Eddy Properties in the Mozambique Channel: A comparison between Observations and two Numerical Ocean Circulation Models


Department of Oceanography, University of Cape Town, Rondebosch, South Africa, 7701
Nansen-Tutu Centre for Marine Environmental Research, University of Cape Town, Rondebosch, South Africa, 7701
LMI ICEMASA, Laboratoire de Physique des Océans (UMR 6523: CNRS, IRD, IFREMER), France
Netherlands Institute for Sea Research, NIOZ, FYS, Den Burg (Texel), Netherlands

Abstract

Analysis of in-situ data and altimetric observations, as well as outputs from 2 different numerical ocean circulation models (ROMS and HYCOM), have been used to investigate the mesoscale eddy properties in the Mozambique Channel. ROMS was forced by climatology data and run at 1/5° of spatial resolution, while HYCOM used an interannual forcing, and run at 1/10° grid resolution. Analysis of power spectral density of the models transport at 17°S, have shown a comparable representation of the transport variability at mesoscale frequencies (range between 3y^{-1} and 10y^{-1}). The models also have shown an exaggerated representation of the lower frequencies (∼< 3y^{-1}), while underestimating the higher frequency signals (∼> 10y^{-1}). The overestimation of the seasonal cycle appeared in our case not related to a misrepresentation of the mesoscale variability. The eddies were identified using an automatic eddy tracking scheme. Both anticyclonic and cyclonic
eddies appeared to have a favourite site of formation within the channel. Eddy density distribution have shown that anticyclonic eddies have exhibited a bi-modal distribution, which may suggest different mechanisms of their formation, while cyclonic eddies had a single mode distribution that follows the first baroclinic Rossby radius, suggesting their origin to be associated with the background turbulence of the system.

**Keywords:** Cyclonic/anticyclonic eddies, Ocean Models, Altimetry,

1. **Introduction**

The Mozambique Channel forms part of the greater Agulhas Current system, which extends from north of Madagascar to the southwestern extremity of South Africa (Lutjeharms, 2006). The greater Agulhas Current system is an important link in the exchange of heat and salt between the Indian and the Atlantic Oceans (Gordon, 1986; Weijer et al., 1999). It has been shown that the flux of warm and salty waters into the Atlantic Ocean via the Agulhas retroflection region plays a decisive role in maintaining the stability of the global meridional overturning oceanic circulation (de Ruijter et al., 1999), and hence the global climate (Beal et al., 2011).

An important way in which warm and salty waters from the Agulhas are transported into the South Atlantic is through the shedding of Agulhas Rings from the Agulhas retroflection south of Africa (Lutjeharms and van Ballegooien, 1988; Reason et al., 2003). This mechanism has been termed
the Agulhas leakage, and studies have shown that the frequency of Agulhas
Ring shedding and thus the inter-ocean leakage is modulated by mesoscale
perturbations originated farther upstreams of the retroreflection area, in the
Mozambique Channel and South of Madagascar (Schouten et al., 2002; Pen-
ven et al., 2006; Biastoch et al., 2008b).

The flow through the Mozambique Channel is characterized by intense
mesoscale eddy activity, and dominated by large anticyclonic eddies (Bias-
toch and Krauss, 1999; Ridderinkhof and de Ruijter, 2003; Schouten et al.,
2003). These eddies play a significant role on the dynamics of the local ma-
ine ecosystems (Weimerskirch et al., 2004). It has been observed that these
eddies trap anomalous water masses with higher nutrient and lower oxygen
(Swart et al., 2010), and also advect coastal waters with high primary pro-
duction into the offshore oceanic environment (Quartly and Srokosz, 2004;
Omta et al., 2009; Tew-Kai and Marsac, 2009).

Mozambique Channel eddy characteristics have been determined from a
number of measurements (Ridderinkhof et al., 2001; de Ruijter et al., 2002).
Observations from a current meter mooring array at ∼ 17°S (Ridderinkhof
and de Ruijter, 2003) have shown that these eddies are up to ∼ 300 - 350 km
wide, reaching all the way to the bottom of the channel over 2000 m deep,
having a strong barotropic component (de Ruijter et al., 2002; Ridderinkhof
and de Ruijter, 2003; Schouten et al., 2003).

These eddies have been shown to be surface intensified, propagating
southward parallel to the western boundary of the channel, with speeds of
about 6 km.day$^{-1}$. Interestingly, between 18 - 21°S, their propagation speed reduces to 3 - 4 km.day$^{-1}$ (Schouten et al., 2003), but further to the south, at 24°S, analysis of the eddy properties by Swart et al. (2010), revealed that the eddies propagation velocities increase to over 6 km.day$^{-1}$, with tangential velocities of about 0.5 m.s$^{-1}$, while maintaining their large diameters (over ∼ 200 km). On average, these eddies transport anomalous heat and salt of about $1.3 \times 10^{20}$J and $6.9 \times 10^{12}$kg, accounted as sufficient to modify the water masses downstream (Swart et al., 2010).

The frequency of occurrence of the Mozambique Channel eddies is quite regular, being about 4 - 5 per annum (Schouten et al., 2003), observed at 17°S. Their passage induces fluctuations in the volume transport, ranging from approximately 20 Sv northward to 60 Sv southward. The mean poleward transport has been estimated to be 15 Sv (de Ruijter et al., 2002). However, this quantity seems variable. Using a longer time series, a lower quantity of about ∼ 8.6 ±14.1 Sv was found by Harlander et al. (2009).

Due to the overwhelming signature of the anticyclonic eddies in the central Mozambique Channel, there is no documented definitive conclusion in the literature regarding the origin of cyclonic eddies in this region. Cyclonic eddies are important dynamical features for the marine ecosystems (Robinson, 1983; Cyril et al., 2011). They usually bring deep rich-nutrient waters into the upper ocean, thereby enhancing primary productivity. Currently the role of the Mozambique Channel eddies in the local ecosystem have been investigated by hydrographic surveys, carried out as part of the Mesoscale dy-
namics influence on Pelagic resources (MESOP) program (Ternon et al., This issue). Physical mechanisms responsible for the generation of these eddies also has been proposed (Roberts et al., This issue). However in spite their important role, little is known about their abundance and characteristics in the Mozambique Channel. For example de Ruijter et al. (2002) found no cyclonic eddies in the Mozambique Channel. The apparent cyclonic anomalies observed from altimetry in this study was attributed to artifacts in the data processing, and an inaccurate knowledge of the mean dynamic topography. They concluded that the cyclonic features are misrepresented simply because of the absence of anticyclonic eddies (de Ruijter et al., 2002). Thus, the present knowledge states: "the frequent passage of positive anomalies through the Mozambique Channel leaves a signal in the mean SSH field, leading to a negative anomaly when no anticyclone is present" (Schouten et al., 2003). Previous studies have identified cyclonic eddies in the Mozambique Channel (Gründlingh, 1995). However, their generation site was uncertain, and later studies (Schouten et al., 2003; de Ruijter et al., 2004) have suggested that these transient features were generated in the southwestern edge of Madagascar, and not within the channel.

The present generation of state-of-the-art numerical ocean models have been shown to simulate the eddy regime in the Mozambique Channel with a reasonable degree of accuracy (Penven et al., 2006; Biastoch et al., 2008a; Backeberg et al., 2009). An extensive comparison of observed and modeled transport, seasonal cycle, and eddy frequencies in the narrows of the channel,
has been conducted by van der Werf et al. (2010). The study suggested that the models in general overestimated the seasonal cycle because the spectral density at other frequencies is underrepresented. This study used outputs from 6 ocean general circulation models, based on similar general characteristics: namely global ocean models, using z-coordinate discretization schemes.

Ocean models are usually classified according to their vertical discretization (Song and Haidvogel, 1994; Bleck, 2002; Chassignet et al., 2006). In this study the outputs from two regional models with very different vertical discretization schemes, and horizontal grid resolutions are compared against available observations. The two models are the Regional Ocean Modelling System (ROMS (Shchepetkin and McWilliams, 2005)) and the Hybrid Coordinate Ocean Model (HYCOM (Bleck, 2002)). ROMS and HYCOM are typical representatives of 2 alternatives of the classical z-coordinate models. These 2 models are at the forefront of the new developments in ocean modelling, using different vertical discretizations, to achieve a more realistic representation of the ocean dynamics.

The regional models were specifically designed to accurately simulate the dynamics of the greater Agulhas Current system (details of these models is provided in section 2.1). The simulated eddies in the Mozambique Channel are compared with eddies observed from satellite altimetry measurements using an eddy detection method to track eddies and monitor their evolution as they propagate southward through the channel. Furthermore, the model-altimetry comparison is augmented by an evaluation of the model transports
against observed transports through the narrows of the channel near 17°S in
a similar manner to van der Werf et al. (2010).

This paper is structured as follows. A description of the models is pre-
presented in section 2.1, followed by the observational data used to evaluate
the models solution in section 2.2. The details of the automatic eddy de-
tection scheme are presented in section 2.3, with the main findings of the
study outlined in section 3. Finally, the discussion and main conclusions are
summarized in section 4.

2. Methods

2.1. Models description

2.1.1. Regional Ocean Modelling System

The Regional Ocean Modelling System (ROMS) is a primitive equation
model designed to realistically resolve basin-scale, regional and coastal ocean
processes, at higher resolution (Shchepetkin and McWilliams, 2005). The
model has a free surface and uses a $\sigma$ topography-following vertical grid.
The higher order numerics of the model allow for an improved simulation of
oceanic mesoscale processes. The subgrid-scale vertical mixing is parameter-
ized by the K-profile (KPP) scheme of Large et al. (1994). The model uses a
centered fourth-order horizontal tracer advection scheme for potential tem-
perature and salinity, with a biharmonic diffusion operator rotated to follow
the isopotentials (Marchesiello et al., 2009). This feature minimizes the prob-
lem of spurious diapycnal diffusion which could arise in $\sigma$-coordinate models.
At the open boundaries, the model uses an adaptive, mixed passive-active implicit radiation scheme that connects the model solution to the surrounding oceanic environment (Marchesiello et al., 2001). A detailed description of the model is given by Shchepetkin and McWilliams (2005).

2.1.2. The South-West Indian ocean Model (SWIM) Configuration

The ROMS based configuration (SWIM) encompasses the South-West Indian Ocean. The configuration was built using the ROMSTOOLS package (Penven et al., 2008). It has been specifically designed to simulate the dynamics of the Mozambique Channel. The domain extends from 0° - 77.5°E, and from 3°S - 47.5°S, with a horizontal grid resolution of $\frac{1}{5}$° (~ 21 km at mean latitude of the channel). Considering that the first baroclinic Rossby radius of deformation in the Mozambique Channel range from 40 km in the south, to 100 km in the north (Chelton et al., 1998), this resolution is sufficiently fine to resolve the mesoscale dynamics of the region. In the vertical, the number of sigma layers was extended to $N=45$ levels, with the controlling stretching parameters (towards the surface: $\theta_s = 5.5$, towards the bottom: $\theta_b = 0$, and for the transition between the layers $hc = 10$ (Haidvogel and Beckmann, 1999)).

The model topography was interpolated to the SWIM grid from the Global Earth Bathymetric Chart of the Oceans (GEBCO1) data. In order to preserve important bathymetric features while limiting pressure gradient errors, the bathymetric smoothing factor was kept equal to $r = \frac{\nabla h}{h} = 0.25$,
where $h$ is the bathymetric depth.

At the surface, SWIM was forced with monthly climatology fluxes. The heat and fresh-water fluxes are derived from the COADS $\frac{1}{2}^\circ$ resolution data (Da Silva et al., 1994). The wind stress used in the climatology experiment is derived from QuickSCAT satellite scatterometer for the period 2000-2007, gridded at $\frac{1}{2}^\circ$ resolution.

For the open boundaries we used a monthly climatology, gridded from the $1^\circ$ World Ocean Atlas 2005 data (WOA2005 (Conkright et al., 2002)). The level of no motion for the calculation of the geostrophic currents at the boundaries is chosen at 1000 m.

A climatology experiment of the model is run for 10 years, and its outputs are averaged every 2 days. Integrated volume properties have shown that the model reached its dynamical equilibrium after 3 years. Therefore, we analyse SWIM outputs from year 4 to year 10.

2.1.3. *Hybrid Coordinate Ocean Model*

The Hybrid Coordinate Ocean Model (HYCOM; (Bleck, 2002)) is a primitive equation model that combines the optimal features of isopycnic-coordinate and fixed-grid ocean circulation models in one framework, dynamically changing its vertical layer distribution between isopycnic ($\rho$) and Cartesian coordinates, adjusting to an optimal structure regularly. This adaptive (hybrid) vertical grid conveniently resolves regions of vertical density gradients, such as the thermocline and surface fronts.
A $\frac{1}{10^6}$ resolution of HYCOM for the greater Agulhas Current system, with
30 vertical hybrid layers was run in a 1 way nested configuration, where a
coarser basin-scale HYCOM of the Indian and Southern Ocean (George et al.,
2010) provides lateral boundary conditions for the regional model. For the
slow varying variables, the boundary condition calculations are based on the
flow relaxation scheme (FRS, (Davies, 1983)) and the barotropic variables are
treated in a hyperbolic wave equation for pressure and vertically integrated
velocities (Browning and Kreiss, 1982, 1986) such that variability simulated
in outer model is transmitted to the regional model.

The geographical domain of the regional nested model of the greater
Agulhas Current system extends from $0^\circ - 60^\circ$E and from $10^\circ - 50^\circ$S, which
includes the Mozambique Channel. The nested model was initialised from
a balanced field from the outer model, interpolated to the high resolution
grid, and following a long spin-up period. Data from years 2001 – 2010 of
the free-running hind-cast simulation are used.

The model bathymetry is also derived from (GEBCO1), which was in-
terpolated to the model grid. Both the nested and outer HYCOM models
are forced inter-annually with 6-hourly synoptic atmospheric forcing fields
from ERA40 before 2002 and then using the operational analyses from the
ECMWF. Cloud cover data from the Comprehensive Ocean-Atmosphere
Data Set (COADS; (Slutz et al., 1985)) and precipitation data from Legates
and Willmott (1990) are also applied.

The ability of the nested model to realistically simulate the region has
been documented in Backeberg et al. (2008, 2009). In particular the importance of a 4th order momentum advection scheme is highlighted, which greatly improved the dynamics of the model.

2.2. Data

2.2.1. Satellite Altimetry data

Satellite altimeters provide information about variations of the sea surface height, used to study mesoscale ocean variability. In regions where in-situ observations are sparse, such as the Mozambique Channel, studies rely heavily in such altimetric observations. To date, altimetry data spans almost 2 decades, starting October 14, 1992.

The gridded data product produced by Ssalto/Duacs and distributed by AVISO, with support from Cnes combines altimeter measurements from a number of satellites through an interpolation mapping technique (Ducet et al., 2000). In this study we use these gridded maps of absolute dynamic topography, that combine sea level anomaly observations merged from Jason-1, Envisat, GFO, ERS-1, ERS-2 and Topex/Poseidon with the Rio09 mean dynamic topography (Rio et al., 2011). The data are provided globally on a regular grid with a spatial resolution of $\frac{1}{4} \times \frac{1}{4}$, every 7 days.

2.2.2. LOCO Data

To evaluate the volume transport and its variability in the models, their outputs are compared with in-situ observations from the Long-term Ocean Climate Observation program (LOCO) (de Ruijter et al., 2006). The LOCO
mooring array is situated across the narrows of the channel near 17°S, and each mooring includes current meters, temperature-depth profilers, Acoustic Doppler Current Profilers, and sediment traps (de Ruijter et al., 2006; Harlander et al., 2009; van der Werf et al., 2010). This array has consistently measured mass and heat transport through the Mozambique Channel since 2000, representing the longest time series of in-situ observations ever recorded in the Mozambique Channel.

Details concerning the LOCO data, instruments and deployment strategy are given by Ridderinkhof et al. (2001); de Ruijter et al. (2002); Ridderinkhof and de Ruijter (2003); Harlander et al. (2009). In the present study we used the data collected from 23 November 2003, to December 16, 2009, which corresponds to the period following a service and redeployment of the instruments (van der Werf et al., 2010).

2.3. Eddy detection and tracking algorithm

Since the ocean circulation in the Mozambique Channel is dominated by the propagation of mesoscale eddies (de Ruijter et al., 2002), it is important that model simulations capture their properties adequately. In order to compare observed eddy properties to those simulated in the models in a robust and consistent manner an eddy detection scheme is implemented.

Among the numerous algorithms employed, the two methods generally used with altimetry data are the methods based on geometric criteria, for example, detecting closed loops in SSH (Chelton et al., 2011), and the meth-
ods based on local deformation properties of the flow, mostly selecting regions where the Okubo-Weiss parameter is below a negative threshold (Isern-Fontanet et al., 2006; Chelton et al., 2007) (i.e. where the flow is dominated by rotation). The Okubo-Weiss parameter is defined as $W = S_n^2 + S_s^2 - \xi^2$, where $S_n = \frac{\partial u}{\partial x} - \frac{\partial v}{\partial y}$, $S_s = \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}$ and $\xi = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}$ (Okubo, 1970; Weiss, 1991), where $u$ and $v$ are the velocity components in the $x$ and $y$ directions.

In the case of altimetry, $W$ is based on second derivatives of SSH. This amplifies the errors in measurements and interpolations, resulting in a significant level of noise (Chelton et al., 2011; Souza et al., 2011). A second problem is the sensitivity of the method to the choice of the threshold in $W$ used for eddy detection (Chelton et al., 2011). Methods based on geometric criteria have appeared less problematic and have been shown to yield improved results compared to the Okubo-Weiss parameter (Chaigneau et al., 2008; Chelton et al., 2011; Souza et al., 2011). Nevertheless, they still require a threshold level to be set in for the SSH anomalies and/or criteria based on the shape of the detected structures (Chelton et al., 2011; Kurian et al., 2011).

To compare eddy statistics from different sources (Altimetry and two ocean models), we need an algorithm independent on tunable parameters. By combining the Okubo-Weiss and geometric methods, the number of parameters is reduced. In this case, a geostrophic eddy is defined as contained within a close loop of SSH and dominated by rotation ($W < 0$).
With a recently published improved mean dynamic topography (Rio et al., 2011) it is now possible to apply the eddy detection scheme to absolute SSH data rather than sea level anomalies. This has two major advantages in that (1) it prevents the spurious detection of current meanders, which are often associated with closed sea level anomaly loops, and (2) in a system dominated by large anticyclonic eddies, such as the Mozambique Channel, negative values of SSH anomalies are often legitimately interpreted simply as the absence of an anticyclonic eddy rather than the presence of a cyclonic eddy (de Ruijter et al., 2002). No specific treatment such as high pass filtering is applied to SSH.

An example of the application of the eddy detection scheme is given in Figure 1 for 15 September 2003 (i.e. the date used by Weimerskirch et al. (2004)). Initially the Okubo-Weiss parameter (W) is computed from the geostrophic velocities. Two passes of a Hanning filter are applied to reduce the grid scale noise. Regions dominated by rotation are then represented by the dark contours in Figure 1a. As discussed in Chelton et al. (2011) there is a high level of noise and several selected regions are obviously not mesoscale eddies. Next, regions inside closed loop of SSH are selected. To prevent selecting an ocean gyre as a closed loop, a diameter limit of 600 km is set. Figure 1b presents the features detected in the Mozambique Channel using this method. As noted by Chelton et al. (2011), in the case of altimetry, the geometric method appears to be more successful in detecting mesoscale geostrophic eddies. However, several problems still remain: several structures
with multiple cores are selected, for example at 17°S in the Mozambique
Channel and at 24°S along the Mozambican coast, and elongated loops, for
example near 20°S west of the Madagascar East Coast.

By combining the regions of negative $W$ (Figure 1a) and the regions
embedded in SSH closed loops (Figure 1b), we obtain a more consistent
pattern where the spuriously detected features associated with noise in $W$
are excluded and the ambiguities in multi-poles / elongated closed loops are
removed (Figure 1c). Note for example the detection of a typical anticyclonic
Mozambique Channel eddy between 16°S and 18°S in Figures 1c and 1d in
comparison with the pattern detected in Figures 1a and 1b.

Three tunable parameters still remain: the interval between the contours
for closed loop detection, the maximum size of a closed loop and the number
of passes of the Hanning filter on $W$. Tests have shown that the number
of detected eddies is not very sensitive to these parameters. They are kept
identical when detecting eddies from altimetry and the 2 different ocean
models.

The algorithm used to track eddies in time follows the method proposed
by Penven et al. (2005), where an eddy detected in one frame is the same
eddy in the subsequent frame if a generalized distance in a non-dimensional
property space is minimum. This eddy detection method is coded in Matlab
3. Results

3.1. Transport at 17°S

The left panels in Figure 2 show the total meridional transport across the narrows of the channel at 17°S, for LOCO (a), SWIM (b), and HYCOM (c). The position of the section from which data from the models is extracted is shown in Figure 3a. The right panels of the Figure 2 show the corresponding power density spectrum, based on a Multitaper Spectral Analysis. The spectrum is presented on a logarithmic scale to capture a wider range of variabilities, specially at higher frequencies.

The observed mean poleward transport from LOCO is 16.3 Sv, while the simulated mean transports from SWIM and HYCOM are 18.6 Sv and 24.3 Sv respectively (1 Sv=10⁶ m³s⁻¹). Maximum variations of the transport range from approximately 60 Sv southward to 40 Sv northward for LOCO. For SWIM the transport variations range from 60 Sv southward to 25 Sv northward, while for HYCOM transports are predominantly southwards with variations ranging from 3 Sv to 45 Sv.

The mean transport in SWIM has a comparable magnitude with the observation from LOCO, while HYCOM overestimates the mean transport by about 50%. Nevertheless, HYCOM is able to reproduce the interannual variability, in particular the increased poleward transport occurring during years 2005 - 2007. High frequency transport fluctuations in LOCO show strong levels of variability that overwhelms the seasonal cycle. These higher frequency signals are only partially represented in HYCOM, with a reduced
strength (one order of magnitude) of the frequencies exceeding 8 cycles/year. In SWIM, these high frequency signals are two orders of magnitudes below the observed power density spectrum.

In the power density spectra (right panels of the Figure 2), the frequency range of variabilities can be separated in three period bands of frequency: above 10 year\(^{-1}\) (high frequencies), between 3y\(^{-1}\) and 10y\(^{-1}\) (typical of the mesoscale regime)), and below 3 year\(^{-1}\) (the annual and semi-annual cycle, and interannual variations). Considering the models representations, it appears that the models overestimates the lower frequencies (i.e. seasonal cycle), and underestimates the higher frequencies, with stronger exaggeration in SWIM than in HYCOM. In the mesoscale regime (i.e. range between 3y\(^{-1}\) and 10y\(^{-1}\)), the magnitude of the density spectra are in good agreement with observations.

3.2. Variability of SSH

Figure 3 shows the root mean square (RMS) of SSH, from altimetry (Figure 3a), from October 14 1992 to March 31 2010, for SWIM (Figure 3b) for 7 years of climatology run, and for HYCOM (Figure 3c) from 2001 to 2010. Enhanced levels of RMS SSH are representative of mesoscale variability. Both models are able to reproduce the enhanced mesoscale variability observed in the central Mozambique Channel, including the pattern that results from the southward propagation of these eddies traveling close to the Mozambican coastline (de Ruijter et al., 2002). HYCOM simulates magnitudes of
maximum RMS (\(\sim 20\) cm) in the central Mozambique Channel comparable to those observed from altimetry, although the geographical extent of RMS exceeding 20 cm is limited to a smaller region, confined to the western part of the domain, south of 20°S. SWIM overestimates the RMS by almost 50%. Furthermore, the spatial extent of these high levels of variability is broader, both to the north and in the center of the channel. In the southeastern region of the channel the variability in both models is approximately 50% less than observed from altimetry.

3.3. Eddy vertical structure at 17°S

The vertical velocity structure across a typical anticyclonic eddy chosen in the Mozambique Channel at 17°S from SWIM and HYCOM is given in Figure 4. These snapshots confirm that the eddies simulated in the models have similar vertical structures as those observed from in-situ measurements ((de Ruijter et al., 2002), see their Figure 3b, for comparison). The eddies are large, spanning almost the entire width of the narrow channel, and also reach the channel bottom, near 2500 m depth, consistent with observations (de Ruijter et al., 2002; Ridderinkhof and de Ruijter, 2003). SWIM has shown a maximum surface poleward flow of about 1.1 ms\(^{-1}\) at the western boundary of the section (Mozambican side), and an equatorward component at the eastern boundary (Madagascar side), relatively smaller, of about 0.8 ms\(^{-1}\). HYCOM also reproduced comparable magnitudes, for the poleward component of about 1.2 ms\(^{-1}\), and equatorward component of about 0.9
ms\(^{-1}\). SWIM reached the channel bottom with its poleward component of 0.2 ms\(^{-1}\), and equatorward component of about 0.1 ms\(^{-1}\), while HYCOM reached the channel bottom with its poleward component of about 0.3 ms\(^{-1}\), and equatorward component of about 0.1 ms\(^{-1}\). The eddies appear to be surface intensified, and exhibited a strong barotropic component as also reported (de Ruijter et al., 2002; Ridderinkhof and de Ruijter, 2003; Schouten et al., 2003). Estimates of their residual poleward drifting have suggested a southward eddy migration at 0.3 ms\(^{-1}\). Interestingly HYCOM section has captured the equatorward flow of the Mozambique Undercurrent, centred at intermediate depth of \(\sim 1500\) m, on the western side of the section, over the Mozambican continental slope. This is also consistent with in-situ observations (de Ruijter et al., 2002). On the other hand, SWIM section has shown relatively stronger equatorward Undercurrent at the eastern boundary of the channel, below 2000 m depth. In general, and in comparison to van der Werf et al. (2010), the vertical structure of the eddies seems to be correctly reproduced by the two regional models.

3.4. Eddy generation site and trajectories

Figure 5 shows the positions of all cyclonic (blue) and anticyclonic (red) eddies tracked in the Mozambique Channel from October 14, 1992 to March 31, 2010 for AVISO (a); the 7 years of climatology run for SWIM (b); and from 2001 to 2010 for HYCOM (c). The tracking was made between 32\(^\circ\)E - 48.5\(^\circ\)E, and 24\(^\circ\)S - 14\(^\circ\)S. From these data it is possible to identify regions
in the Mozambique Channel favoured by cyclonic or anticyclonic eddy formation, and their pathways. The formation site is identified by bold dots surrounded by black rings, while their trajectory is identified by continuous lines. Greater concentration of the bold dots can be considered as a primary site for eddy generation.

Anticyclonic eddies tend to form near 12°S, to the west of Cape Amber, between Madagascar and Mozambique, around the Comores Archipelago. Interestingly, these data identify a secondary anticyclonic eddy formation region south of the narrows in the eastern boundary of the channel near 20°S, 43°E. This secondary site is evident in the altimetry and both model simulations, and has not yet been discussed in the literature. To the south of the narrows, at the eastern boundary of the channel near 20°S, 43°E a secondary site for anticyclonic formation is shown at the eastern boundary of the channel, near Madagascar coast, at 20°S, 43°E. Another site for anticyclonic generation is also evident near the southern flank of the Davies Ridge, to the east of the channel, near 17.5°S, 42.5°E. To the south of the tracking domain a secondary eddy generation site is located also at the eastern boundary, near Madagascar coastline, around 25°S, 44°E.

Cyclonic eddies appear to be more chaotic, and their distribution in the channel is less well defined, although there is a tendency toward favouring the eastern part of the channel, near Madagascar coastline. At the western part of the channel, between the pathway of the anticyclonic eddies and the African coast (Figure 5), there is also a localized site for generation of
cyclonic eddies, near 17°S.

Figure 6 shows the probability of presence of an eddy in a box of $\frac{1}{2^2} \times \frac{1}{2^2}$ grid size. The data start from October 14, 1992 to March 31, 2010 for AVISO (a); the 7 years of climatology run for SWIM (b); and from 2001 to 2010 for HYCOM (c). Higher probabilities tend to appear along the western boundary of the channel, indicative of their main southwestward pathway. A secondary propagation pathway also seems generated in the eastern part of the channel, near 20°S, 44°E, and propagates southwestwards, but with stronger tendency to the south.

3.5. Eddy statistical census

Table 1 summarizes the statistical census of the tracked eddies, and includes basic properties, such as, the number of eddies tracked /year, their mean lifetime, amplitude and diameter. From these data it is evident that there are more cyclonic than anticyclonic eddies tracked in the channel each year. Cyclonic eddies are in general smaller, with shorter life-spans, and have lower amplitudes than anticyclonic eddies.

In general, the modelled eddy properties are comparable with observations. The altimetry data indicates that a total of 43 cyclonic and anticyclonic eddies were tracked in the channel each year. 56% of these were cyclonic, while 44% were anticyclonic eddies. In SWIM an average total of 33 eddies were tracked each year, with 52% being cyclonic and 48% anticyclonic. Compared to altimetry, the anticyclonic eddies in SWIM are larger,
overestimated by $\sim 17\%$. The SWIM anticyclones have higher amplitudes, 
50\% higher than observed in altimetry. The 50\% exaggeration in SSH RMS 
may be explained by this overestimate in anticyclonic eddy amplitude. 

The amplitudes and diameters of cyclonic eddies are also reasonably well 
represented in SWIM, but their lifespan is underestimated by 37.6\% com-
pared to the altimetry observations. 

In HYCOM a annual mean total of 49 eddies are found, with 59\% being 
cyclonic and 41\% of anticyclonic. The total number of cyclonic eddies in 
HYCOM are in good agreement with the altimetry observations, while the 
number of anticyclonic eddies are slightly higher. The eddies in HYCOM 
are generally smaller, with reasonable anticyclonic eddy size, but with a 
underestimation, by 23.7\%, of the size of cyclonic eddies. Similarly, the 
amplitude of the anticyclonic eddies in HYCOM is comparable to altimetry, 
but the amplitude of the cyclones is underestimated by 45.5\%. The lifetime 
of the cyclonic eddies simulated in HYCOM are comparable to those observed 
from altimetry, however the lifespan of anticyclonic eddies are overestimated 
by 22\%. 

Figure 7 shows the frequency distribution of the eddies diameters, for 
Altimetry, SWIM and HYCOM. The cyclonic eddies (Figure 7, upper pan-
els), observed from altimetry have a near symmetric distribution in terms of 
their radius, centered around the 70 km radius for the observation. This is 
in agreement with SWIM, while in HYCOM, the highest peak is centered 
at 40 km radius. The peak at 70 km correspond to the mean baroclinic
Rossby radius of deformation in the Mozambique Channel (Chelton et al., 1998), which is consistent with the expected size of the mesoscale oceanic turbulence at this latitude.

Contrary to the cyclonic eddies, anticyclonic eddies exhibit a bimodal distribution, with observed diameters peaking at 60 km and 100 km for AVISO. In SWIM, the two peaks are slightly shifted toward larger scale at 70 km and 120 km, while in HYCOM they are in good agreement with the altimetry observations: 60 km and 100 km.
4. Discussion

By comparing the observed (LOCO) volume transport and its variability, with outputs from SWIM and HYCOM at 17°S, it is evident that the models are able to reproduce, with reasonable accuracy, the variability of the transport in the mesoscale range. Both models reproduce the mean transport although it is exaggerated in HYCOM. This could be associated with the representation of the remote influence of the Indonesian Throughflow. The seasonal cycle is also exaggerated, particularly in SWIM. In this case, it may be related to the monthly climatological forcing fields used to drive the model. This is improved in HYCOM, which is forced using inter-annual forcing fields and lateral boundary conditions.

A general tendency for numerical ocean circulation models to exaggerate the seasonal cycle has been noted by van der Werf et al. (2010), which is also the case here. In their analysis of 6 global ocean models, van der Werf et al. (2010) have concluded that the exaggeration of the seasonal cycle is related to a reduced representation of the high frequency variability in the Mozambique Channel. In particular the mesoscale variability, represented by the 5/year - 6/year spectral range in the power density spectrum.

Comparing the power density spectra of LOCO with SWIM and HYCOM (Figure 2), it is evident that, at the mesoscale frequency range (∼3 - 8 cycles/year), the models are able to reproduce the power density spectra accurately. The difference between the models and the observations is only ∼1 Sv²/year. Yet, despite the models ability to reproduce the mesoscale vari-
ability, the seasonal cycle is still exaggerated. This suggests that, for these
two models, the misrepresentation of the eddy activity is not the cause of the
exaggerated seasonal cycle. This suggests an alternative mechanism to that
proposed by van der Werf et al. (2010). There is no clear mechanism yet
explaining this exaggeration of the seasonal cycle. A possibility could be as-
associated with connections to the tropical ocean, where monsoonal variations
are large (Schott and McCreary, 2001).

At frequencies higher than the mesoscale (>8 cycles / year), the power
density spectra of SWIM and HYCOM is significantly less than observed.
The underestimate in SWIM is almost two orders of magnitude, while in
HYCOM it is approximately one order of magnitude. This underestimate of
higher frequencies is likely associated with small-scale processes that are not
resolved in the monthly climatology forcing fields in SWIM, and subgrid-scale
dynamics that the models are unable to capture.

It is well known that the flow in the Mozambique Channel is dominated
by mesoscale eddies (de Ruijter et al., 2002). From the transport at 17°S
(Figure 2), it is clear that these play a role in the transport variability. The
presence of eddies is also reflected in the SSH variability observed from satel-
lite altimetry (Figure 3a). Both models are able to reproduce the pattern of
SSH variability. Important to mention that for both models and observation,
the SSH variability have been computed by removing the seasonality. How-
ever SWIM (Figure 3b) appears to exaggerate the level of variability in the
centre of the channel compared to observations, while in HYCOM (Figure 3c)
these are slightly under-represented. For SWIM, the overestimation of the
SSH variability appears to have an influence on the observed overestimation
of the mean amplitude and diameter of the anticyclonic eddies (Table 1),
suggesting that the anticyclonic eddies dominates the signals of the mean
SSH. On the other hand for HYCOM, the underrepresentation of the vari-
ability appears to have an influence on the observed underestimation of the
mean amplitude and diameter of the cyclonic eddies (Table 1). In terms of
their spatial spreading, SWIM appears to overestimate the variability in the
northern part of the channel, which seems originated in the northern tip of
Madagascar, and propagates into the channel. On the other hand, to the
southeast of the channel (south of 20°S), both SWIM and HYCOM appears
to underestimate the spatial spreading, which may suggest that the models
reproduce fewer eddies in this part of the channel.

The typical vertical structures of the eddies simulated by the two ocean
models (Figure 4) are in good agreement with observations (de Ruijter et al.,
2002; Ridderinkhof and de Ruijter, 2003). The same is true for the models
used by van der Werf et al. (2010). Anticyclonic eddies observed at 17°S, are
known to be wider, over 300 km, and have a strong barotropic signal, reaching
the channel bottom, near 2500 m depth, with swirling velocities around
0.1 ms⁻¹ (de Ruijter et al., 2002; Ridderinkhof and de Ruijter, 2003). This
is also the case for the eddies reproduced by SWIM and HYCOM (Figure
4). It is likely that these eddies obtain their barotropic signal due to their
mechanisms of formation. In the ocean models, the formation of the Mozam-
Mozambique Channel eddies have been related with the barotropic instabilities in the South Equatorial Current, at the northern tip of Madagascar (Biastoch and Krauss, 1999). Recent modelling studies have shown that the formation of the anticyclonic eddies in the narrows of the channel are also related to variability in the transport of the South Equatorial Current, at the northern tip of Madagascar (Backeberg and Reason, 2010). In-situ observations have revealed that the formation of the anticyclonic Mozambique Channel eddies at the narrows of the channel are related with a separation of a poleward flow from the coastline, near 16°S (Ridderinkhof and de Ruijter, 2003; Harlander et al., 2009).

The pattern of the tracked anticyclonic eddies agrees well with the SSH variability patterns of Figure 3. This suggests that the anticyclonic eddies are responsible for most of the SSH variability. The trajectories of the anticyclonic eddies on the western side of the channel indicate that they are steered by topography. On the other hand, cyclonic eddies predominantly occur at the edges of anticyclonic eddies, suggesting that cyclonic eddies are spun up by anticyclonic eddies. They propagate closer to the coast, suggesting they are shallower than the anticyclonic eddies.

Throughout the channel, it appears that there are several eddy generation sites (Figure 5a): In the north, around the Comores Archipelago, between Madagascar and Africa, around 12°S, appeared to be a favourite place for anticyclonic eddy formation. In the centre of the channel, near 20°S, 43°E, also appeared to be a site favouring anticyclonic eddy formation. To the
south of the tracking domain, also anticyclonic eddy generation site was evident near 23°S, 43°E. This pattern is also evident in the ocean models, but less in SWIM than in HYCOM. This may be due to the higher resolution, and longer timeseries of the HYCOM configuration.

In the north, the generation site identified around the Comores Archipelago, near between Madagascar and Africa, around 12°S, found in Figure 5 is in agreement with the eddy formation process discussed in Backeberg and Reason (2010). Positive vorticity (anticyclonic rotation) and shear instabilities are generated at Cape Amber by the friction between the SEC with the coastline (Biastoch and Krauss, 1999), contributing toward the eddy formation process. Although maximum shear occurs at Cape Amber, the eddies are only fully formed and detected to the west of the Cape. Note that to the west of Cape Amber lies the Comores Archipelago, which is made of about 4 islands, extending zonally between Madagascar and the African continent, located in a region of rough topography characterized by shallow oceanic banks. These local features may also influence the generation of the eddies in the region. Cyclonic eddies generated in this region may be induced by the dynamics of the anticyclonic eddies.

The flow field in the northern Mozambique Channel is irregular and complex. Previous studies have shown that generation of Mozambique Channel eddies may be related to the arrival of a train of baroclinic Rossby waves that propagates westwards near 12°S (Schouten et al., 2002), or local generation of barotropic Rossby waves with periodicity of 50 days to 55 days (Schott
et al., 1988). More recently, it has been shown that the anticyclonic eddy formation process may be directly linked with the SEC (Backeberg and Reason, 2010). Positive vorticity anomalies can be traced from Cape Amber to the western edge of the Mozambique Channel, where the eddies form (Figure 5).

From the eddy tracking algorithm, favoured eddy generation sites have been identified in the channel. Cyclonic eddies have been shown to originate mostly along the eastern boundary of the channel. Also a localized site for generation of cyclonic eddies is evident on the western boundary of the channel, near the narrows of the channel \( \sim 16.5^\circ S \). This is consistent with formation of lee coastal trapped cyclonic eddies mentioned by Lutjeharms (2006, see Figure 3.25). Note that this is also a place where the Angoche upwelling occurs (Lutjeharms, 2006).

The cyclonic eddies generated in the eastern part of the central channel propagate southwestward. Origin of cyclonic eddies within the channel may explain the origin of some cyclonic eddies found by Gründlingh (1995); Quartly and Srokosz (2004). This also corroborates Harlander et al. (2009), who suggested that cyclonic eddies in this region could be expected, but weaker and less consistent when compared with the regular presence of the anticyclonic eddies.

The cyclonic eddy formation near the southeastern boundary of the channel is also enhanced, suggesting that these are formed due to turbulence associated with currents interacting with the continental shelf of Madagascar. Furthermore, the tracking algorithm located a number of eddies formed to
the southwest of Madagascar in all three data sets. This is in agreement with previous studies (Quartly and Srokosz, 2004; de Ruijter et al., 2004; Siedler et al., 2009), suggesting that cyclonic eddies are thought to be generated by the friction of the inshore edge of the southern extension of the South East Madagascar Current with the continental shelf, as the current flows past the southern tip of Madagascar. Inspection in the region south of the tracking domain for AVISO, have given evidence that some eddies could be generated outside of the channel, specially at south east of Madagascar, and migrate into the southern Mozambique Channel. This is consistent with previous results by Quartly et al. (2006) and Morrow et al. (2004).

Anticyclonic eddies originated in the northern Mozambique Channel tend to propagate south westwards, following the African coastal bathymetry (Figure 6), in agreement with previous studies (Schouten et al., 2003). These eddies appeared to be large in size, centred around a mean radius of 100 km for AVISO, 120 km for SWIM, and 100 km for HYCOM. This is consistent with an eddy diameter of about 300 km found by Schouten et al. (2003). Figure 7 suggests that these eddies define the second mode of the mesoscale field. On the other hand, anticyclonic eddies generated at the eastern part of the channel, appears to be smaller, centred around a mean radius of about 60 km for AVISO, 70 km for SWIM, and 60 km for HYCOM. These eddies seems to define the peak at smaller scale of the size distribution. It appears to be at similar range size with the single mode distribution in the cyclonic eddy field, for observation and for the models. This length scale is characteristic
of baroclinic instability.

The probability of presence of eddies (Figure 6) closely agrees with Figures 3 and Figure 5. The pattern confirms previous discussion regarding formation sites of eddies as well as their trajectories. AVISO and HYCOM suggest that the secondary anticyclonic eddy generation site (near 20°S, 43°E) is connected with the narrows of the channel, whereas in SWIM such a connection is not evident, probably suggesting an independent eddy formation mechanism.

With regard to the size distribution of the eddies (Figure 7), it is evident that the presence of cyclonic eddies in the channel has been confirmed from both models and satellite altimetry observations. Table 1 indicates that more eddies have been found in HYCOM and less in SWIM, when compared to AVISO. This is likely associated with the higher horizontal resolution of the HYCOM configuration.

Cyclonic eddies appeared to have a modal distribution, and follows the Rossby radius of deformation. The anticyclonic eddies on the other hand appeared to have a bi-modal distribution, suggesting two mechanisms of their formation: Mesoscale oceanic turbulence associated with the Rossby radius of deformation at that latitude, and a mechanism independent of the baroclinic Rossby radius of deformation, similar to Agulhas retroflection eddies, associated with the connection to South Equatorial Current. It is likely that the width of the channel plays a role in limiting the size of the anticyclonic eddies in the narrows of the channel (Figure 4).
5. Conclusion

In-situ observations and two different regional ocean models, covering the greater Agulhas systems, used to investigate eddy properties in the Mozambique Channel, have shown a good agreement in the representation of transport variability at the mesoscale range, but the models have shown to overestimate the lower frequency signals (seasonal cycle), and underestimate the higher frequency signal. These differences in the models could be possibly related to the forcing fields and boundary conditions (for overestimation), and also the subgrid-scale of unresolved processes in the models (for higher frequencies). The overestimation of the seasonal cycle appeared in our case not related to a mis-representation of the mesoscale variability.

Analysis of eddy properties such as number, site generation, pathway, polarity, lifetime and size of the eddies reproduced by the models were also compared against altimetric observations. Both cyclonic and anticyclonic eddies were found to be generated within the channel. Cyclonic eddies appeared to be more abundant, and smaller when compared with the anticyclonic eddies. Though cyclonic eddies seemed more chaotic than anticyclonic eddies, they favoured to be formed along the eastern part of the channel. Anticyclonic eddies appeared to be formed mostly in the northern part of the channel, around 12°S, between Madagascar and African continent. They propagated parallel to the western boundary of the channel, in agreement with previous studies. A novel secondary site of anticyclonic eddy formation in the central Mozambique Channel, at the eastern part of the channel was also identified.
(around 20°S, 43°E).

Analysis of eddy size have shown that cyclonic eddies appeared to have a single mode distribution, with the mean radius centred near the first baroclinic Rossby radius of deformation of the region. Anticyclonic eddies on the other hand, have shown a bi-modal distribution, with the first mode also centred around a typical first baroclinic Rossby radius, and the second mode centred at larger scale around 100 km radius. This is consistent with large Mozambique Channel anticyclonic eddies propagating on top of a background mesoscale oceanic turbulence.
Acknowledgments

The principal author of this work greatly acknowledge the IRD-DSF (France), and the NRF (South-Africa) research grant for the funding provided.
6. Bibliography


Table 1: Eddy properties derived from the tracked eddies. Number of eddies /year (Neddies. year$^{-1}$), mean lifetime ($\bar{\tau}$), mean amplitude ($\bar{\eta}$), and mean diameter ($\bar{L}$).

<table>
<thead>
<tr>
<th>Eddy</th>
<th>N [eddies. year$^{-1}$]</th>
<th>$\bar{\tau}$ [day]</th>
<th>$\bar{\eta}$ [cm]</th>
<th>$\bar{L}$ [km]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Altimetry</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cyclones</td>
<td>24</td>
<td>85</td>
<td>11</td>
<td>139</td>
</tr>
<tr>
<td>Anti-cyclones</td>
<td>19</td>
<td>101</td>
<td>14</td>
<td>157</td>
</tr>
<tr>
<td><strong>SWIM</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cyclones</td>
<td>17</td>
<td>53</td>
<td>9</td>
<td>137</td>
</tr>
<tr>
<td>Anti-cyclones</td>
<td>16</td>
<td>96</td>
<td>21</td>
<td>184</td>
</tr>
<tr>
<td><strong>HYCOM</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cyclones</td>
<td>29</td>
<td>76</td>
<td>6</td>
<td>106</td>
</tr>
<tr>
<td>Anti-cyclones</td>
<td>20</td>
<td>123</td>
<td>12</td>
<td>138</td>
</tr>
</tbody>
</table>
Figure 1: Evaluation of the automatic eddy detection algorithm. Panel a: regions of negative Okubo-Weiss parameter. Panel b: regions enclosed a closed loop of SSH. Panel c: combination between Okubo-Weiss parameter and closed loop of SSH. Panel d: final result of the eddies identified, and selected according to their nature (i.e. cyclonics (blue), and anticyclonics (red). Grey contours in the background corresponds the mean SSH. Data selected for September 15, 2003, as used by Weimerskirch et al. (2004), for comparison purpose.
Figure 2: Transports timeseries across the narrow channel, at 17°S, calculated with reference to the ocean bottom. Negative (positive) values indicate a southward (northward) transport. LOCO (a), SWIM (b), and HYCOM (c). The right panels show their corresponding power density spectra. Gray band indicates the 95% confidence level.
Figure 3: Ocean variability, expressed as root mean square of sea surface heights (cm): AVISO (a), SWIM (b), and HYCOM (c).
Figure 4: Eddy vertical structure at -17°S. See Figure 3a for the section line. Left panel (a) SWIM, snapshot at year4-month2-day22, and right panel (b) HYCOM, at year, month, day. Continuous (discontinuous) isolines indicate poleward (equatorward) flow respectively. Note that the topography in SWIM was not accurately represented due to its relatively lower resolution.
Figure 5: Eddies tracked in AVISO (a), SWIM (b), and HYCOM (c). Anticyclonic eddies (red), and cyclonic eddies (blue). The background contours are isobaths.
Figure 6: Probability of presence of eddies in a box with $\frac{1}{2} \times \frac{1}{2}$. AVISO (a), SWIM (b), and HYCOM (c).
Figure 7: Eddy density distribution. Left panels for AVISO (a,d), middle panels for SWIM (b,e), right panels for HYCOM (c,f). Lower panels for anticyclonic eddies (red), and upper panels for cyclonic eddies (blue).