in agreement
with the results of Halo et al. (this issue) who, using high resolution regional circulation
models, show that a variety of eddy (both cyclonic and anticyclonic) generation sites exist
within the channel.

The complex history of anticyclonic cells makes it difficult to infer biogeochemical properties
related to the eddy dynamics. In particular, the concept of “constrained” versus “free” eddies
used by Bakun (2006) to express reversed biological signature of an eddy depending on its
maturation, valid in an open ocean, seems to be questionable in the MZC. Eddy-eddy (or
eddy-coast) interactions add complexity to the evolution of particular eddies. This was
observed in 2010 where an anticyclone shifted from the centre of the channel to the western
boundary within a few days. Such behaviour complicates the analysis of the eddy driven biological response.

4.2 Cyclonic component of the eddy field.

There is no documented process that describes the generation of cyclonic eddies in the MZC - except at some particular location where such structures appear to be (semi) permanent (lee eddies) - (Lutjeharms and Jorge da Silva, 1988; Lutjeharms, 2006). SLA time series show that cyclones in the MZC are constrained by the evolution of the anticyclonic eddy field. The signature of cyclonic eddies however is clearly evident in in-situ measurements from the horizontal current distribution, the vertical structure of isopycnals and the vertical distribution of nutrients and biogeochemical signature such as deep chlorophyll maxima (see Lamont et al., this issue; Roberts et al., this issue). These features appear to be closely linked to the dynamics of anticyclonic eddies.

In some circumstances however, cyclones remain stable over several weeks, and do so independently from the dominant anticyclonic eddy field. This was the case in 2010 when a cyclone remained near the narrows (from 14°S to 17°S) from mid-March to mid-May (cruise MC10A). This particular eddy had dynamical characteristics (amplitude, edge velocity, vertical structure) comparable to the anticyclones generally formed at the narrows. Such a fully developed structure may well influence the local ecosystems (upwelling, transport, coastal interaction).

A stable cyclonic structure has been repeatedly observed in the SLA time series data on the eastern side of the Comoran Basin. Such a cyclone was sampled (S-ADCP) during the MC07 cruise (Figure 2-b). A similar cell was also found in October 2008 - but shifted westward and extended across the narrows of the channel between 14°S and 16°S - and was sampled at the beginning of the MC08A cruise. The presence of a cyclonic eddy in the north-east of the MZC seems to be a common feature of the circulation in the northern MZC (see also Pripp et al., this issue). This eddy is superimposed on the general anticyclonic circulation in the northern MZC (e.g. Piton and Donguy, 1991; Backeberg and Reason, 2010). North-east cyclones were not present during the two periods (January to April 2005 and March to May 2010) where the eddy formation was associated with the presence of a positive SSH anomaly in the eastern MZC.
4.3 Circulation in the south-eastern MZC

The relatively invariable sea surface topography in the southeast MZC compared to the mesoscale eddy field over most of the channel does not seem to hinder substantial currents in this area. This is evident from S-ADCP current measurements both in 2007 (MC07) east of the transect at 24.5°S (Figure 3) and in 2010 (MC10A) along the coast of Madagascar. South-eastward (in 2007) and eastward (in 2010) currents up to > 30 cm s\(^{-1}\) were measured in the surface layer that were apparently not related to any strong eddy structures. A thin coastal current was evident along Madagascar in 2007 between 23.5°-24°S, which was clearly disconnected from the wider flow in the same direction ~100 km away from the coast.

Measurements during the cruises do not indicate the origin of these coastal flows. The gridded wind data (QuickSCAT in 2007 and ASCAT in 2010) showed moderate south-easterlies at the time of the measurements, indicating these currents cannot be driven by the wind. Interestingly, south-eastward flow along the south-western coast of Madagascar was proposed in earlier circulation schemes in the MZC (see Figure 1-a from Særte and Jorge da Silva, 1984; Donguy and Piton, 1991). The presence of cyclonic eddies, potentially formed in the lee of the southern tip of Madagascar (Cap Sainte Marie) are evident in SeaWiFS chlorophyll composite maps (Quartly and Srokosz, 2004). Surface drifters also clearly showed the occurrence of south-eastward coastal currents along Madagascar (Hancke et al., this issue).

The east and south-east regions are not as well studied as the rest of the MZC. However, observations during the MESOBIO cruises highlight the complexity of the circulation in this area. Moreover, the potential effect of coastal currents on the living resources available to the Madagascar population makes it essential to obtain a better understanding of the circulation in this part of the MZC.

4.4 Altimetry versus in-situ observations of the eddy field.

The description of the eddy field within the MZC has mainly been based on altimetry observation (e.g. Schouten, 2003). The mooring line deployed in the channel narrowed confirmed eddy formation and their southward migration at this latitude (eg Ridderinkhof and de Ruijter, 2003; Harlander et al. 2009; Ridderinkhof et al., 2010). Observations along transects perpendicular to the coast of Mozambique at 20°S and 24°S (Swart et al., 2010) also indicated anticyclonic eddy activity along the coast of Mozambique. In the present study, the substantial in-situ current measurement dataset obtained between 2005 and 2010 has been used to test the accuracy of the geostrophic approximation to describe the circulation in the MZC. While the geostrophic currents (from the altimetry) and in-situ measurements (from
both S-ADCP data and drifters trajectories) clearly show good qualitative agreement, altimetry based currents were 20 to 30% weaker compared to in-situ measurements. Departures of the drifter trajectories from altimetry derived geostrophic currents also occurred on several occasions (Hancke et al., this issue) despite acknowledgement of high wind events (see below).

The underestimate of the velocity deduced from altimetry in the MZC was already observed by Swart et al. (2010). Reasons for this are firstly, the very different spatial and temporal resolution of each type of measurement (best resolution of 1/4 degree and one day for the altimetry product compared to the instantaneous and localized S-ADCP measurements and the daily averaged data from drifters) and the comparison of a geostrophic velocity with values determined from S-ADCP (surface closest value, around 8m depth) and surface (0-15m) drifters. It should be noted that the geostrophic velocity field deduced from altimetry has been significantly improved by the use of the Rio09 Mean Dynamic Topography recently released, which includes an improved estimate of the geoid (Rio et al., 2011). Despite the improved resolution of the altimetry product used (1/4 degree and 1 day) however, the velocity field remains smoothed and underestimated compared with the in-situ measurements.

A second reason is that an a-geostrophic component of the velocity field is expected. An Ekman component of the surface circulation is evident in the drifter trajectories in the case of strong wind events (also see Hancke et al., this issue), although the global data set did not allow us to conclude on a systematic bias resulting from the wind. However, regarding the independence of the eddy field and the wind distribution, and that geostrophic currents are weak in the centre of an eddy, moderate winds might drive a significant Ekman surface drift relative to the eddy induced velocity in this particular circumstance. This may have a significant influence on the transport of drifting organisms. Short time variability in the wind field makes it difficult however to quantify the wind effect. A-geostrophic currents are also evident in the coastal currents measured at 16°S along the Mozambique (MC10A) and at 23.5°S along Madagascar. While most of the previous studies on the circulation in the MZC focused on the mesoscale eddy component and the modulation by the large scale variability, a-geostrophic currents need to be considered particularly in understanding connectivity in the MZC ecosystem.

5. Summary and conclusion
Recent measurements at sea have been used here to illustrate features and processes occurring in the MZC. The observations not only confirm the presence of eddies and dipoles in the MZC but also document the horizontal and vertical flow characteristics in and around these structures. Tracking has confirmed that eddies preferentially form in the northern MZC and then migrate south-westward along the western boundary of the channel. Anticyclones are generally the dominant structure within eddy dipoles, and their ocean current signature is evident to depths of 500 m (anticyclones) and to 100 m (cyclones). In the most common situation, cyclones appear to be “by-products” of the anticyclonic mesoscale dynamics (as already described by others – e.g. de Ruijter et al., 2002) and tend to be weaker.

However, an alternative unusual scenario was also observed in our study whereby a dominant cyclonic feature developed in the narrows of the MZC (e.g. April 2010). The dynamical characteristics of the cyclone (speed at its edge, depth penetration) were comparable to that of “typical” anticyclones generally present at this latitude. Due to their pronounced dynamical signature, these cyclonic structures may have a local impact on the biological productivity. The presence of a cyclonic cell in the north-eastern MZC basin also seems to be a common feature that is superimposed on the general anticyclonic circulation in the northern basin. The development of the cell into a strong eddy feature (as in April 2010) might be linked to the presence of positive SLA in the eastern channel as already mentioned by Palastanga et al (2006), resulting in an alternative – and temporary – mesoscale scenario in the MZC. In the situation surveyed in April 2010, a very narrow coastal current flowing in an opposite direction to the western edge current of the cyclone was observed. Our measurements do not allow us to conclude whether such currents are typically associated with cyclones located in the narrows, nor if these might be part of the episodic continuous Mozambique Channel Current as recently described by Lutjeharms et al. (2012).

The a-geostrophic component (i.e. not driven by mesoscale turbulence) of the MZC circulation has been shown to be significant at times. Wind may play a significant role during extreme weather conditions, such as atmospheric cyclones that occur almost every year within the MZC. Also, the circulation southeast of Madagascar appears to be independent of mesoscale activity at times, and should be investigated more directly in future studies.
The mesoscale dynamics observed using in-situ measurements during the MESOBIO cruises potentially influence the biological productivity within MZC ecosystems. Due to the interactions between the eddies themselves, the interactions with the coastal areas as well as the influence of inter-annual variability linked to large scale remote forcing such as El Niño Southern Oscillation and the Indian Ocean Dipole, the variability at a local scale is highly variable and extremely unpredictable. In order to better understand local processes, including connectivity and biodiversity issues, these have to be measured over long scales, taking into consideration the role that regional and basin scale variability may have.

6. Acknowledgements

This study relies mostly on in situ measurements conducted using the research vessels FRS Algoa (DEA, South Africa), Fridtjof Nansen (FAO) and Antea (IRD, France) within the different projects of ACEP (African Coelacanth Ecosystem Programme), ASCLME (Agulhas Somali Current Large Marine Ecosystem) and SWIOFP (South West Indian Ocean Fisheries Project). The MESOBIO project which unified these projects was supported by a grant from the West Indian Ocean Marine Science Association (WIOMSA). We are grateful to the officers and crew of these research vessels for their contribution to the success of these operations. We also appreciate the contribution of the IRD engineers (Jacques Grelet and Fabrice Roubaud) who supported the physics operations onboard the R/V Antea, as well as the provision of satellite data in a “quasi real time” onboard R/Vs by Dominique Dagorne (IRD). We finally thank the referees for their contribution to the improvement of the manuscript.

7. References


Sete C., Ruby, J., Dove, V., 2002. Seasonal variation of tides, currents, salinity and temperature along the coast of Mozambique. http://hdl.handle.net/1834/188, Eds Instituto Nacional de Hidrografia e Navegação, Maputo


Table 1: Latitude / longitude limits of the ten boxes of the gridding used for the wind speed analysis.

<table>
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<tr>
<th>zone 1</th>
<th>zone 2</th>
<th>zone 3</th>
<th>zone 4</th>
<th>zone 5</th>
<th>zone 6</th>
<th>zone 7</th>
<th>zone 8</th>
<th>zone 9</th>
<th>zone 10</th>
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</table>

Table 2: Characteristics of the surface (0-25 m) velocity field associated with the dipole sampled in 2007 (MC07 cruise). South C: southern edge of the cyclone; C-AC normal: transect across the cyclone/anticyclone boundary; West AC: western edge of the anticyclone; C-AC: transect along the C/AC boundary; East C: eastern edge of the cyclone; West AC: western edge of the anticyclone.

<table>
<thead>
<tr>
<th>South C</th>
<th>C-AC normal</th>
<th>West AC</th>
<th>C-AC parallel</th>
<th>East AC</th>
<th>West C</th>
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<td>1.59</td>
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<td>U_{\text{mean}} (m s^{-1})</td>
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<td>0.19</td>
<td>0.17</td>
<td>0.13</td>
<td>0.14</td>
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Table 3: Characteristics of the surface (0-25 m) velocity field associated with one of the dipoles sampled in 2008 (MC08A cruise). Columns “A-D” and “D-F” (in grey) are shown for a global comparison between the two eddies – See Figure 6-a for the transect labelling.

<table>
<thead>
<tr>
<th>A-B</th>
<th>B-C</th>
<th>C-D</th>
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<tr>
<td>STD (m s^{-1})</td>
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<td>0.24</td>
<td>0.46</td>
<td>0.10</td>
<td>0.10</td>
<td>0.11</td>
</tr>
</tbody>
</table>
List of figures

Fig. 1. Historical view of the circulation in the MZC, from Særte and Jorge da Silva (1984) who proposed 2 schemes depending on the monsoon season: (a): northeast monsoon in austral summer; (b): southwest monsoon in austral winter (I, II and III represent the three major rotating cells described by the authors); and (c): from Schouten et al. (2003), in a scheme dominated by the MZC eddies (MCE). Other currents: South Equatorial Current (SEC), South East Madagascar Current (SEMC), North East Madagascar Current (NEMC), East African Coastal Current (EACC), Agulhas Current (AC). Dotted lines stand for the uncertain Mozambique Current (MC) and for the unclear connection between SEMC and AC. Geographic locations cited in the text are labelled on this figure. Bathymetry is featured in grey (scale on the right).

Fig. 2. Maps of cruise tracks conducted between 2005 and 2010 in the MZC superimposed on the eddy field for a given day during the cruise. Black dots and open circles represent hydrological stations.

Fig. 3. Near-surface (0-50m) velocity in the southern Mozambique Channel measured during cruise MC07, superimposed on the eddy field (12 Sept. 2007). Gray scale (on right) indicates SLA (cm). A velocity scale is shown in the bottom LH corner.

Fig. 4. Near-surface circulation (0-50m) in the Comoran basin (cruise MC07): (a) velocity field superimposed on the eddy field (3 Oct. 2007). Grey scale indicates SLA (cm). Velocity scale is shown in the bottom LH corner. (b): bathymetry of the Comoran basin and locations cited in the text (Comoros archipelago: from Grande Comore in the east to the Glorioso Islands in the west; . The Comoros: Grande Comore, Mohéli and Anjouan).

Fig. 5. Sampling of a dipole in the western Mozambique Channel (cruise MC07): near-surface (0-50m) velocity distribution over the eddy field (19 Sept. 2007) measured by an S-ADCP. Grey scale on the RHS indicates SLA (cm). The velocity scale is represented in the bottom left of the diagram.

Fig. 6. S-ADCP measurements across an east-west dipole during the MC08 cruise: (a) surface velocity over the eddy field (10 Dec 2008). Grey scale indicates SLA (cm) and the velocity scale is shown in the bottom left ; (b) vertical distribution of velocity (cm s\(^{-1}\)) along the transect A–G to a depth of 300 m.

Fig. 7. Vertical distribution of velocity measured during cruise MC10A: (a) cruise track over the eddy field observed on 14 April 2010) during leg 1; (b) velocity measured by the S-ADCP to a depth of 300 m. The velocity scale is indicated on the RHS (cm s\(^{-1}\)). (c): same as (a) for leg 2 with the eddy field observed on the 28 April 2010; (d): same as (b) for leg 2. Note that the strong coastal current at the start of leg2 (G) is not visible in (d) as this section is plotted off the continental shelf (see also Figure 8).

Fig. 8. Near-surface (0-50m) velocity distribution over the eddy field (14 April 2010) during the cruise MC10A (leg 2). Grey scale indicates the SLA (cm) and the velocity scale is shown in the bottom left. The surface geostrophic velocity from altimetry (not scaled) is superimposed on the SLA map. Note the thin coastal counter current found close to the shelf.

Fig. 9. Comparison of S-ADCP surface (0-25m) velocity during the MC07 and MC08A cruises and geostrophic velocity at the corresponding date and location. (a): ship tracks used for the comparison; (b) regression plot for each cruise. Regression lines for each cruise (dashed lines) and the \(V_{ADCP}=V_{altimetry}\) line (full line) are presented. Note that the vertical line effect of the dot distribution is due to the nearest neighbour procedure used to interpolate geostrophic velocity (\(\Delta x = 33\)km) to the ADCP measurements position (\(\Delta x = 5\)km).
Fig. 10. Comparison of surface drifter (drifter#49, 01/10/2007-10/03/2008) and geostrophic velocity at the corresponding date and location. (a): drifter track in the MZC; (b) drifter (light grey) and geostrophic (dark grey) velocity magnitude along the drifter track; (c) drifter (light grey) and geostrophic (dark grey) velocity direction along the drifter track.

Fig. 11. Histogram of the mean wind speed per zone and per speed class over one year periods (mean values for the period 2003-2010). Error bars represent the standard deviation of the mean for the 8 years of satellite measurements.
Figure 1: Historical view of the circulation in the MZC, from Særte and Jorge da Silva (1984) who proposed 2 schemes depending on the monsoon season (a): northeast monsoon in austral summer; (b): southwest monsoon in austral winter (I, II and III represent the three major rotating cells described by the authors); and (c): from Schouten et al. (2003), in a scheme dominated by the MZC eddies (MCE). Other currents: South Equatorial Current (SEC), South East Madagascar Current (SEMC), North East Madagascar Current (NEMC), East African Coastal Current (EACC), Agulhas Current (AC). Dotted lines stand for the uncertain Mozambique Current (MC) and for the unclear connection between SEMC and AC. Geographic locations cited in the text are labelled on this figure. Bathymetry is featured in grey (scale on the right).
Figure 2: Maps of cruise tracks conducted between 2005 and 2010 in the MZC superimposed on the eddy field for a given day during the cruise. Black dots and open circles represent hydrological stations.
Figure 3: Near-surface (0-50m) velocity in the southern Mozambique Channel measured during cruise MC07, superimposed on the eddy field (12 Sept. 2007). Gray scale (on right) indicates SLA (cm). A velocity scale is shown in the bottom LH corner.
Figure 4: Near-surface circulation (0-50m) in the Comoran basin (cruise MC07): (a) velocity field superimposed on the eddy field (3 Oct. 2007). Grey scale indicates SLA (cm). Velocity scale is shown in the bottom LH corner. (b): bathymetry of the Comoran basin and locations cited in the text (Comoros archipelago: from Grande Comore in the east to the Glorioso Islands in the west; The Comoros: Grande Comore, Mohéli and Anjouan).
Figure 5: Sampling of a dipole in the western Mozambique Channel (cruise MC07): near-surface (0-50m) velocity distribution over the eddy field (19 Sept. 2007) measured by an S-ADCP. Grey scale on the RHS indicates SLA (cm). The velocity scale is represented in the bottom left of the diagram.
Figure 6: S-ADCP measurements across an east-west dipole during the MC08 cruise: (a) surface velocity over the eddy field (10 Dec 2008). Grey scale indicates SLA (cm) and the velocity scale is shown in the bottom left; (b) vertical distribution of velocity (cm s$^{-1}$) along the transect A–G to a depth of 300 m.
Figure 7: Vertical distribution of velocity measured during cruise MC10A: (a) cruise track over the eddy field observed on 14 April 2010) during leg 1; (b) velocity measured by the S-ADCP to a depth of 300 m. The velocity scale is indicated on the RHS (cm s$^{-1}$). (c): same as (a) for leg 2 with the eddy field observed on the 28 April 2010; (d): same as (b) for leg 2. Note that the strong coastal current at the start of leg 2 (G) is not visible in (d) as this section is plotted off the continental shelf (see also Figure 8).
Figure 8: Near-surface (0-50m) velocity distribution over the eddy field (14 April 2010) during the cruise MC10A (leg 2). Grey scale indicates the SLA (cm) and the velocity scale is shown in the bottom left. The surface geostrophic velocity from altimetry (not scaled) is superimposed on the SLA map. Note the thin coastal counter current found close to the shelf.
Figure 9: Comparison of S-ADCP surface (0-25m) velocity during the MC07 and MC08A cruises and geostrophic velocity at the corresponding date and location. (a): ship tracks used for the comparison; (b) regression plot for each cruise. Regression lines for each cruise (dashed lines) and the $V_{ADCP}=V_{altimetry}$ line (full line) are presented. Note that the vertical line effect of the dot distribution is due to the nearest neighbour procedure used to interpolate geostrophic velocity ($\Delta x = 33$km) to the ADCP measurements position ($\Delta x = 5$km).
Figure 10: Comparison of surface drifter (drifter#49, 01/10/2007-10/03/2008) and geostrophic velocity at the corresponding date and location. (a): drifter track in the MZC; (b) drifter (light grey) and geostrophic (dark grey) velocity magnitude along the drifter track; (c) drifter (light grey) and geostrophic (dark grey) velocity direction along the drifter track.
Figure 11: Histogram of the mean wind speed per zone and per speed class over one year periods (mean values for the period 2003-2010). Error bars represent the standard deviation of the mean for the 8 years of satellite measurements.