Tracking Mesoscale Eddies within a Regional Model of the Cape Basin

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This study is part of a project that deals with the analysis of the output of numerical models.

This project is founded by the French Navy and it aims at identifying mesoscale eddies with an objective method, time tracking these eddies and evaluating their properties and the mass they transfer.

We maintain web pages about the project at this address.
A numerical model of the ocean region around the South of Africa has been developed on the basis of the ROMS code.

Here shaded colours show the bathymetry of the model domain.

The horizontal resolution is one tenth of degree and allows a good reproduction of mesoscale variability.

The model solution is started from rest and calculated for height years. Model outputs are averaged and stored every 2 days of simulation.

The model forcing was derived from different climatologies: open boundaries conditions are calculated from OCCAM model, wind forcing from Quicksat satellite data, and heat and fresh waters fluxes from the atlas COADS comprehensive Ocean-Atmosphere Data Set.
In order to identify mesoscale structures, horizontal slices of relative vorticity are decomposed with the wavelet technique following a classical approach in image processing.

To do this we use the Wavelab library for Matlab.

As shown here in a fixed area of the model domain, the wavlets allow to identify several structures.

For each structure the center is defined as the point of maximum relative vorticity or minimum velocity.

The criterion is chosen to allow the longest possible tracking.

Some structures are superimposed, a few others are not eddies but rather filaments or meanders.

On the other hand structures as numer 9 and number 11 are well defined cyclonic and anticyclonic eddies and in the following I will show you that we are able to track them.
The wavelets method has been accurately tested with sensitivity analysis and comparison with other criteria for eddy identification.

Here I show you the free surface field of the entire domain of the model and you can observe the signature in the elevation due to the two eddies previously detected.
To track in time the identified eddies, we fixed this criterion, that is in backward direction the eddy center at the time $t$ has to belong to the set of points of the eddy at the previous time.

Here I show you an example of successful tracking: the dot representing the center is always surrounded by the eddy contour.

The backward direction presents the advantage of a simpler initialization.
To establish the vertical extension of an eddy, we adopted a criterion analogous to time tracking.

At each level eddy center must belong to the set of the point of the upper level.

The eddy upper limit is fixed to 200m in order to cut off the model superficial levels, strongly influenced by the boundary condition.

Lower limit instead is fixed on the basis of the position of the salinity anomaly.

In this way at each timestep we know the 3D structure of the eddy.
In this movie I show you the cyclone Asterix.

It initially moves northward and its shape is stretched.

Then it assumes a circular shape and starts to move west-southwestward until it reaches the western boundary of the model.
Wavelet Analysis – 4D tracking

Cyclone ASTERIX

Anticyclone PANORAMIX

<table>
<thead>
<tr>
<th>September to February (spring/summer)</th>
<th>July to October (winter/spring)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Vel = 0.08 [ms⁻¹]</strong></td>
<td><strong>Vel = 0.11 [ms⁻¹]</strong></td>
</tr>
<tr>
<td><strong>Diam= 179 [km]</strong></td>
<td><strong>Diam = 147 [km]</strong></td>
</tr>
<tr>
<td><strong>Vol=15.8 10¹² [m³]</strong></td>
<td><strong>Vol=5.9 10¹² [m³]</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Diameter [km]</th>
<th>120</th>
<th>200</th>
<th>160</th>
<th>190 – 320</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity [m/s]</td>
<td>0.036</td>
<td>0.038</td>
<td>0.046</td>
<td>0.04 – 0.09</td>
</tr>
<tr>
<td>Volume [10¹²m³]</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>11.2 - 33.8</td>
</tr>
</tbody>
</table>

Divergent pathways [Morrow et al., 2004]

Here I resumed the analysis of the two eddies we tracked.

The volume is shown each month.
On the bottom is reported the eddy center trajectory.
Color represents the time, in blu young eddies, in red old eddies.

In little bit more than five months the cyclone moves westward with a mean velocity of heigth centimeters per second. 
Its mean diameter is and mean volume is

The anticyclone is followed little less then four months.
It moves northwestern going around the Vema seamount.
Doing this the eddy interacts with the sponge layer at the western boundary of the model.
Consequently analysis is less accurate.
In any case, the estimated mean velocity is
Its mean diameter is and mean volume is

This values are compatible with field data.
Also the divergence in eddies pathways is observed in satellite and drifter data.
Knowing velocity, volume and diameter, we can calculate an instantaneous transport of the eddy with this formula.

\[ T_r = v \cdot V \cdot D^{-1} \]

Time series of instantaneous eddy transport show modulations in time mainly driven by the changes in velocity.

Cyclone transport is always larger than anticyclone one.

For Asterix the error is equally distributed on the three variables used to derive transport.

For Panoramix instead the error is mainly due to the poor estimation of the volume during central period, when eddy interacts with the seamount.

Time averaged transport is 0.69 SV for cyclone and 0.41 for anticyclone.
Knowing the volume of the eddy, we can disseminate it with lagrangian particles using ARIANE toolkit.

We integrated backward in time.

The trajectory show that particles are trapped within the eddy and follow the trajectory as the one detected with the wavelet analysis, here represented by the blak line.

This is a robust validation of the ability of the wavelets analysis to track eddy cores within the time.
Integration lagrangian particles trajectories for 3 years we obtain an estimation of remote origins of water trapped in eddies.

Here isolimes correspond to the general features of the movement of all particles. About 45% of the cyclone particles come from Agulhas current, while about 40% come from Atlantic.

For the anticyclone the percentage of particles originating from the Agulhas current increases, while Atlantic water contribution decreases.

The differences between this two different origins partially explain the cold and fresh anomaly of the cyclone as well the warm and salty asignal carried by the anticyclone.

Nevertheless the high percentage of Agulhas origin is surprising.
Lagrangian particles - *Remote Origins*

**Agulhas origin**

<table>
<thead>
<tr>
<th>Cyclone ASTERIX</th>
<th>Anticyclone PANORAMIX</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \langle t \rangle = 427 ) days</td>
<td>( \langle t \rangle = 361 ) days</td>
</tr>
<tr>
<td>( \langle z \rangle = 670 ) m</td>
<td>( \langle z \rangle = 478 ) m</td>
</tr>
<tr>
<td>( \langle T \rangle = 10.2 \degree )C</td>
<td>( \langle T \rangle = 13.2 \degree )C</td>
</tr>
<tr>
<td>( \langle S \rangle = 34.85 ) psu</td>
<td>( \langle S \rangle = 35.01 ) psu</td>
</tr>
</tbody>
</table>

Thus we studied in more details the Agulhas origin.

We founded that the anticyclone particles are the fastest to connect the agulhas current to the western domain.

In fact, the mean age of the cyclone particles is 427 days against 361 days for the anticyclone.

So, the cyclone particles spend more time in the Cape Cauldron mixing with the ambient water.

Furthermore cyclone particles in the Agulhas current are deeper, colder and fresher than anticyclone ones.
In summary we can say that

the wavelet analysis proved successful in tracking eddies;

tracked model mesoscale eddies present realistic dynamics;

wavelets+lagrangian diagnostics offer estimates of eddy mass transport and origins;

Despite the robustness of our result we have noted two warnings:

our model domain was too narrow and eddies too soon interacted with western boundary.

Furthermore the OCCAM open boundaries conditions doesn't represent perfectly the temperature and salinity distribution.
To resolve these problems we have now new runs with a larger domain, extending in longitude until 10 degree west, and a new open boundary conditions.

Recently we have already tracked 2 very nice eddies.

One anticyclone tracked for 11 months and a cyclone tracked for 7 months.
A quick look at the anticyclone shows a very realistic stratification with respect to measurements effectued by Schmid et al. 2003.

So, analysing this data, we hope to answer to several questions such as

- Which mixing with the ambient waters?
- Which interaction with other mesoscales features?
- What happens at the Walvis Ridge?
OUTLOOK

AND...
what about cyclones?

And what about cyclones that are less known.
Wavelet Analysis – transport

\[ Tr = V \cdot \Delta t^{-1} \]

\[ Tr = v \cdot V \cdot D^{-1} \]

\[ D = \max \left\{ \frac{\max \left\{ D^{EW} \right\}}{\max \left\{ D^{NS} \right\}} \right\} \]
Wavelet Analysis – transport

\[ T_r = v \cdot V \cdot D^{-1} \]

Relative errors

\[ \nu_{err} = \frac{\sigma_z(u)}{v} \quad D_{err} = \frac{\max_z \{ D_{EW} \} - \max_z \{ D_{NS} \}}{D} \]

\[ V_{err}(t) = \frac{(z_L - z_L) \cdot A_k}{V} + \frac{4 \Delta x \Delta z \sum_{k=1}^{n_{z}} A_k D_k^{-1}}{V} \]

vertical \quad horizontal
Lagrangian particles - Remote Origins

Inflow Atlantic

Cyclone ASTERIX

Anticyclone PANORAMIX