Beyond the Superficial: Delving deeper into the currents around Madagascar

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Introduction

The Retroflection Question

The Agulhas Current has a retroflection to the south of S. Africa, where the deep fast-flowing western boundary current (WBC) turns back on itself due to its gain in relative vorticity on moving southward. The mean pattern is not fully stable, with the retroflection point progressing westwards until meanders cause the occlusion ("pinching off") of an Agulhas Ring.

Similar behaviour has been hypothesised for the East Madagascar Current (EMC). The region south of Madagascar is relatively cloud-free, with thermal (infra-red) and chlorophyll (ocean colour) images sometimes showing complex contortions of the flow. Lowered ADCP sections in this region during ACSEX 2 showed some recirculation near the surface. But was this one-time survey typical of the mean flow in this location?

2006 and all that!

Quartly et al. (2006) declared that individual images were misleading and that multi-plots or animations showed that eddies moving through the region temporarily wrapped EMC waters around themselves, but that there was no permanent eastward flow with which to connect. They termed the spurious feature a "retro-fiction".

Siedler et al (2006) showed the mean flow pattern from altimetry had a retroflection and an eastward current, the South Indian Ocean Countercurrent (SICC). However at least 5 years data were needed to show the feature and the mean retroflection was ~300 km southwest of where previously thought, with the return current having to negotiate the Madagascar Ridge.

In April 2006, the MadEx II cruise recovered three moorings along a TOPEX/Jason altimeter track to the south of Madagascar. Their 14-month record was then the longest deployment in the EMC, and the only one at the south of Madagascar, where the "retroflection" is seen.

Surface Drifters

Collation of occasional drifter data spanning almost two decades does not provide sufficient coverage to give an unequivocal view of the flow. In the mean, an East Madagascar Current flowing southward along the coast and then WSW towards S. Africa is clear. However the interpretation of other patterns is somewhat subjective.

References

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Cruises

MadEx & MadEx II

MadEx (Madagascar Experiment) in Jan-Feb 2005 surveyed many sections running into the south coast of Madagascar, using CTD, ship-mounted ADCP and SeaSoar (a towed undulator that samples the top 300m or so). All the sections across the EMC showed it to be deep (the ship-mounted 75 kHz ADCP recorded it down to ~700m), whilst the eastward flow further south was only in the top 150m. Three moorings were laid along the TOPEX/Jason altimeter path. Moorings were recovered (and further CTD stations done) during MadEx II (Mar-Apr 2006).

Survey of TOPEX track

The SeaSoar survey along the altimeter line showed a depression of the salinity maximum and isotherms consistent with anticyclonic circulation. There was no clear change in the depth of the deep chlorophyll maximum (shown by the fluorescence). The bottom plot shows the cross-track velocities from the 75 kHz ADCP.

51˚E section

After a major detour to Réunion, a section was run across a cyclonic eddy to the southeast of Madagascar. The east and west transports at depth balance out, but in the top 150m there is an excess flow to the east of ~4 Sv (Srokosz & Quartly, 2012).

Moorings

Deployment

The moorings were placed south of Madagascar in waters of depth 1600m to 2400m, with the northern and southern moorings featuring an upward-looking ADCP at 500m depth to help survey the velocity structure of the top of the ocean. The middle mooring had standard combined CTD / current meters to allow some record of the temperature and salinity changes. Both moorings with ADCP ended up in deeper water than intended, with the ADCP units at ~580m, so their 500m range did not quite reach the surface. Indeed all three moorings suffered significant bouts of knockdown, with a strong 12-hour component.

Movie available

Movie available

Weekly composites of satellite data, with mean currents (150m) for that period. (top) SST for day 108 in 2005; (bottom) chlorophyll concentration (logarithmic scale) for day 180.

Satellite comparisons

Current vectors were extracted for all three moorings at 150m depth. The inferred currents across the mooring array show a good consistency with the flow directions that would be inferred from infra-red and optical imagery. The mooring currents were used to calibrate the velocities derived from Jason-1 (there are uncertainties in altimetric values due to the incomplete knowledge of the geoid). After this adjustment, agreement is good, but there are a number of short-lasting features that cannot be resolved by the altimeter's 10-day sampling cycle.

Zonal currents at 150m depth on northern, central and southern moorings (blue line) compared with altimetrically-derived geostrophic velocitiesring.

Time series

Hovmöller analysis of the full depth information from the two ADCP buoys shows the northern mooring to have mostly consistent deep flow to the west with occasional reversals. The southern mooring does show the surface flow to be predominantly to the east, with the flow at depth usually being negligible. For both moorings, "events" produce a marked change at all depths; correlation analysis shows the currents at all depths recorded are highly correlated.

Daily average zonal flow from the ADCP units on top of 1st & 3rd moorings, plus associated statistics (mean, median etc.) (top) Northern mooring; (bottom) southern mooring.

Correlation between daily average zonal flows at each depth, (left) ADCP from northern mooring; (right) southern mooring.

Models

Overview

Whilst not perfect, numerical models can be useful to give some insight into the dynamics of the region, especially when there are so few hydrographic observations. These panels focus on the zonal velocity in two significantly different models. Both examples shown are from 0.25˚ runs performed at NOC. Although both OCCAM (top row) and NEMO (bottom) are layer models, they were configured on different grids, and experienced different forcing fields

The left-hand panels show the 5-year mean for each model (at ~25m depth), with some zonal coherence apparent. OCCAM shows some latitudes to have a mean eastward flow of about 0.1 m/s, but such a feature is less clear in NEMO. The second set of panels are Hovmöller diagrams of the flow at 55˚E during those 5 years, revealing that even in models the SICC in intermittent, holding latitude for 6 months at a time.

These panels show vertical sections of the mean and variability in the zonal flow at 48˚E and 55˚E. In the model the eastward flow is only in the top 150m, but by 55˚E the cores are not clearly defined

Virtual drifters

Insertion of virtual particles into the NEMO model shows a wide range of possible trajectories. Of those released near the surface more than half exit the region to the west of the Madagascar Ridge; whilst at 181m depth nearly all leave via the western edge of the box.

NEMO's view

Movie available

Pictorial representation of the flow at 25m and 181m shows coherence in the portrayal of the East Madagascar Current as a mini-WBC with large deep anticyclonic rings to the west, but any eastward flow corresponding to the SICC has no analogue at depth. In animations, all disturbances are seen to move westwards, even where the mean flow is to the east recorded are highly correlated.

Conclusions

The evidence for a SICC continues to grow, with both models and occasional in site observations supporting the concept. However, it is shallow and has no strong latitudinal preference. Its role in the irregular summer blooms noted to the east of Madagascar remains uncertain. Models, moorings and satellites show that deep-reaching features propagate westwards at this latitude and produce major "events" to the south of Madagascar. Float releases in both reality and models show that the majority head westward, indicating that the retroflection is not so much an apt dynamical description of the flow as an average state of an eddy-rich flow field