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# Eddies and variability in the Mozambique Channel

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## Abstract

Between 1995 and 2000, on average 4 eddies per year are observed from satellite altimetry to propagate southward through the Mozambique Channel, into the upstream Agulhas region. Further south, these eddies have been found to control the timing and frequency of Agulhas ring shedding.

Within the Mozambique Channel, anomalous SSH amplitudes rise to 30 cm, in agreement with in situ measured velocities. Comparison of an observed velocity section with GCM model results shows that the Mozambique Channel eddies in these models are too surface intensified. Also, the number of eddies formed in the models is in disagreement with our observational analysis.

Moored current meter measurements observing the passage of three eddies in 2000 are extended to a 5-year time series by referencing the anomalous surface currents estimated from altimeter data to a synoptic LADCP velocity measurement. The results show intermittent eddy passage at the mooring location.

A statistical analysis of SSH observations in different parts of the Mozambique Channel shows a southward decrease of the dominant frequency of the variability, going from 7 per year in the extension of the South Equatorial Current north of Madagascar to 4 per year south of Madagascar. The observations suggest that frequency reduction is related to the Rossby waves coming in from the east.


## 1. Introduction

For some time, there have been doubts about the nature of the flow through the Mozambique Channel. Several sketches of the circulation give different flow patterns: Harris (1972) found the Channel to be dominated by three large anticyclonic eddies and attributed observed variability in the Agulhas water characteristics to the non-stationarity of these features. Sætre and Da Silva (1984) described the circulation in the channel by giving two different flow patterns for the winter and summer seasons, both characterized by several eddies. The discrepancies between their findings and those of Harris (1972), all based on non-synoptic hydrographic observations, seems to have resulted from strong time dependence of the circulation. Extensive hydrographic observations enabled Donguy and Piton (1991) to describe a large anticyclonic circulation filling most of the

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Northern part of the Channel (north of the narrowest part around 17°S). The surface flow in the Mozambique Channel also has been estimated from surface drift observations (Sætre, 1985; Lutjeharms et al., 2000). They also find strong variability, and show a mean circulation with a southward Mozambique Current along the continental slope, and a northward flow in the eastern part of the Channel. This is in agreement with an average over many eddies at different latitudes in the Channel. Gründlingh (1995) analyzed TOPEX/Poseidon altimeter data for the presence of propagating eddies around South Africa. He found numerous anticyclonic eddies to propagate westward from the South Indian Ocean into the Agulhas region, but these could not be followed once they reach the western boundary regime. Several cyclonic eddies from the southern tip of Madagascar and from farther south were seen to become attached to the offshore side of the Agulhas. Gründlingh (1995) found one cyclonic eddy to propagate southward through the Mozambique Channel.

Propagation of anticyclonic eddies through the channel was simulated in a numerical model of the ocean circulation around Southern Africa by Biastoch and Krauss (1999). In their model, eddies are formed by barotropic instability of the South Equatorial Current north of Madagascar, and propagate southward along the coast. Their modeled eddies are strongly surface intensified. The existence and southward propagation of the Mozambique Channel Eddies into the Agulhas source region was confirmed from altimetric data (Biastoch and Krauss, 1999; Schouten et al., 2002b). On reaching the southern Agulhas, they were shown to control the timing and frequency of Agulhas ring shedding into the Atlantic by two mechanisms. First, Schouten et al. (2002b) showed that the eddies may trigger the onset of a Natal Pulse, a large cyclonic meander in the Agulhas (Lutjeharms and van Ballegooyen, 1988a, b). The Natal pulses were shown to precede the shedding of Agulhas Rings by about 180 days (Van Leeuwen et al., 2000). Second, the migration of Mozambique Channel Eddies into the Agulhas Retroflection region may lead to an early occlusion of the retroflection loop (Schouten et al., 2002b). Such an occlusion is associated with the shedding of Agulhas Rings (Ou and De Ruijter, 1986; Lutjeharms and van Ballegooyen, 1988a, b).

In 2000 and 2001, two hydrographic cruises took place in the Mozambique Channel, during the Agulhas Current Sources Experiment (ACSEX (De Ruijter et al., 2000)). This project was aimed at the determination of the sources of the Agulhas Current, both from the north (the Mozambique Channel) and the east (from east of Madagascar). The nature of the flow in the Mozambique Channel was investigated qualitatively in terms of water mass characteristics, quantitatively in terms of transports of these water masses, and dynamically in terms of flow pattern characteristics at the surface and at depth. The dominance of anticyclonic eddies was confirmed by using a combination of in situ CTD and lowered ADCP observations, buoyant drifter tracks and satellite altimetry (De Ruijter et al., 2002). Also, negative anomalies in the altimetric anomalous SSH fields were found to be most likely artifacts of the data handling: 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. Vessel-mounted ADCP current measurements and XBT lines (measuring the upper 400 m temperatures) through the locations of negative SSH anomalies showed no sign of cyclonic dynamic features (De Ruijter et al., 2002). A few cyclones have been observed farther south (Gründlingh, 1995), but these do not seem to originate from the northern Mozambique Channel. Based on in situ observations during the third ACSEX cruise cyclones (paired with anticyclones) have been shown to be generated at the southern tip of Madagascar where the extension of the East Madagascar Current forms lee eddies when separating from the continental slope of the island.

A schematic picture of the circulation in the Mozambique Channel region is shown in Fig. 1. The total westward transport in the region of the South Equatorial Current (SEC), concentrated between 10°S and 20°S, is about 50 Sv (Schott and McCreary Jr., 2001). This flow bifurcates around 17°S, and flows northward in the Northeast Madagascar Current (~30 Sv), and southward

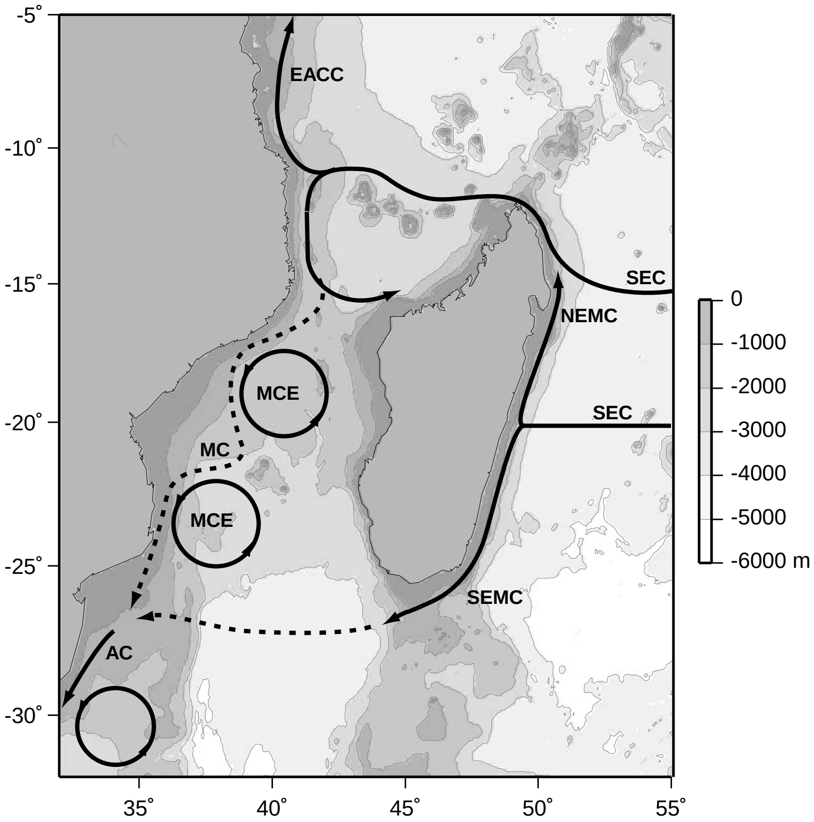


Fig. 1. Bathymetry of the region around Madagascar and the Mozambique Channel. Also, the main currents and flow features are schematically shown. Features shown are the South Equatorial Current (SEC), the Northeast and Southeast Madagascar Currents (NEMS and SEMC), the East African Coastal Current (EACC), the Agulhas Current (AC), Mozambique Channel Eddies (MCE) and the Mozambique Current (MC). The latter has been drawn by a dotted line, as its existence and nature are unclear. The same holds for the connection between the SEMC and the AC, which is possibly formed by eddies formed near the southern tip of Madagascar.

as the Southeast Madagascar Current (~20 Sv) (Swallow et al., 1988; Schott and McCreary Jr., 2001). The extension of the SEC northwest of Madagascar reaches the African coast around 11°S, where it again bifurcates into the northward East African Coastal Current (EACC) and a southward flow into the northern Mozambique Channel. In April 2000, a hydrographic section at 12°S near the African coast yielded a southward transport in this current of about 30 Sv (De Ruijter et al., 2002) of water similar to that found in the EACC. It is unlikely that this strong southward flow is a permanent feature, but its strength shows that the time-varying part of the circulation may have a strong impact on the large-scale transports. Within the Mozambique Channel, the circulation is dominated by large anticyclonic eddies. An average of four of these eddies per year passing southward through the channel leads to an estimate of about 15 Sv southward transport through the channel (De Ruijter et al., 2002). In April 2000, no evidence was found for the existence of a western boundary current along the continental slope (the Mozambique Current, MC), but there may be an extra southward transport associated with this (possibly meandering; Donguy and Piton, 1991) current, consistent with the general southward flow through the channel (DiMarco et al., 2002). The seasonal cycle found in several numerical models (Biastoch et al., 1999; Matano et al., 2001) shows a minimum in southward transport during April. These simulated seasonal fluctuations in the regional model of Biastoch et al. (1999) and the global Parallel Ocean Climate Model studied by Matano et al. (2001) (20 and 12 Sv, respectively) are large compared to the annual mean flow (0 and 12 Sv). In these two models, the seasonal fluctuations in the transport are separated from the eddy occurrence: the seasonal signal is found to be a narrow boundary current along the western boundary, and the frequency of eddy formation remains constant throughout the year. In the observations presented in Section 2 of this paper, we also find no seasonal effect on the formation of the eddies, although the process is rather irregular. It is therefore likely that such a seasonal signal, if realistic, is found in the Mozambique Current, rather than in a modulation of the rate of Mozambique Channel eddy generation. Year long current measurements obtained recently across the narrow section of the Mozambique Channel do not support the existence of a seasonal signal (Ridderinkhof and De Ruijter, 2003).

Recently, a connection between equatorial wind variability and eddy formation in the Mozambique Channel was found (Schouten et al., 2002b). The analysis showed that Rossby waves seem to carry variability originating in the equatorial region across the subtropical gyre, and that the rate of eddy formation within the Mozambique Channel of about 4 per year may be related to this remote forcing. Two spatial bands of variability were found near the 4 per year frequency. We analyzed 6 years of gridded ERS/TOPEX/Poseidon SSH data provided by the CLS Physical Oceanography Division, France (http://www-aviso.cnes.fr). The variability in the 4 per year frequency band may be compared to that in the semi-annual frequency band (Fig. 2). Up till now, only semi-annual and annual signals have often been shown to propagate through the subtropical gyre (Périgaud and Delecluse, 1992; Morrow and Birol, 1998). Fig. 2b clearly shows that the 4 per year variability has a significant amplitude in the Mozambique Channel, and also in the region east of Madagascar. The northern region between 15°S and 10°S is significantly weakened at the Mascarene Ridge (situated just east of the region plotted). East of this ridge, the 4 per year annual signal has an amplitude of 3–5 cm (not shown). This signal, though weakened, seems to propagate through the passage in the Ridge around 13°S (Schouten et al., 2002b). The southern region between 30°S and 20°S shows strong intensification near Madagascar, with amplitudes over 10 cm and relatively small spatial scales.

In this paper, we investigate the formation and propagation of eddies in the Mozambique Channel from satellite altimeter observations combined with in situ observations from the ACSEX programme. First, we explore the SSH observations of the 6 years between 1995 and 2001, to obtain some basic statistics on the number of

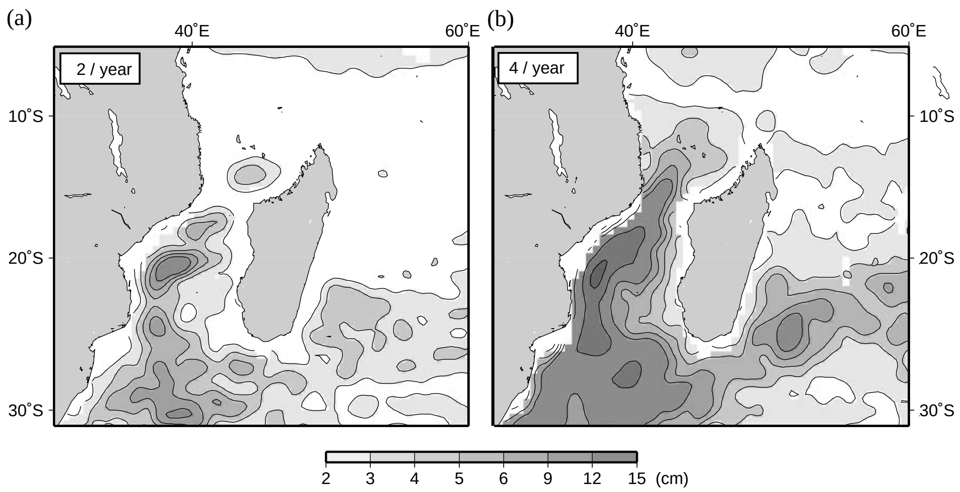


Fig. 2. Variability of 6 years of combined ERS/TOPEX/Poseidon altimeter data in the (a) semi-annual and (b) 4 per year frequency band.

eddies, their dimensions and propagation characteristics (Section 2). Here, we also use the altimeter data to enlarge the timeseries obtained by a moored current meter in the narrow part of the Mozambique Channel, where the passage of eddies into the central part of the channel can be observed from the in situ current observations (Ridderinkhof and De Ruijter, 2003). We then explore the dominant frequencies of the variability in the Mozambique Channel, and then the possible interaction between Rossby waves from the east, the island of Madagascar, and its possible effects on the propagation and merging of anomalies from the north.

## 2. Observations of the Mozambique Channel eddies

In 6 years of combined TOPEX/Poseidon and ERS1/2 altimeter data, eddies in the Mozambique Channel have been tracked by manually following the positive SSH anomalies through the Mozambique Channel. Between 1995 and 2000, 4 eddies per year (on average) were found to propagate from the central Mozambique Channel (15°S) towards the Agulhas retroflection region (35°S, Fig. 3). Sixteen eddies make it all the way into the retroflection region at 35°S (Fig. 4). The eddy paths are rather uniform, and follow the African coastal bathymetry. North of the narrows of the

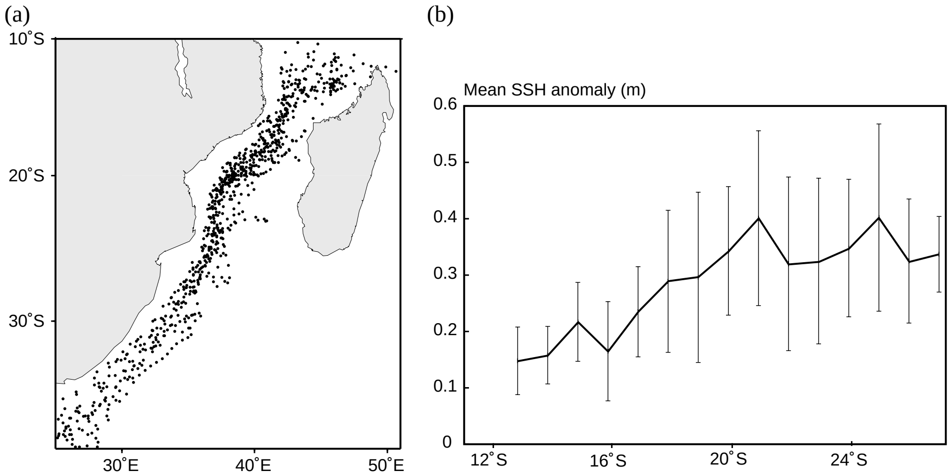


Fig. 3. (a) Paths of 25 Mozambique eddies that were altimetrically tracked between 1995 and 2000. (b) Mean SSH expression of the Mozambique eddies along their way south. The vertical bars show one standard deviation over the observed 25 eddies.

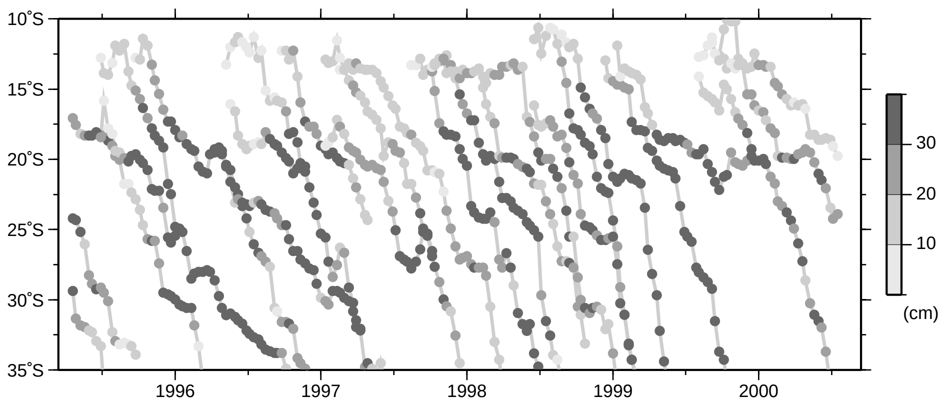


Fig. 4. Time/latitude plot of the 25 eddies observed in the Mozambique Channel over the period 1995–2000. The gray scales denote the maximum SSH anomaly in the center of the eddy (in m). Clearly, this anomaly increases once the eddy has passed the narrow section of the channel. It is not clear whether the anomalies in the north are already eddies, but in the Mozambique Channel it was shown (from surface drifters and in situ observations) that they are (De Ruijter et al., 2002).

channel tracking is often problematic due to interfering anomalies with periods of 50–60 days. Also, smaller features may merge into larger ones, especially in the central part of the channel between 17°S and 20°S. The 0.25° resolution of the gridded dataset does not reflect the resolution that can be achieved by the present altimeter configuration of Topex/Poseidon and ERS. The scales that are well resolved are larger than this 25 km resolution, and closer to several hundred kilometers (Greenslade et al., 1997), especially in our case of (sometimes relatively fast) moving anomalies. The spatial scale of the eddies we are tracking is around 300 km. Consequently, keeping in mind the problems that may arise due to interpolation procedures, it is possible to follow eddies from consecutive snapshots, as has been done here for the Mozambique Channel. Similar studies have been successfully applying Geosat and TOPEX/Poseidon altimetry to investigate rings shed by the North Brazil Current (Didden and Schott, 1993; Fratantoni et al., 1995; Goñi, 2001) and Agulhas Rings in the southeastern Atlantic (Byrne et al., 1995; Schouten et al., 2000). The sizes of these eddies are comparable to those in the Mozambique Channel. Our collection of Mozambique eddy observations enables us to give some statistics about the mean SSH anomalies of the eddies, their size and propagation characteristics. It should be kept in mind, however, that the anomalous SSH deviations we call 'maxima' were obtained after an interpolation, which leads to smoothing and thereby always smaller than the real extrema. They may be considered a lower bound.

The mean maximum SSH anomaly in the center of the eddies is plotted in Fig. 3b as a function of latitude. The eddies appear to strengthen between 12°S and 20°S from 15 to 35 cm. Between 20°S and 30°S, they fluctuate around this 35 cm SSH anomaly. Part of the apparent strengthening between 12°S and 20°S could be accounted for by the latitudinal displacement of the eddy through the planetary vorticity gradient. Moving from 12°S to 20°S, this effect would increase the SSH anomaly of an eddy with constant rotational velocity by 60%. This is less than observed (3b). Moreover, half of this increase should take place between 12°S and 15°S where the potential vorticity gradient is strongest. The observed increase in SSH expression is moderate over this range, and is strongest between 15°S and 20°S. Here, we observe almost a doubling of the anomalous SSH values, whereas the effect of the change in the Coriolis parameter can only account for a 30% increase. The diameters of the eddies are very constant, ranging between 300 and 350 km. The southward propagation speed of the 25 eddies under examination was about 6 km/day between 12°S and 27°S in the Mozambique Channel, with the exception of the region between 18°S and 21°S, where on average the southward propagation was only 3–4 km/day (Fig. 4). Between 27°S and 35°S, the eddies seem to feel the advection by the background inflow into the northern Agulhas, as they speed up to 8–10 km/day.

### 2.1. Vertical structure of the Mozambique Channel eddies

In April 2000, three Mozambique eddies were hydrographically sampled during the first Agulhas Current Sources Experiment campaign (ACSEX I; De Ruijter et al., 2002). Lowered ADCP current measurements for one eddy at 17°S, in the narrowest part of the Channel (Fig. 5) show that the eddy has a strongly barotropic component with speeds over 10 cm/s reaching to the bottom around 2000 m depth. The SSH anomaly that was associated with this eddy was almost 20 cm, determined by satellite altimetry.

State-of-the-art numerical ocean models have met limited success in realistically reproducing the Mozambique Eddies. In the Parallel Ocean Climate Model (POCM) (Semtner and Chervin, 1992), eddies are very regularly shed in the Mozambique Channel. They are strongly surface intensified, with meridional velocities up to 50 cm/s in the upper layers, but with velocities above 5 cm/s only in the upper 1000 m (Fig. 6). The underrepresentation of the barotropic component in modeled eddies as compared to in situ observations has similarly been observed for the eddies of the North Brazil Current (Fratantoni et al., 1995).

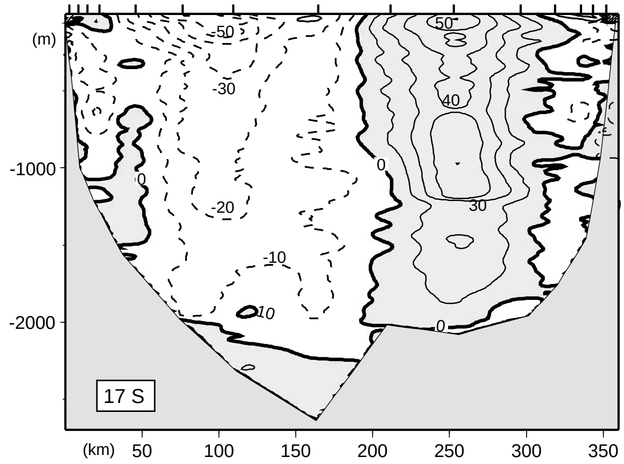


Fig. 5. Velocity section through an eddy taken in April 2000 in the Mozambique Channel near 17°S. Shown are the meridional velocities (cm/s) observed using a Lowered Acoustic Doppler Current Profiler (LADCP). Positive values denote northward flow (from De Ruijter et al., 2002). Station locations are indicated by black bars on top of the figure.

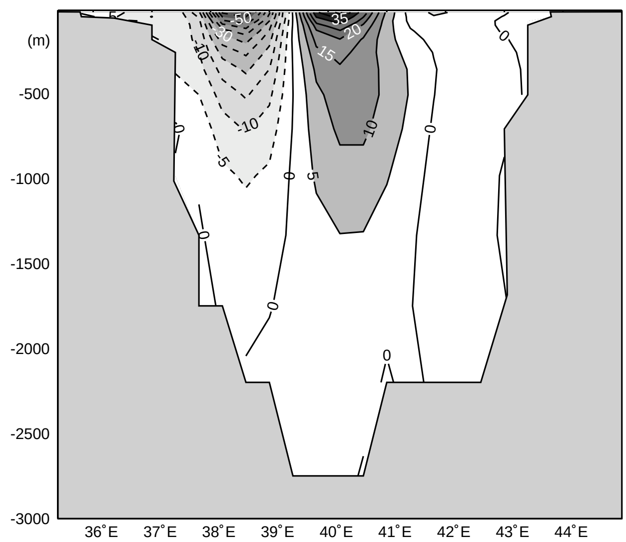


Fig. 6. Velocity section through an eddy in the POCM model in the Mozambique Channel at 19°S. Shown are the meridional velocities (cm/s). Positive values denote northward flow. This simulated eddy has a much weaker barotropic structure than those observed.

Also, the rate of eddy formation is larger in the model than it seems to be in reality: for 12 modeled years between 1986 and 1998, 74 eddies were identified in the channel. This comes down to a periodicity of once every 60 days, comparable to 50 days found in the model of Biastoch and Krauss (1999) and in observations in the South Equatorial Current (Quadfasel and Swallow, 1986). The eddies in the regional model from Biastoch and Krauss (1999) are also concentrated mainly in the upper 400 m, and are formed by barotropic instability of the South Equatorial Current north of Madagascar (Biastoch and Krauss, 1999). Also, earlier studies have attributed the 55 days periodicity found in this region to barotropic instability (Quadfasel and Swallow, 1986; Schott et al., 1988). Recently, Warren et al. (2002) suggested an alternative mechanism for the generation of this signal. They found the Mascarene Basin (east of Madagascar) to exhibit a barotropic eigenmode at almost that period. The difference between the models and observations presented here is in the number of anomalies that enter the Mozambique Channel and travel southward towards the Agulhas retroflection. Also, in both models the barotropic component of the Mozambique Eddies is much weaker than observed.

### 2.2. *Current variability across the narrow section of the Channel*

The passage of four eddies through the narrow part of the Mozambique Channel was documented by an array of moored current meters deployed and recovered during the Agulhas Current Sources EXperiment (ACSEX) I and III campaigns in 2000 and 2001, respectively (De Ruijter et al., 2000; Ridderinkhof and De Ruijter, 2003). We have used data from one of the moorings to verify the altimeter data. The altimeter data were then used to extend the current meter time series to a longer period, and investigate interannual changes. As the present day geoid models cannot resolve the mean state of the ocean at mesoscale resolution, we cannot derive the mean sea surface from the altimetric measurements. Therefore, only the surface current anomalies can be inferred from anomalous SSH gradients.

The geostrophic approximation was used to compute the anomalous surface currents from the combined ERS/Topex/Poseidon SSH fields. These flow anomalies, interpolated to the time of the ACSEX I cruise, were subtracted from the total velocity as determined from the LADCP measurements during the cruise (averaged over the upper 200 m, see Fig. 5). The resulting 'background' flow was then added to the anomalous flow velocity timeseries obtained from altimetry. The sum of these is an approximation of the 'total' surface flow at the location of the CTD/LADCP station.

To check the validity of this method, we have used the, independent, current measurements from a moored current meter. This was done for one of the moorings in the western part of the narrow section of the Mozambique Channel (Fig. 7). Although the amplitudes are distinctly different, the flow directions in general agree very well. The correlation between the flow as measured by the mooring and by the altimeter (under geostrophic assumption) is high: 0.83 and 0.79 for the zonal and meridional velocities. The amplitude of the flow at the moored current meter is lower than that of the combined altimetry/LADCP observations, because the latter is a measure of the surface flow and the current meter measurements were taken at a depth of at least 250 m. Usually, the current meter was measuring even deeper than 250 m, as the flow pushes the moored current meter downward, especially during the eddy passages when strong currents occur. As velocities decrease with depth (see Fig. 5), this leads to a systematic underestimation of the current speed. The current speeds measured by the current meter are about one-quarter of those at the surface, which is in agreement with the strong intensification of the velocity towards the surface that is shown in Fig. 5.

Apparently, the altimeter estimates combined with the background flow determined from the LADCP observations represent the surface flow reasonably well. This makes it possible to extend our analysis period from the 1 year of the moored current meter array, to several years when the combination of TOPEX/Poseidon and ERS1/2 satellite altimeters has been operational. We do not attempt to estimate the currents for the period before 1996, as the Topex/Poseidon measurements by themselves have too little spatial resolution to adequately resolve the eddies in this region (there is only one ascending, and one descending track crossing the narrowest section of the channel, and the mooring location is in the middle of a diamond-shaped region between tracks). The resulting longer timeseries obtained from the altimeter data, is shown in Fig. 8.

These altimetry data show that the number of anticyclonic eddies passing through the narrow part of the Mozambique Channel is irregular over the years: from 5 in 1997, 1999 and 2000, down to

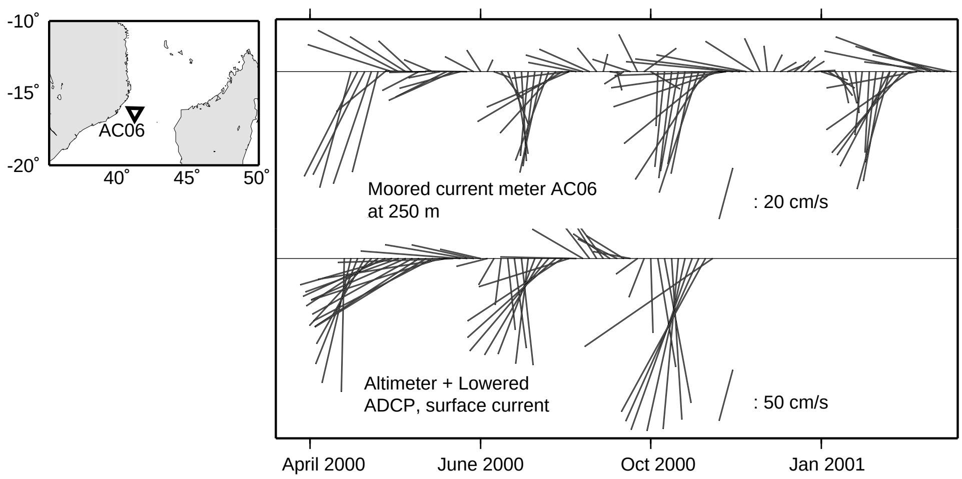


Fig. 7. Current measurements from mooring AC06 (upper line, see left panel for the location of the mooring) compared to the result of the LADCP-referenced geostrophic currents measured by altimetry (lower line). There is good qualitative agreement between the two: the passage of anticyclonic vortices (of which the western half passes by the mooring) is evident from the clockwise rotation of the velocity vectors. Although the surface intensification is considerable, the eddies have a notable barotropic component.

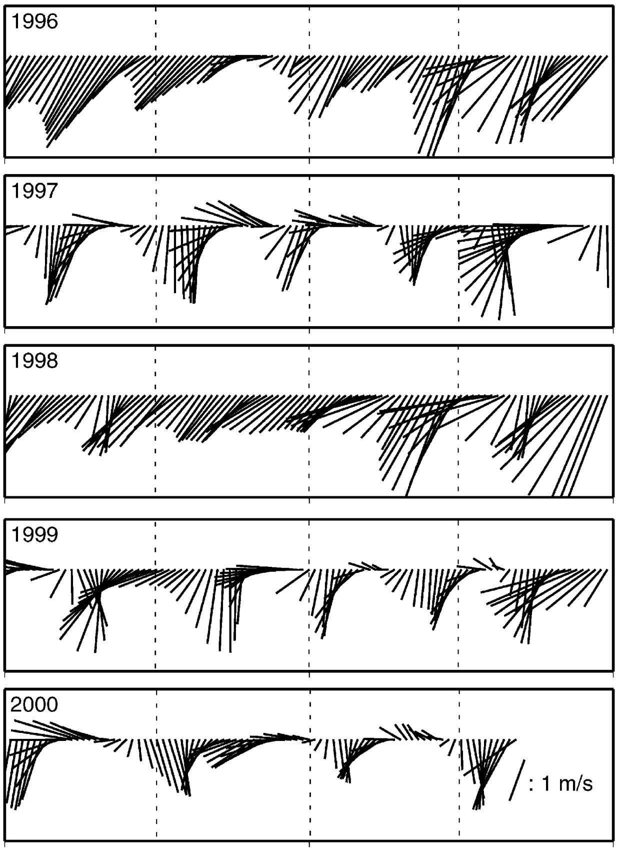


Fig. 8. Like the lower panel of Fig. 7, but now extended to almost 5 years of combined TOPEX/Poseidon and ERS1/2 measurements. Velocity fluctuations at the 5 per year frequency are dominant, mostly related to passing eddies. During the first halves of 1996 and 1998, no eddies were formed in this region.

only two in 1998. Extended periods without eddies also appeared in the first halves of 1998 and 1996, but also these periods show velocity fluctuations at a frequency of 5 per year.

## 3. Southward reduction of the dominant frequency of variability

The main source of variability in the region north of Madagascar is probably the barotropic instability of the South Equatorial Current, which has a dominant period of 55 days (Schott et al., 1988; Quadfasel and Swallow, 1986). At this point it is unclear why this strong signal is not propagating at that frequency of about 7 per year through the narrows of the channel: in the former section, we have shown that the frequency of the passage of anomalies through the narrows is close to 5 cycles per year. To explore this further, we have computed the average SSH spectrum, by averaging the spectra of all individual points where SSH is observed by altimetry, in three regions in the Mozambique Channel. The three regions and their average SSH spectra are shown in Fig. 9.

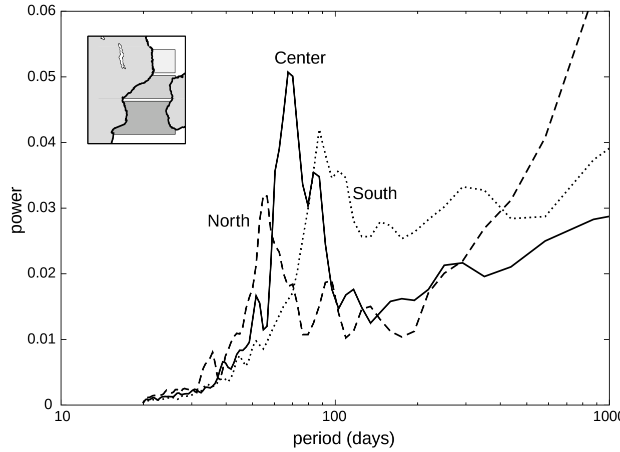


Fig. 9. Average SSH spectra over three regions in the Mozambique Channel. The spectra have been normalized by their total variance (the interannual signal is about the same for the three regions).

The northern region clearly shows a peak in the spectrum at the 55 days period, consistent with the earlier observations (Quadfasel and Swallow, 1986; Schott et al., 1988). However, going southward through the Channel, the dominant, eddy period increases. The southern part of the Channel is dominated by 4 per year variability. The SSH variability in the central part of the Channel lies somewhere in the middle, with a broader peak at frequencies between 4 and 7 per year. This is consistent with the 5 eddies or flow pulses per year that seem to pass through the narrows (Fig. 8). A possible explanation for the slow change of the dominant eddy time scale for these three regions is presented below.

### *3.1. Variability of the Northern region*

We have used altimeter data of a relatively small region between 40.55°E and 16.5°S (so north of the narrows of the Mozambique Channel) to focus on the variability of this specific region. A high-pass filter (a cosine window running mean with a half-width of 200 days) has been applied to remove the interannual and annual components. These are strong in this region (see Fig. 9) and are probably related to the Indian Ocean Dipole and/or El Niño events (Webster et al., 1999).

We have applied the multichannel singular spectrum analysis (MSSA) technique (Plaut and Vautard, 1994) to extract the oscillatory modes of variability for this region from the SSH anomaly fields over the period 1995–2000. This technique is the extension of the widely used empirical orthogonal functions (EOF) technique, and is more capable of detecting propagating signals. MSSA is also known as 'extended empirical orthogonal function (EEOF) analysis', but with MSSA the number of lagged copies to be included in the data-matrix is generally an order of magnitude larger. In EEOF analyses, typically three or four well-chosen lags are included in the analysis. The MSSA technique includes a complete timeseries in the statevector, yielding it spectral properties much different to EEOF analysis (Venegas, 2001). The reconstructed components of an MSSA analysis can be considered strongly band-pass filtered versions of the data, with the narrowband filter properties determined from the data themselves.

We use a window-length of 1 year (37 lagged copies) to ensure the detection of oscillating signals with periods up to 1 year. The resulting eigenvectors (MSSA-EOFs) describe dominant patterns of the dataset, but unlike EOFs they may contain propagating signals. Several MSSA-EOFs with (almost) equal eigenvalues, and out-of-phase patterns and time components (MSSA-PCs) may describe a propagating signal in the data (Plaut and Vautard, 1994) but one has to be careful in interpreting these pairs, as Allen and Robertson (1996) have shown that such pairs may also arise from red noise. The technique enables one to separate several processes (at different timescales) that make up the variability of the dataset, and has been successfully applied in oceanographic research regarding pacific sea surface temperature data (Allen and Robertson, 1996) and in SSH measurements of the North Atlantic Gulf Stream region (Schmeits and Dijkstra, 2000). A detailed description of the MSSA technique, its application and validation of the results can be found in these papers.

Applying the MSSA technique to the SSH anomaly fields over the period 1995–2000 in the region northwest of Madagascar (40–55°E; 16–5°S) yields a limited number of dominant modes:

The first two MSSA-EOFs describe a semi-annual cycle along the northern limit of the region. This semi-annual variability is limited to the equatorial region. As there is no direct connection between this semi-annual variability of the equatorial band and the variability in the Mozambique Channel we do not discuss it here. The second and third pairs of eigenvectors (3–4 and 5–6), however, seem to describe oceanic signals which are of relevance to the variability inside the Mozambique Channel.

The dominant period of the second pair (3–4) is 55 days, a period that has been found to dominate the variability of the South Equatorial Current north of Madagascar (Quadfasel and Swallow, 1986). We will refer further to this mode as the 7 per year mode. The first two EOFs of this oscillatory mode, describing it almost completely (Figs. 10a, b), show westward propagating

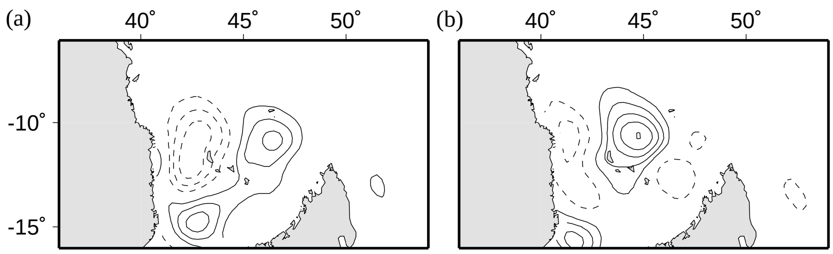


Fig. 10. First two EOFs of the 55 days MSSA mode of the SSH anomalies (a and b) for the region shown. Positive (negative) values are indicated by solid (dotted) contours. The spectrum of the timeseries associated with these EOFs is plotted in Fig. 12.

wave-like features in SSH with a length scale of 400 km west of the northern tip of Madagascar, where the South Equatorial Current separates from the island and flows westward as a free jet. The amplitude of these first two EOFs is fully concentrated in the region between Madagascar and the African continent, north of the Comores Islands at 12°S. As they have very little amplitude east of Madagascar, this 55 days mode most likely describes a regional phenomenon, related to the barotropic instability of the free jet (Schott et al., 1988; Biastoch and Krauss, 1999).

The third pair of MSSA modes that form an oscillatory signal in the Northern region of the Mozambique Channel contains variability of longer period. Its spectrum is dominated by frequencies centered around 5 per year (see Fig. 12 for a comparison of the spectra of the 5 and 7 per year mode). Fig. 11 shows the two dominant EOFs of this 5 per year mode. They show propagating anomalies entering the Mozambique Channel through the narrows, consistent with the extended current meter record of Fig. 7.

A secondary maximum in the variability of the 7 per year mode is found near the entrance of the central Mozambique Channel (Fig. 13). This is also the region where the 5 per year mode has its maximum amplitude. The two modes are thus not completely separated, and cannot be considered fully apart from each other. A possible reason for this secondary maximum is that anomalies in the SEC extension cause anomalous transport close to the African coast, which might not be captured by the altimeter measurements. Two years of continuous current meter measurements at the mooring section along 17°S show indications of this 7 per year variability added to the dominant 5 per year signal of variability (Ridderinkhof and De Ruijter, 2003). The pattern of variability of the 5 per year mode also suggests a connection between anomalies east and west of Madagascar.

### 3.2. Variability of the Central region

The 5 per year frequency present in the dominant MSSA modes of the northern region is also the frequency with which anomalies were observed to pass through the mooring array at 17°S (Fig. 8). It is therefore likely that this is also the frequency at which the anomalies are passing through the central part of the Channel.

Unlike the region further north, the central part of the Mozambique Channel shows rather regular variability. The main process causing the variability here is the passage of eddies from North to South. As this process is well captured by the first two EOFs of the high-pass filtered data,

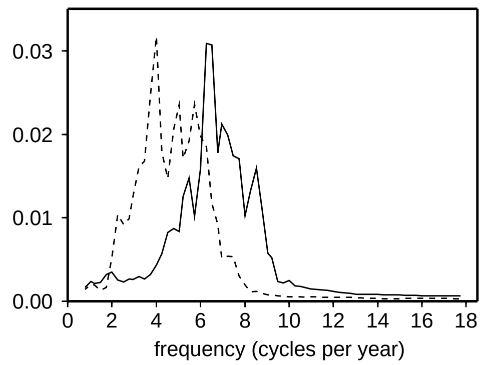


Fig. 12. Frequency spectra of the principal components of the 7 per year eddy mode (solid line) and the 5 per year mode (dotted line) in the northern region of the Mozambique Channel (see Fig. 13 for the region).

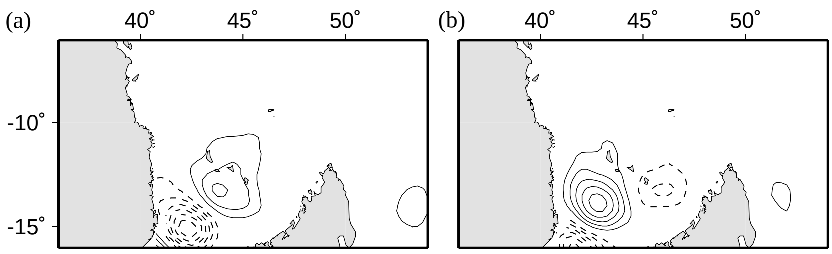


Fig. 11. First two EOFs of the reconstructed MSSA mode with a dominant frequency of 5 per year (a and b). The spectrum of the timeseries associated with these EOFs plotted in Fig. 12.

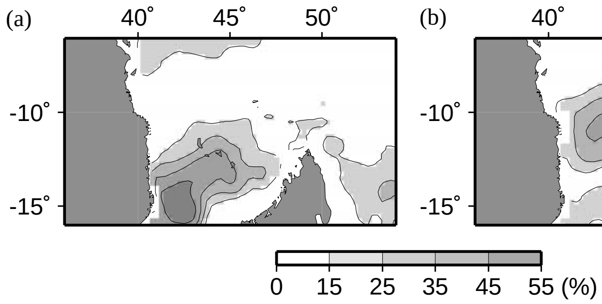


Fig. 13. Variability of the 5 per year (a) and 7 per year (b) MSSA components for the region shown, divided by the total variance of the high-pass filtered SSH data. The 7 per year variability is mainly confined to the region north of the Comores islands, whereas the 5 per year modes shows the propagation into the central Mozambique Channel. Also, the 5 per year mode shows more variability east of Madagascar, with values over 15%.

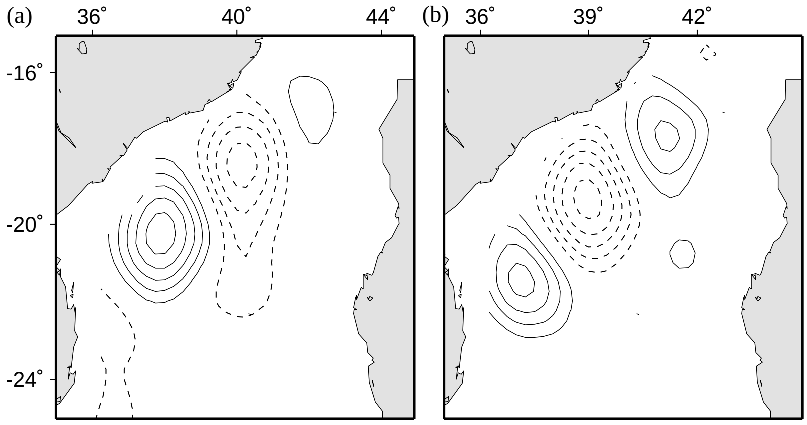


Fig. 14. First two EOFs of the high-pass filtered SSH data for the central Mozambique Channel. Anomalies propagate in southwestward direction, at a frequency of about 5 per year. The spectrum of the associated time series is plotted in Fig. 15.

there is no need to apply the MSSA analysis, which was needed in the north to separate the two dominant modes of variability that make the variability there more complicated than it is in the central region.

The first two EOFs of the high-pass filtered SSH data (Fig. 14) both explain almost 15% of the variability, and together show the southwestward propagation of SSH anomalies through the central part of the Mozambique Channel. In situ observations, including drifters, have shown that the positive anomalies correspond to anticyclonic eddies (De Ruijter et al., 2002). The spectrum of the timeseries corresponding to the EOFs (Fig. 15) shows a rather broad peak centered around 5 times per year and resembles that of the 5 per year MSSA mode from the analysis in the north (reproduced in Fig. 15).

## 4. Dominant variability around Madagascar

South of 20°S, there seems to be a further reduction in the number of eddies: not all eddies present in the central part of the Channel propagate southward. The altimeter data suggest that some eddies dissipate around 20°S, while others are observed to merge into larger structures. Also, propagation of the above described eddies occasionally slows down considerably around this latitude (see Fig. 4).

Statistical techniques fail to produce a clear picture of these processes, as the variability here is too non-stationary and diverse to get statistically significant results. Nonetheless, an MSSA analysis of the complete Mozambique Channel and its surroundings may give a clue as to what processes may be involved in the reduction of the eddy frequency along the channel. The first couple of MSSA modes (1–2) show the eddy propagation in the central part of the channel (Fig. 16). South of Madagascar this mode shows enhanced variability. The second couple of MSSA modes with frequencies around 4 per year (5–6) (Fig. 17) shows the 4 per year variability that is dominant in a band across the southern Indian Ocean around 25°S (see Fig. 2 and Birol and Morrow, 2001; Schouten et al., 2002a) reaching Madagascar. South of Madagascar, this mode shows formation and (south) westward propagation of anomalies. Within the Mozambique Channel, it shows large meridionally elongated structures that propagate westward over the full meridional extent of the Channel. The incoming Rossby waves from the east, along the southern band of variability, and maybe also from the northern band of variability around 12°S (Schouten et al., 2002a and Figs. 2 and 13), seem to connect to these elongated anomalies inside the Mozambique Channel. If and how these elongated structures play a role in the reduction of the number of anomalies from the initial 7 per year in the very north to 4 per year in the south remains unclear.

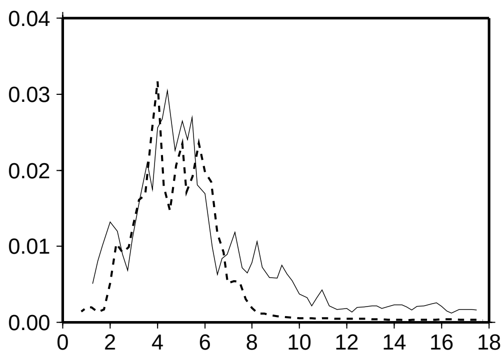


Fig. 15. The spectrum of the principal components shown in Fig. 14 (solid line), together with the spectrum of the 5 per year MSSA mode of the northern region shown in Fig. 11 (dotted line).

The meridionally elongated anomalies are also observable in the original data: Fig. 18 shows a sequence of SSH anomalies in the Mozambique Channel region for February and March 1996. A meridionally elongated anomaly (with anomalous SSH values of over 10 cm) has left the coast of Madagascar in February. A month later (right panel), it has merged with the eddy at (39°E, 20°S) resulting in a strengthening of the eddy in the central Mozambique Channel. This might (partly) explain the rather weak correspondence between the occurrence of anomalies in the central Mozambique Channel, and that of the anomalies in the north. It also may be an example of a process of reduction of the number of anomalies and the associated merging and synchronization of the signals propagating from the north and east (Schouten et al., 2002b).

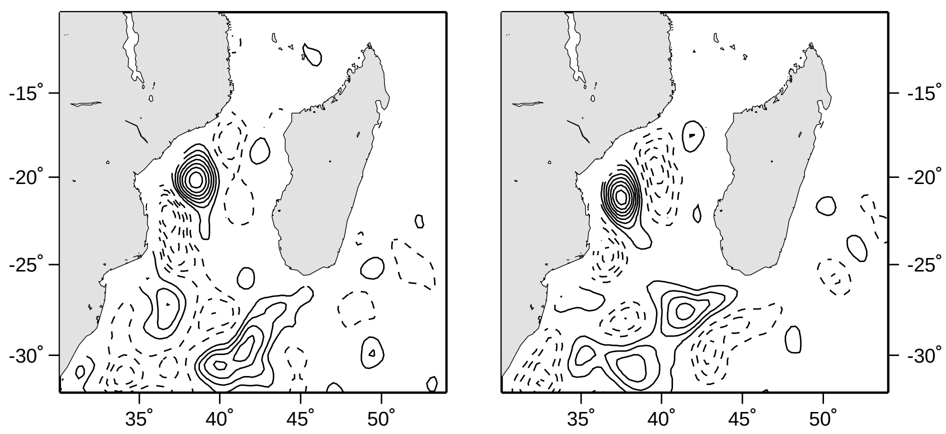


Fig. 16. Two EOFs (together representing over 80% of the variance of the MSSA reconstructed component) of the first MSSA mode of 6 years of SSH data, with a frequency around 4 per year. Most of the eddy propagation signal through the central Mozambique Channel (see Fig. 14) is contained in this mode, as well as westward propagation of anomalies south of Madagascar.

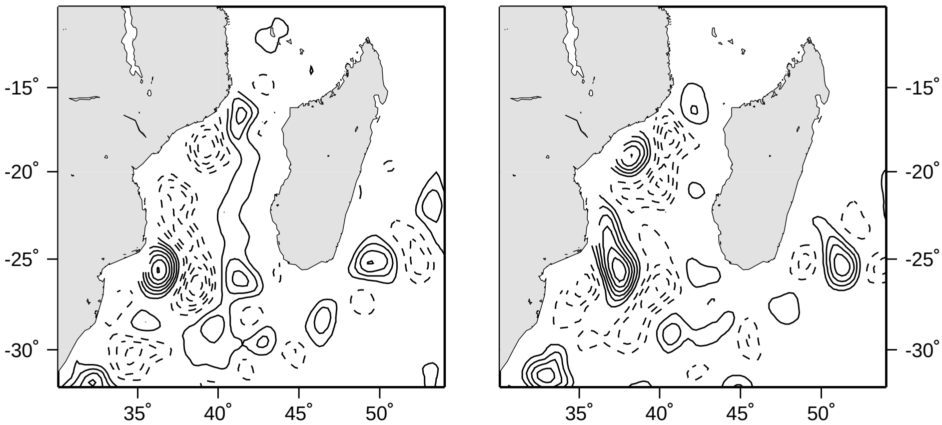


Fig. 17. Like Fig. 16, but now for the second MSSA mode with frequencies around 4 per year (mode 5/6). Here the incoming anomalies from the east (between 20°S and 27°S) can be observed. The southern part of the propagation of the Mozambique eddies, south of roughly 22°S, is captured by this mode. Also, meridionally elongated features are observed in the Mozambique Channel propagating westward from the coast of Madagascar.

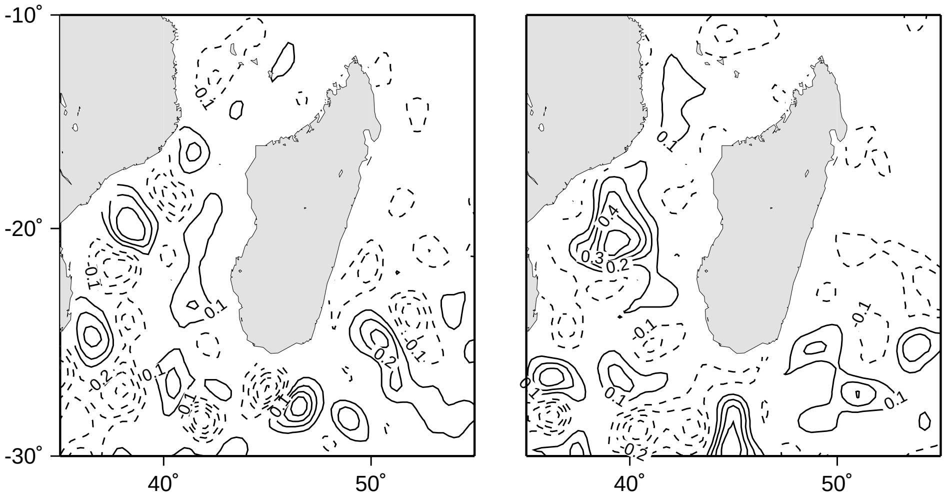


Fig. 18. Anomalous SSH elevations for February and March 1996 (contours are 0.1 m apart, the 0 m contour has been left out). In February (left panel), a meridionally elongated anticyclonic feature is initiated from the west coast of Madagascar. A month later (right panel), the eddy already present in the channel, and the elongated anomaly, have merged into a stronger Mozambique Channel eddy.

## 5. Summary and discussion

A compilation of 6 years of altimeter data analyzed for the existence and propagation of anticyclonic eddies in the Mozambique Channel shows that about 4 of these eddies per year propagate southward through the channel. The average SSH anomaly associated with these eddies increases from 20 cm in the northern part of the Channel, to 35 cm in the central and southern regions. This increase is more than can be accounted for by the gradient of the potential vorticity field.

The vertical structure of an in situ observed Mozambique Channel eddy has been compared to that of an eddy in the POCM model. The model seems to generate eddies with realistic horizontal scales and surface velocity, although the number of eddies generated is too high, and the eddies are too strongly surface intensified. Both this surface intensification and unrealistic frequency are likely simulated by the model of (Biastoch and Krauss, 1999).

Moored current meter observations in the narrow section of the channel near 17°S show the passage of three eddies. This timeseries agrees well with an estimate of the surface velocities from a combination of altimeter-derived anomalies velocity and a LADCP-derived background flow. Using this technique, we extended the timeseries to 5 years, showing intermittency in the passage of eddies through this region.

An attempt has been made to describe the variability in several regions around Madagascar, and to explain the observed reduction of the number of anomalies found in the north (7 per year) to about 4 in the south.

Northwest of Madagascar, the instability of the extension of South Equatorial Current (Schott et al., 1988) seems to result in large westward propagating anomalies of the SSH, most likely associated with meandering of the current. This 7 per year signal seems not to dominate the variability that propagates southward through the Mozambique Channel. About 5 strong anomalies per year do enter the Channel from the north. Once within the Mozambique Channel, their frequency is further reduced, while the eddies become more energetic. Even less eddies leave the Mozambique Channel southward and propagate into the Agulhas Current region. South of Madagascar, in situ observations have shown eddy pairs to be generated. These propagate southwestward while interacting in a complicated fashion with the Mozambique Channel eddies.

A factor determining the transmission of Rossby waves 'through' an island, is in the integral constraint on the islands' streamfunction. The demand of pressure continuity around the island gives that only one streamfunction value can exist at the island. An incoming Rossby wave pattern should fit within this boundary condition on the island. As a result, a wave emanates from on the western side of the island (Pedlosky, 2000).

The direct correspondence with theoretical studies (Pedlosky and Spall, 1999; Pedlosky, 2000) may be non-trivial, as we are dealing with a dispersive wave field impinging on the island, and not with a beta plane. However, the 4 per year forcing by Rossby waves from the east seems to result in the formation of elongated westward propagating anomalies over the full meridional extent of the Mozambique Channel. The associated 4 per year fluctuation in the total southward flow through the channel may form the large-scale modulation that controls the reduced number of eddies that enter the Mozambique Channel. In the north, the link between the SEC anomalies and the formation of eddies may be dependent on the strength of the southward background flow. The modulated southward advection of the anomalies (conserving potential vorticity) may result in eddy formation around 16°S (Ridderinkhof and De Ruijter, 2003). This may explain the high number of eddies found in the POCM model: this model also has a stronger mean and seasonal southward flow (other than that formed by eddy propagation) than is observed in the observations.

Further study of observations, combined with theoretical analysis and supported by numerical simulations is necessary to unravel the complex interactions between Rossby waves and eddies in this complex region around Madagascar and the Mozambique Channel.

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