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## Tracking coherent structures in a regional ocean model with wavelet analysis: Application to Cape Basin eddies

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### Abstract:

This study is mainly aimed at proposing objective tools for the identification and tracking of three-dimensional eddy structures. It is conducted with a high-resolution numerical model of the ocean region around South Africa, and emphasis is put on Cape Basin anticyclones and cyclones thought to be actively implicated in the Indian-Atlantic interocean exchange. We settle on wavelet analysis for the decomposition and processing of successive maps of relative vorticity for a simulation run with ° resolution. The identification of three-dimensional coherent structures comes with the calculation of eddy trajectories and the time evolution of eddy properties. Instantaneous mass transport and momentum of eddies are calculated from the knowledge of instantaneous drift velocities, volumes, and diameters. The success of the regional model and of the analysis technique is assessed through comparisons with equivalent observations.

**Keywords:** Oceanic eddies; regional modeling; wavelet analysis; Agulhas current system; Southeast Atlantic ocean.

## 1. Introduction

31 The Agulhas Current is the most intense western boundary current of the World Ocean,  
32 and its retroreflection shows one of the highest signals in eddy kinetic energy. Mesoscale  
33 eddies and large current rings pinch off from the Agulhas Retroreflection and are usually  
34 associated with an Indian Ocean water leakage to the Atlantic Ocean [*Gordon, 2003*;  
35 *Richardson et al., 2003*]. Satellite measurements in this area allow eddy tracking from sea  
36 surface height (SSH) anomalies [e.g., *van Ballegooyen et al., 1994*; *Goñi et al., 1997*; *Arhan*  
37 *et al., 1999*]. Eddy trajectories can be reconstructed from successive surface elevation  
38 maps and coupled with in situ observations during concomitant cruises [e.g., *Garzoli and*  
39 *Goñi, 2000*]. As pointed out by *Morrow et al. [2004]*, altimetry defines a robust way to  
40 track propagating features provided their typical scales are correctly sampled both in time  
41 and space by remote sensing. However, gaps in knowledge of the full three-dimensional  
42 (3D) identity of anticyclones and cyclones can obstruct more accurate diagnostics like the  
43 mass transport achieved by the eddy field. In this respect, numerical experiments are  
44 often fruitful. A primitive equation model of the Atlantic circulation allowed *Treguier*  
45 *et al. [2003]* to define Agulhas eddies from SSH anomalies with respect to a time mean.  
46 More recently, but for another oceanic region, *Penven et al. [2005]* developed an algorithm  
47 based on the calculation of the Okubo-Weiss parameter to systematize the process of eddy  
48 tracking in the Peru Current System. Indeed, *Okubo [1970]* and *Weiss [1991]* derived a  
49 criterion to separate flows into hyperbolic regions, where strain dominates, and elliptic  
50 ones where vorticity dominates. This criterion has been widely used to analyze numerical  
51 simulations of two-dimensional (2D) turbulence [*McWilliams, 1984*; *Elhmaidi et al., 1993*,

52 among others]. However, as pointed out by *Basdevant and Philipovitch* [1994], the validity  
53 of the criterion key assumption is restricted to the core of the vortices, i.e., the strongest  
54 elliptic regions of the flow. The Okubo-Weiss criterion is, therefore, not fully appropriate  
55 for a decomposition of a flow into background and eddy components.

56 The identification technique developed throughout this study is based on the wavelet  
57 analysis of modeled relative vorticity. Wavelets form an efficient basis set for localized  
58 structures such as ocean eddies. The main advantage of wavelets compared to Fourier  
59 transforms is that the former give information about a function or dataset with respect  
60 to scale and location in contrast to the latter, which provide a one-parameter family  
61 of coefficients representing the global frequency content. For the ocean, *Jameson and*  
62 *Miyama* [2000] applied wavelet analysis to the numerical resolution of Kelvin and Rossby  
63 waves. *Luo and Jameson* [2002] presented an application of wavelet analysis to time-  
64 evolving structures such as eddies and fronts described by numerical modeling or by satel-  
65 lite data. In fluid dynamics, both for numerical simulations and laboratory experiments  
66 [*Ruppert-Felsot et al.*, 2005; *Siegel and Weiss*, 1997, and references therein], the coherent  
67 and incoherent background components of a turbulent flow have been separated with a  
68 wavelet-based decomposition of the relative vorticity field. These successful applications  
69 drove us to apply the wavelet analysis technique used in 2D turbulence to the identifi-  
70 cation of eddies within horizontal slices of modeled relative vorticity. Then, in order to  
71 capture and track the full 3D envelope of each eddy, we developed an original and simple  
72 algorithm based on superimposing structures at different instants and different vertical  
73 levels.

74 Recently, *Boebel et al.* [2003] reviewed the theories proposed in the literature for the  
75 Indo-Atlantic interocean exchange. They limited the concept of “isolated Agulhas Rings  
76 embedded in a sluggish Benguela Drift” to the northwestern Cape Basin and called “Cape  
77 Cauldron” the southeastern Cape Basin, where mesoscale cyclone/anticyclone interactions  
78 result in vigorous stirring and mixing. This region is very appropriate as a field of study  
79 to test our technique with the aim to propose new clues to open questions about the role  
80 of oceanic mesoscale eddies. Our discussion is mainly devoted to four eddies, i.e. three  
81 anticyclones and one cyclone, obtained in a high-resolution numerical simulation of the  
82 ocean dynamics around Southern Africa. Section 2 describes the ocean model, whereas  
83 section 3 reports on the method we developed to identify 3D coherent structures and  
84 follow them as a function of time. In section 4, these structures are compared with those  
85 observed in the area under study, and then we introduce some parameters useful for eddy  
86 characterization. Our conclusions are drawn in section 5.

## 2. Ocean model

87 Our circulation model is based on the IRD (Institut de Recherche pour le  
88 Développement) version of the Regional Ocean Modeling System (ROMS). The reader  
89 is referred to *Shchepetkin and McWilliams* [2003, 2005] for a more complete description  
90 of the numerical code. The model domain extends from 10°W to 34°E and from 50°S  
91 to 25.4°S (Fig. 1). Its grid, forcing, initial and boundary conditions were built with the  
92 ROMSTOOLS package [*Penven, 2003*]. The model grid is  $441 \times 317$  points with a resolu-  
93 tion of  $\frac{1}{10}^\circ$  corresponding to 9 km in mean grid spacing, which allows a correct sampling  
94 of the first baroclinic Rossby radius of deformation throughout the whole area (about  
95 30 km according to *Chelton et al.* [1998]). The horizontal grid is isotropic with no intro-

duction of asymmetry in the horizontal dissipation of turbulence. It therefore provides  
a fair representation of mesoscale dynamics. The model has 32 vertical levels, and the  
vertical s-coordinate is stretched for boundary layer resolution. The bottom topography  
is derived from a 2' resolution database [*Smith and Sandwell, 1997*]. Although a numerical  
scheme associated with a specific equation of state limits errors in the computation  
of the horizontal pressure gradient [*Shchepetkin and McWilliams, 2003*], the bathymetry  
field,  $h$ , must be filtered to keep the slope parameter,  $r$ , as  $r = \frac{\nabla h}{2h} \leq 0.3$  [*Beckmann  
and Haidvogel, 1993*]. All the model external forcings are derived from climatologies.  
At the surface, the heat and fresh water fluxes introduced in the model are extracted  
from the Comprehensive Ocean-Atmosphere Data Set (COADS) [*Da Silva et al., 1994*].  
For the wind stress, a monthly mean climatology is computed from QuikSCAT satellite  
scatterometer data gridded at  $\frac{1}{2}^\circ$  resolution [*Liu et al., 1998*]. The contrast in resolution  
between the thermodynamical and dynamical atmospheric fields gives more weight to the  
dynamical forcing of the region [*Capet et al., 2004; Blanke et al., 2005*]. At the four lateral  
boundaries facing the open ocean, the model solution is connected to the surroundings  
by an active, implicit and upstream-biased radiation condition [*Marchesiello et al., 2001*].  
Under inflow conditions, the solution at the boundary is nudged toward temperature-,  
salinity- and geostrophic velocity-fields calculated from Levitus 1998 climatology (NOD-  
CWOA98 data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from  
their Web site at <http://www.cdc.noaa.gov/>), which is also used for the initial state of the  
model. The geostrophic velocity is referenced to the 2000 dbar level. The width of the  
nudging border is 150 km, and the maximum viscosity value for the sponge layer is set to  
1000 m<sup>2</sup>s<sup>-1</sup>.

119 We run an 11-year simulation with model outputs averaged and stored every 2 days of  
120 simulation. Fig. 2 shows the model-climatology of SSH and barotropic velocity obtained  
121 averaging these fields over the last 8 years of simulation. We find a fair agreement between  
122 simulated and observed circulation patterns [*Richardson et al.*, 2003, their Fig. 5]. A  
123 narrow and intense Agulhas Current flows along the eastern coast of Africa and eventually  
124 retroflects between 15°E and 20°E. In addition to the good reproduction of the meandering  
125 structure of the Agulhas Return Current, the simulation highlights the development of a  
126 high-level mesoscale activity characterized by the generation of Agulhas rings, anticyclones  
127 and cyclones, filaments and meanders (e.g., Fig. 3 and Fig. 4). The vigorous stirring and  
128 mixing processes observed by *Boebel et al.* [2003] in the so-called Cape Cauldron are  
129 well simulated. The model reproduces shear-edge cyclonic eddies in the bight of Agulhas  
130 Bank in good agreement with observed features [e.g. *Penven et al.*, 2001; *Lutjeharms*  
131 *et al.*, 2003]. Moreover, through a recent analysis of the same simulation, *Doglioli et al.*  
132 [2006] diagnosed an Indo-Atlantic interocean exchange of intensity comparable with the  
133 one inferred from observations.

### 3. Eddy identification and tracking

134 From the Wavelab library [<http://www-stat.stanford.edu/~wavelab/>] we developed a set  
135 of MATLAB routines to analyze the circulation calculated by the ocean model. Our  
136 procedure can be decomposed into three steps: wavelet analysis, time tracking and vertical  
137 tracking.

### 3.1. Wavelet Analysis

138 The wavelet analysis consists in the decomposition of a signal under study into orthog-  
139 onal, multi-resolution wavepackets in a way similar to a Fourier decomposition. Such a  
140 technique allows efficient data compression of various signals such as images or sounds. A  
141 wavepacket is a square integrable modulated waveform well-localized in both position and  
142 wavenumber. Since such a method was applied in the past to the extraction of eddies in  
143 2D turbulence [*Siegel and Weiss, 1997*], the reader is referred to this paper for a thorough  
144 discussion about the pertinence and details of the wavelet transform. Here, the wavepack-  
145 ets are used to decompose successive horizontal maps of relative vorticity and to extract  
146 localized structures in space. We also choose the Haar basis, which is an orthonormal ba-  
147 sis of  $L^2(R^2)$  [*Daubechies, 1988, 1992*]. The algorithm in use has four different sub-steps:  
148 at first, a best basis is found to minimize a cost function (here, the Shannon entropy)  
149 [*Wickerhauser, 1994; Coifman and Wickerhauser, 1992*]; this basis varies with each time  
150 step under consideration and allows one to find the best location for the wavepackets.  
151 Second, the model relative vorticity is expanded on this basis. Third, the wavelets are  
152 sorted out as a function of their wavelet coefficients. Only the wavelets with the largest  
153 coefficients are kept. The number of coefficients that are kept depends on the dimension of  
154 the basis computed using the Shannon entropy (usually 10% of the initial set of wavelets).  
155 The method acts as pattern recognition since the reconstructed signal is zero wherever  
156 there is no identified pattern. Four, the structures are extracted one after the other by  
157 searching, first, the maximum of the vorticity modulus, then by spreading the structure  
158 in each direction in space till finding a minimum in vorticity. At last we merge together  
159 adjacent structures with more than 6 gridcell edges in common, and we eliminate filamen-

160 tary patterns by ignoring structures less than 4-gridpoint wide. The resulting localized  
161 structures that cover more than 30 model gridcells, i.e., roughly 2500 km<sup>2</sup>, are kept and  
162 used to separate and define eddies.

163 Processing relative vorticity with a wavelet-based decomposition gives excellent results  
164 in terms of eddy identification (as already shown by *Ruppert-Felsot et al.* [2005]). Relative  
165 vorticity tends to overemphasize frontal structures since it intensifies with the vertical  
166 motions that develop in oceanic fronts [*Wang*, 1993]. This quantity is, therefore, suitable  
167 for eddy edge detection. It also reveals small-scale filaments that can be easily removed  
168 because of their elongated shape and small coverage area. Moreover, relative vorticity  
169 is free from large-scale gradients unlike Ertel potential vorticity, which incorporates the  
170  $\beta$  effect and is sensitive to large-scale spatial density gradients. Equivalent gradients  
171 are also present in temperature, salinity and SSH. On the other hand, the use of relative  
172 vorticity does not require the somewhat arbitrary definition of a reference field to calculate  
173 anomalies. Lastly, the Okubo-Weiss parameter lies on an assumption that restricts eddy  
174 detection to eddy cores [*Basdevant and Philipovitch*, 1994]. Its use would prevent an  
175 efficient decomposition between background and eddy signals.

176 We performed several tests to optimize the parameters involved in the first step of our  
177 analysis. It turns out that the critical parameter is the number of spectral coefficients kept  
178 for signal reconstruction. Our best results are obtained with a percentage of about 9 to  
179 11%. Fig. 3 shows an example of results issued from our analysis. The 256  $\times$  256-gridpoint  
180 domain spans the region to the northwest of the Agulhas retroflection. The relative  
181 vorticity map (Fig. 3a) is calculated at -200 m on day 11 / month 3 / year 7. Among the  
182 44 identified structures, some patterns look like filaments or meanders, but most of them



183 are well-defined eddies. The following discussion will focus on (i) the cyclone at 33°S, 9°E  
184 (letter P, hereafter referred to as Panoramix), (ii) the anticyclone at 30°S, 10°E (letter  
185 I, hereafter referred to as Idefix), (iii) the anticyclone at 32°S, 5°E (letter O, hereafter  
186 referred to as Obelix) and (iv) the anticyclone at 36°S, 4°E (letter A, hereafter referred to  
187 as Asterix). The eddy signal is also clearly present in SSH (Fig. 3b). The wavelet-based  
188 eddy contours fit well with the negative anomaly induced by cyclone Panoramix (contour -  
189 0.1 m) and with the positive anomalies of anticyclones Idefix, Obelix and Asterix (contours  
190 +0.3, +0.4 and +0.5 m, respectively). SSH captures only the large-scale patterns of the  
191 eddy field because it is related to the baroclinic streamfunction characterized by weak  
192 gradients at the eddy periphery. Patterns in temperature (Fig. 3c) and salinity (Fig. 3d)  
193 at depth 200 m are also in good agreement with the wavelet analysis for the cyclone  
194 (colder and fresher than surrounding water) and anticyclones (warmer and saltier). This  
195 is true for most of the eddies except for some discrepancies likely due to the presence  
196 of a large-scale salinity and temperature gradient superimposed on the eddy signature.  
197 A better eddy identification based on temperature or salinity fields would require the  
198 removal of a mean climatological component. The comparison of the wavelet analysis  
199 with the Ertel potential vorticity at -200 m (Fig. 3e) confirms that our technique is  
200 able to correctly detect the whole eddy area. Identified cyclones (anticyclones) precisely  
201 overlap with the contours of  $7 (5) \times 10^{-10} \text{ m}^{-1} \text{ s}^{-1}$ . The Okubo-Weiss criterion was also  
202 tested for comparison (Fig. 3f). In this field, the cores of the vortices correspond to  
203 the strongest elliptic regions (where vorticity dominates strain) and are characterized by  
204 strongly negative values of the parameter. However, our analysis is somewhat better since

205 it gives eddy contours close to the structure shown by the Ertel potential vorticity. The  
206 Okubo-Weiss criterion characterizes only the inner core of the eddies.

207 At the end of this step, each identified structure is numbered, and its area,  $A$ , is mea-  
208 sured. The eddy center is defined as the gridpoint of local maximum of absolute relative  
209 vorticity over the eddy area,  $A$ , with a precision corresponding to the model grid spacing.  
210 Let us define the diameter,  $D$ , as the average of the zonal ( $D^{EW}$ ) and meridional ( $D^{NS}$ )  
211 cords that intercept each eddy center with both endpoints on the edge of the structure  
212 (defined through the wavelet analysis). This definition accounts for stretched shapes.

### 3.2. Time tracking

213 Tracking identified eddies forward in time requires that the following criterion be satis-  
214 fied:

$$215 c_{t,z=-200} \in \mathfrak{E}_{t-\Delta t,z=-200} \tag{1}$$

216 where  $c_{t,z=-200} \equiv (ic, jc)_{t,z=-200}$  is the eddy center at the time,  $t$ , and depth -200 m and  
217  $\mathfrak{E}_{t-\Delta t}$  is the set of gridpoints of the same eddy at the previous time step. The sampling  
218 period of the model output,  $\Delta t = 2$  days, was proven by several tests to cause no bias  
219 in the analysis (data not shown). The translational velocity of the eddy is calculated as  
220 the distance covered by the eddy center over successive 2-day intervals. At each time step  
221 of the analysis, the instantaneous translational velocity,  $v$ , and the diameter,  $D$ , of each  
222 coherent eddy are both recorded. As criterion (1) can be easily adapted for backward time  
223 tracking, we checked that both tracking directions led to very comparable results. Thus,  
224 an eddy identified at a specific instant is tracked both backward and forward in time until  
225 criterion (1) cannot be satisfied, which stops the analysis. The last instants of the forward

226 and backward trackings are considered as the “death” and “birth” of the eddy, respectively.  
 227 Fig. 4 shows eddy contours and surrounding relative vorticity at the end of Panoramix and  
 228 Idefix time trackings. Cyclone Panoramix stops when it becomes an elongated filament  
 229 of negative vorticity (Fig. 4a1), whereas its backward time tracking shows its formation  
 230 on the continental slope near Cape Columbine (Fig. 4a2). Anticyclone Idefix is followed  
 231 forward in time until it merges with a larger anticyclone to the north of Walvis Ridge  
 232 (Fig. 4b1) and backward in time till it detaches itself from a large anticyclonic structure  
 233 under pressure from a cyclone moving southwestward (Fig. 4b2).

### 3.3. Vertical tracking

234 The analysis is repeated at several depths to diagnose the vertical extent of an eddy  
 235 identified at first at -200 m. The analysis is started at this depth to eliminate the model  
 236 surface layers liable to be affected by a dynamics too much sensitive to air-sea interactions.  
 237 Let us state that a structure identified at the level,  $z$ , belongs to an eddy already identified  
 238 at the level,  $z - \Delta z$ , on condition to satisfy criterion (2):

$$239 \quad c_z \in \mathfrak{E}_{z-\Delta z} \quad (2)$$

240 where  $c_z \equiv (ic, jc)_z$  is the center of the structure identified at the level,  $z$ , and  $\mathfrak{E}_{z-\Delta z}$   
 241 is the set of gridpoints of the selected eddy at the level,  $z - \Delta z$ . After sensitivity tests  
 242 and computing time considerations, we set the distance between two successive horizontal  
 243 slices to  $\Delta z = 100$  m. The vertical tracking ends at depth  $iz_L$  just before the eddy signal in  
 244 relative vorticity becomes too weak to be detected. In order to avoid an excessive vertical  
 245 extent of eddies, our vertical tracking was stopped at  $z_{max} = -1000$  m (see Fig. 5).  
 246 This maximum depth matches the vertical extent of Agulhas rings that are usually found

247 in field measurements [*Garzoli et al.*, 1999; *Schmid et al.*, 2003] and numerical models  
248 [*Donners et al.*, 2004].

249 We also checked that the vertical extent found for the eddies was in agreement with  
250 a maximum depth based on the *Flierl* [1981] criterion. It is worth noting that, with  
251 this criterion, an eddy can be tracked with depth as long as its rotational speed exceeds  
252 its translation speed. We calculated the rotational speed of our eddies by averaging  
253 the tangential velocity at the ends of both diameters  $D^{EW}$  and  $D^{NS}$ , and we defined  
254 their translation speed,  $v$ , as in section 3.2. After computation of the deepest immersion  
255 at which *Flierl* [1981] criterion could be satisfied (hereafter  $z_{Flierl}$ ), this parameter was  
256 considered as undefined when it approached the local ocean floor by less than 1000 m.  
257 Fig. 5 exhibits smooth evolutions of  $z_{Flierl}$  and  $iz_L$  for cyclone Panoramix (upper panel)  
258 and anticyclone Idefix (bottom panel) except on the occasion of sudden deepenings for  
259 brief periods. These events happen mostly when the translational velocity of the eddy  
260 decreases, and the upper 1000 m of the structure are able to spin up movements in the  
261 layers underneath. Indeed, *van Aken et al.* [2003] showed that an Agulhas ring rotating  
262 with relatively intense kinetic energy can extend down to the ocean bottom. In our  
263 simulation, we observed good correlation of  $z_{Flierl}$  and  $iz_L$  with the translational velocity,  
264  $v$ , of the eddy, and to stop vertical tracking at  $z_{max} = -1000$  m when  $z_{Flierl}$  reaches  
265 deepest values seems realistic. Then, for cyclone Panoramix (Fig. 5a), the *Flierl* criterion  
266 confirms that the eddy extends at least down to 1000m for quite some time (from 5 to day  
267 60). The vertical extension of anticyclone Idefix is smaller (Fig. 5b) and both definitions  
268 of its maximum depth give equivalent results.

269 In summary, at a fixed time step, the area,  $A_k$ , and diameter,  $D_k$ , are both diagnosed  
270 at each level,  $k$ , and the volume,  $V$ , taken up by each eddy can be calculated as:

$$271 \quad V = \sum_{k=1}^{iz_L} A_k \cdot \Delta z. \quad (3)$$

272 The knowledge of instantaneous velocity  $v$ , diameter  $D$  and volume  $V$  of each structure  
273 enables one to calculate an instantaneous transport and an instantaneous momentum  
274 denoted  $T_{inst}$  and  $M_{inst}$  respectively (see Appendix A and section 4).

#### 4. Results and discussion

275 Let us, now, focus on the three anticyclones, Asterix, Idefix and Obelix, and the  
276 cyclone, Panoramix, successfully tracked by our technique between the end of year 6  
277 and the end of year 7 of our 11-year simulation. In slightly more than 6 months (day  
278 10 / month 11 / year 6 to 14/5/7, in southern summer and fall) Panoramix moved mainly  
279 west-southwestward and eventually turned south just before turning into a filament (Fig. 1  
280 and Fig. 4a). Tracking of Idefix for slightly less than 10 months, from 3/12/6 to 11/10/7  
281 (in southern summer, fall and winter) highlighted a northwestward motion (Fig. 1 and  
282 Fig. 4b). Obelix (from 10/11/6 to 5/3/7) and Asterix (from 14/1/7 to 13/6/7) also moved  
283 along this direction (Fig. 1). Such a divergence in eddy pathways between cyclones and  
284 anticyclones has been also reported from satellite- and drifter-data [Boebel *et al.*, 2003;  
285 Morrow *et al.*, 2004]. According to Morrow *et al.* [2004], it is induced by changes in  
286 planetary and relative vorticity on the flanks of the eddy, but other causes are possible.

287 The time series for cyclone Panoramix (Fig. 6 and Appendix A for details on the  
288 calculation of the associated error bars) show different periods in the life of the eddy.  
289 When the eddy moves over the continental slope, its translational velocity is weak, and

290 its shape is more or less circular. Indeed, there is nearly no change in diameter and  
291 volume during this first stage. Then, the cyclone moves into the Cape Basin and starts to  
292 interact with other eddies and filaments. Before it becomes itself a filament, the successive  
293 growth and reduction of its volume as well as a high variability of its diameter indicate  
294 that it incorporates and loses some mass. Its instantaneous transport and momentum are  
295 increasing both in magnitude and variability during this stage.

296 Among the time series obtained for the three anticyclones, the Idefix one is the longest  
297 (Fig. 7). Velocity, volume and diameter show significant variability at the stage of eddy  
298 formation. Then, there is a central period over which the eddy is well structured, and  
299 its volume and diameter remain nearly unchanged as it is moving within the Cape Basin.  
300 These small variations indicate that our algorithm works fairly well for eddy identification:  
301 the eddies that do not interact with their surroundings should indeed conserve their tracer  
302 properties in time. The variation in volume and velocity between 170 and 210 days of its  
303 lifetime is caused by the crossing of the Walvis Ridge (Fig. 5b). Beyond the ridge, the  
304 eddy volume is reduced and the velocity is less regular. Here, large standard deviations  
305 in diameter with no correspondence with large standard deviations in volume are the  
306 sign of a shape becoming more and more stretched. The instantaneous transport and  
307 momentum show a general decline over the eddy lifetime, suggesting a loss of impetus  
308 during its northwestward journey, whereas modulations in time look mainly driven by  
309 velocity changes.

310 Table 1 summarizes the time-averaged values of eddy parameters. The cyclone,  
311 Panoramix, and the anticyclone, Idefix, have similar translational velocities, whereas the  
312 other two anticyclones are moving faster. The difference may partly come from the short-

ness of the tracking of Obelix and Asterix since a short time series likely induces a bias on the calculation of average values. A comparison with previous studies suggests that our estimates of drift velocity, volume and diameter for Cape Basin eddies are realistic. Cyclones and anticyclones tracked by *van Ballegooyen et al.* [1994] had drift velocities between  $0.037 \text{ ms}^{-1}$  and  $0.090 \text{ ms}^{-1}$ . In *Arhan et al.* [1999], the anticyclone, R3, displays a path very close to the one we obtain for Idefix, with a mean drift velocity of  $0.09 \text{ ms}^{-1}$  (when averaged over 100 days). Similar values were found by *Garzoli et al.* [1999] who pointed out that such velocities fall within the range of previous observations [*Goñi et al.*, 1997]. More recently, *Schmid et al.* [2003] observed and tracked a specific Agulhas Ring with satellite altimetry and RAFOS trajectories; the translational velocity estimated by altimetry ranged from  $0.011$  to  $0.273 \text{ ms}^{-1}$  (with an estimated error of about  $0.03 \text{ ms}^{-1}$ ). For some periods, these authors also found a match between drift estimates calculated from RAFOS floats and averaged values calculated from altimetry. *van Aken et al.* [2003] calculated drift velocities of about  $0.03$  and  $0.10 \text{ ms}^{-1}$  for two different rings. Observations reported by *Boebel et al.* [2003] and *Morrow et al.* [2004] showed a faster motion of anticyclones compared with cyclones. Our results agree with this statement, but our modeled drift velocities are about twice their estimates. In a model of the Atlantic circulation, *Treguier et al.* [2003] calculated the average velocity of Agulhas Rings once they had crossed Walvis Ridge, and pointed out that their result ( $0.06 \text{ ms}^{-1}$ ) was similar to velocities diagnosed by *Schouten et al.* [2000] and *Garnier et al.* [2003] from altimetry data.

As regards volume and diameter, our anticyclones are in average smaller than observed Agulhas rings [*van Aken et al.*, 2003, and references cited therein]. This bias is mainly

336 attributable to the nature of the comparison. Estimates cited in literature often cor-  
337 respond to instantaneous or short-term averaged values, whereas our mean parameters  
338 were calculated over several months of tracking. Our recorded maximum values (omit-  
339 ting error bars) of  $V=23, 31$  and  $33 \cdot 10^{12} \text{ m}^3$  and  $D=195, 273$  and  $219 \text{ km}$  for Idefix,  
340 Obelix and Asterix, respectively, are in fact in fair agreement with typical observations at  
341 sea. Furthermore, our definition of eddy volume is not based on hydrological criteria as  
342 done in most previous studies (e.g., the water volume above the  $10^\circ\text{C}$  isotherm), and our  
343 definitions of diameter and area apply also to non-circular eddies. Planned analyses of  
344 hydrological properties of modeled eddies will address a more accurate comparison with  
345 observations. Nevertheless, we already point out that our estimate of the ratio between  
346 diameter and volume is in good agreement with the one found for observed eddies. Our  
347 conclusions also hold for cyclones though the data available in the literature about this  
348 topic in the Cape Basin are far less numerous. *Boebel et al.* [2003] found a typical diameter  
349 of  $120 \text{ km}$  for these structures, whereas *van Ballegooyen et al.* [1994] measured an initial  
350 dimension of  $160 \text{ km}$  for a cyclone formed near the Agulhas retroflection.

351 Besides translational velocity, volume and diameter, we suggest two other physical quan-  
352 tities that we consider to be meaningful for differentiating individual contributions to  
353 transport by coherent eddies: the instantaneous transport,  $T_{inst}$ , and the instantaneous  
354 momentum,  $M_{inst}$  (see Appendix A for mathematical definitions).  $T_{inst}$  represents the  
355 instantaneous transport induced by an eddy of a given volume crossing completely a fixed  
356 imaginary section positioned in front of it, i.e., covering a distance equal to its diameter  
357 while moving at its drift velocity.  $M_{inst}$  accounts directly for the momentum of the  
358 eddy and is obtained by multiplying its mass by its velocity. Our definition for transport



359 differs from the one generally used in data analysis [e.g., *van Ballegooyen et al.*, 1994] or  
360 models [*Treguier et al.*, 2003]. The “classical” approach calculates the individual trans-  
361 port by dividing the typical volume of an eddy by 1 yr. Multiplying this transport by  
362 the average number of equivalent propagating structures per year gives an estimate of  
363 the mean transport achieved by the eddy field and can be used, for instance, to diagnose  
364 the transmission of water from the Indian to the Atlantic Ocean in the form of coherent  
365 eddies. This definition would lead to transport values of about 0.4 Sv for Obelix and  
366 Asterix. On the contrary, as our definition of instantaneous transport does not lie on the  
367 arbitrary definition of a reference time interval, it is appropriate for the intercomparison  
368 of individual structures because of the involvement of three main characteristics of an  
369 eddy (velocity, shape and volume). The application of our definition to specific eddies  
370 with available data about drift velocity, volume and diameter [e.g. *van Ballegooyen et al.*,  
371 1994; *van Aken et al.*, 2003; *Schmid et al.*, 2003] leads to values for  $T_{inst}$  of the same  
372 order of magnitude as our modeled eddies.

## 5. Summary and conclusions

373 The main goal of our study was to propose objective tools for identification and tracking  
374 of 3D coherent structures. Wavelet analysis allowed us to follow eddies in space and time  
375 as long as they exist as coherent structures in the model and to evaluate their translational  
376 velocity, diameter, volume and derived parameters.

377 This study was carried out in a regional ocean model that accounts for eddy displace-  
378 ments within the Cape Basin region. This oceanic region around Southern Africa is a  
379 critical water mass crossroads within the so-called warm-water route of the global over-  
380 turning circulation [*Gordon*, 1986; *Gordon et al.*, 1992; *Gordon*, 2003]. Oceanic eddies are

381 of key importance in the distribution of properties like heat and salt throughout the World  
382 Ocean, and Agulhas rings are thought to play a key role in the Indo-Atlantic interocean  
383 exchange [*Gordon, 1986; de Ruijter et al., 1999; Weijer et al., 1999*]. The Indo-Atlantic  
384 connection appears crucial in global ocean models too [*Speich et al., 2001, 2002*]. Fur-  
385 thermore, recent studies based on observations found a highly nonlinear regime in the  
386 Cape Basin (the first Atlantic basin to collect leakage of Agulhas water) [*Boebel et al.,*  
387 *2003*]. Turbulence is so intense in this area that it could prevent the continuous advection  
388 of Indian or South Atlantic waters [*de Ruijter et al., 1999*]. Indeed, in the Cape Basin,  
389 eddies of different types interact with each other and with the main retroflection of the  
390 Agulhas Current, in a context of vigorous stirring and mixing [*Gordon, 2003; Boebel et al.,*  
391 *2003; Morrow et al., 2004*].

392 In this turbulent framework, we processed maps of modeled relative vorticity with a  
393 wavelet-based decomposition. Then, in order to capture and track the full 3D envelope  
394 of each eddy, we developed an algorithm based on superimposing structures at different  
395 instants and different vertical levels. The brief presentation of our validation dealt with  
396 only a few of the numerous mesoscale structures simulated by the model. Indeed, we  
397 decided to focus mostly on two types of mesoscale vortices, i.e. i) cyclonic eddies ejected  
398 into the open ocean from the Southwestern African continental slope and ii) anticyclonic  
399 eddies present in the Cape Basin. Our tracking evidenced divergent pathways for both  
400 types with a westward and equatorward propagation at a speed within  $0.08$  and  $0.13 \text{ ms}^{-1}$   
401 for anticyclones and a westward, but poleward propagation at  $0.08 \text{ ms}^{-1}$  for the studied  
402 cyclone. Both behaviors are very similar to those observed with altimetry along differ-  
403 ent subtropical eastern boundaries [*Morrow et al., 2004*]. Our translational velocities are

404 slightly larger than those derived from altimetry and RAFOS floats, but the tracking cri-  
405 teria were not alike [*van Ballegooyen et al.*, 1994; *Boebel et al.*, 2003; *Morrow et al.*, 2004].  
406 Diameter and volume timeseries obtained with our analysis provide useful information on  
407 the evolution of the shape of an eddy and on the interactions with surrounding structures.  
408 Time-averaged diameters range from 81 to 156 km with instantaneous values exceeding  
409 200 km and time-averaged volumes range from 4 to 14  $10^{12}$  m<sup>3</sup> with instantaneous val-  
410 ues exceeding 30  $10^{12}$  m<sup>3</sup>, in good agreement with observational data [*van Aken et al.*,  
411 2003, and references cited therein]. Analyses of hydrological properties of modeled eddies  
412 will be necessary for a more thorough comparison. Then, besides translational velocity,  
413 volume and diameter, we suggest the calculation of two derived parameters that prove  
414 appropriate for the intercomparison of individual structures: the instantaneous transport  
415 and the instantaneous momentum.

416 Tracking techniques based on the calculation of Lagrangian trajectories also exist, as  
417 shown for instance by a recent analysis of the same numerical simulation [*Doglioli et al.*,  
418 2006]. Such Lagrangian computations coupled with the wavelet-based definition of each  
419 eddy volume will be used in a future paper to calculate the remote origins and fates  
420 of the water carried by each structure. Heat and fresh water transport estimates will  
421 also be derived for each type of eddy. This will allow the evaluation (in models) of the  
422 relevance of the ocean off South Africa in the organization of the return branch of the  
423 global thermohaline circulation. We plan to evaluate accurately the net exchanges across  
424 the Cape Basin in order to gain more insight into the complex role of the mesoscale  
425 processes affecting the origin and fate of water masses.

426 **Acknowledgments.**

427 The authors wish to thank Michel Arhan, Xavier Carton, Steven Herbette, Guillaume  
428 Rouillet and Anne-Marie Treguier for enlightening discussions about eddy dynamics, and  
429 Marie-Paule Friocourt for her assistance in correcting the manuscript. A. M. Doglioli  
430 is supported by SHOM, under contract number CA 2003/03/CMO (Contact: Alain Ser-  
431 pette). This study is also a contribution to InterUp, a project funded by the French LEFE-  
432 IDAO program (Les Enveloppes Fluides et l'Environnement - Interactions et Dynamique  
433 de l'Océan et de l'Atmosphère), formerly PATOM (Programme National Atmosphère et  
434 Océan à Multi-échelles).

**Appendix A: Definitions**

435 Let us define the instantaneous mass transport of a coherent eddy as the ratio between  
436 the eddy volume,  $V$ , and the time,  $\Delta t$ , needed to cross entirely a fixed section perpendic-  
437 ular to the direction of propagation of the eddy center:

$$438 \quad T_{inst} = V \cdot \Delta t^{-1}. \quad (A1)$$

439 Assuming that the time interval is  $\Delta t = D \cdot v^{-1}$  where  $D$  is the eddy diameter and  $v$  is  
440 the velocity of the eddy center, the transport is estimated as:

$$441 \quad T_{inst} = v \cdot V \cdot D^{-1}. \quad (A2)$$

442 In our calculations,

$$443 \quad v \equiv v(t) = \frac{1}{i z_L} \sum_{k=1}^{i z_L} v_k$$

444 is the vertical average of the velocity of the eddy center as computed for each z-layer with a  
445 backward difference scheme involving successive positions. The relative error  $v_{err} \equiv v_{err}(t)$

446 made on velocity is estimated as:

$$447 \quad v_{err} = \frac{\sigma_z(v)}{v}, \quad (A3)$$

448 where  $\sigma_z$  is the standard deviation of the distribution along the vertical axis.

449 As described above, our analysis gives the eddy volume at each time step. Our estimate  
450 of the relative error  $V_{err} \equiv V_{err}(t)$  on the volume calculation is

$$451 \quad V_{err}(t) = \frac{\Delta z \pi \left(\frac{D}{2}\right)^2}{V} + \frac{4\Delta x \Delta z \sum_{k=1}^{iz_L} A_k D_k^{-1}}{V}, \quad (A4)$$

452 that is the sum of errors due to the vertical (step  $\Delta z$ ) and horizontal (step  $\Delta x$ ) discrete  
453 representations of the eddy. The first term on the right-hand side is the volume of the  
454 cylinder that the method may neglect at the base of the eddy. The second term is the  
455 approximate volume of a cylindrical ring neglected or taken by mistake around the eddy  
456 whose area,  $A_k$ , and diameter,  $D_k$ , are diagnosed at each level,  $k$ .

457 Let us define the diameter,  $D$ , as the mean between the zonal ( $D^{EW}$ ) and the meridional  
458 ( $D^{NS}$ ) cords that intercept each eddy center with both endpoints on the edge of the  
459 structure. Then, by repeating this average at each level,  $k$ , the reference diameter used  
460 in A2 is:

$$461 \quad D = \frac{1}{2 iz_L} \sum_{k=1}^{iz_L} (D_k^{EW} + D_k^{NS}). \quad (A5)$$

462 For stretched eddies in rotation, the relative error made on the calculation of  $D$  with  
463 A5 is estimated as:

$$464 \quad D_{err} = \frac{1}{iz_L} \frac{\sum_{k=1}^{iz_L} |D_k^{EW} - D_k^{NS}|}{D}. \quad (A6)$$

465 The relative error on our transport estimate is the sum of the errors defined in A3, A4  
466 and A6:

$$467 \quad Tinst_{err} = v_{err} + V_{err} + D_{err}.$$

468 The mean transport,  $\overline{Tinst}$ , is the time average of  $Tinst$ . Equivalently, we introduce the  
469 instantaneous momentum (and associated error) of a coherent structure as the product  
470 of its instantaneous velocity and volume. Ignoring density variations within the structure  
471 and thus using  $\rho_0 = 1020kg/m^3$  lead to:

$$472 \quad Minst = \rho_0 \cdot V \cdot v,$$

473 and

$$474 \quad Minst_{err} = v_{err} + V_{err}.$$

475 Finally, the mean momentum,  $\overline{Minst}$ , is the time average of  $Minst$ .

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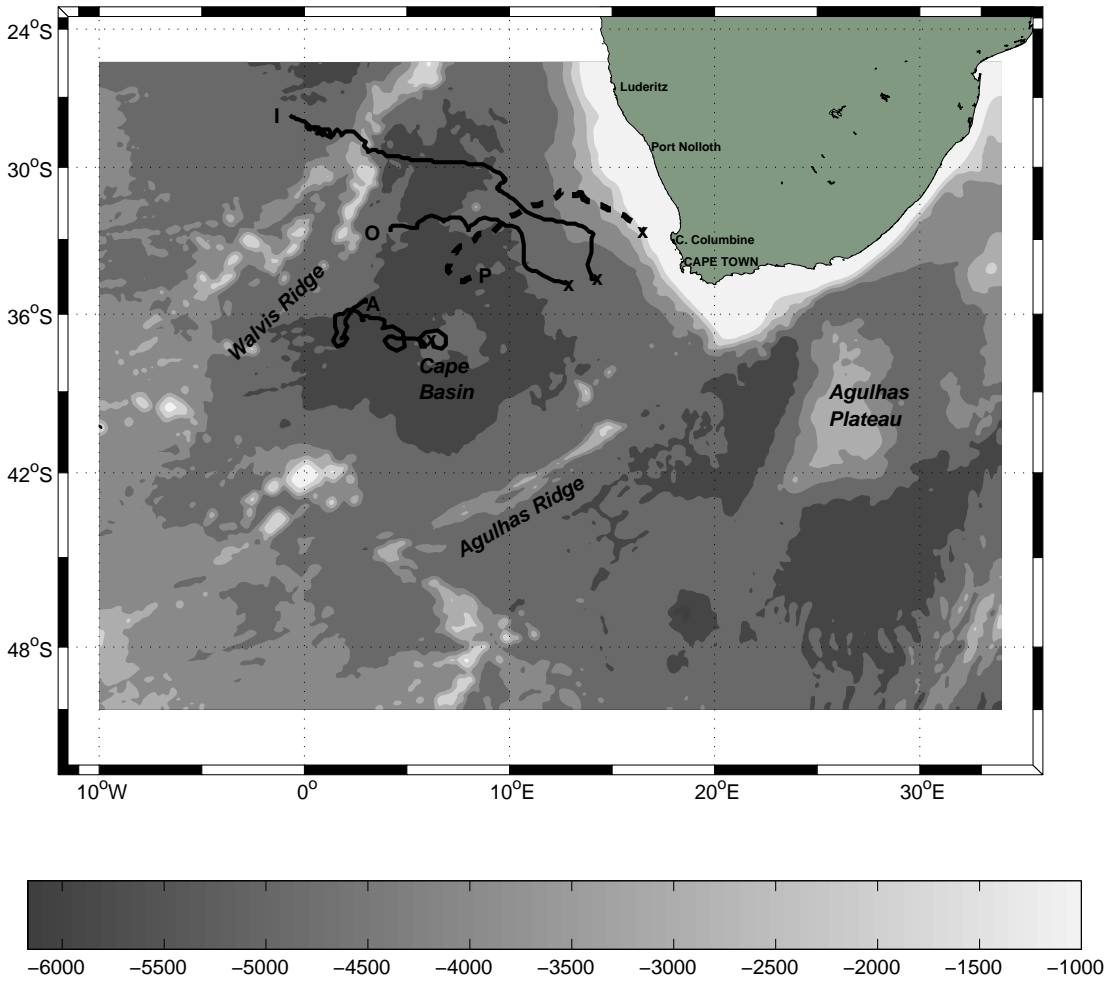
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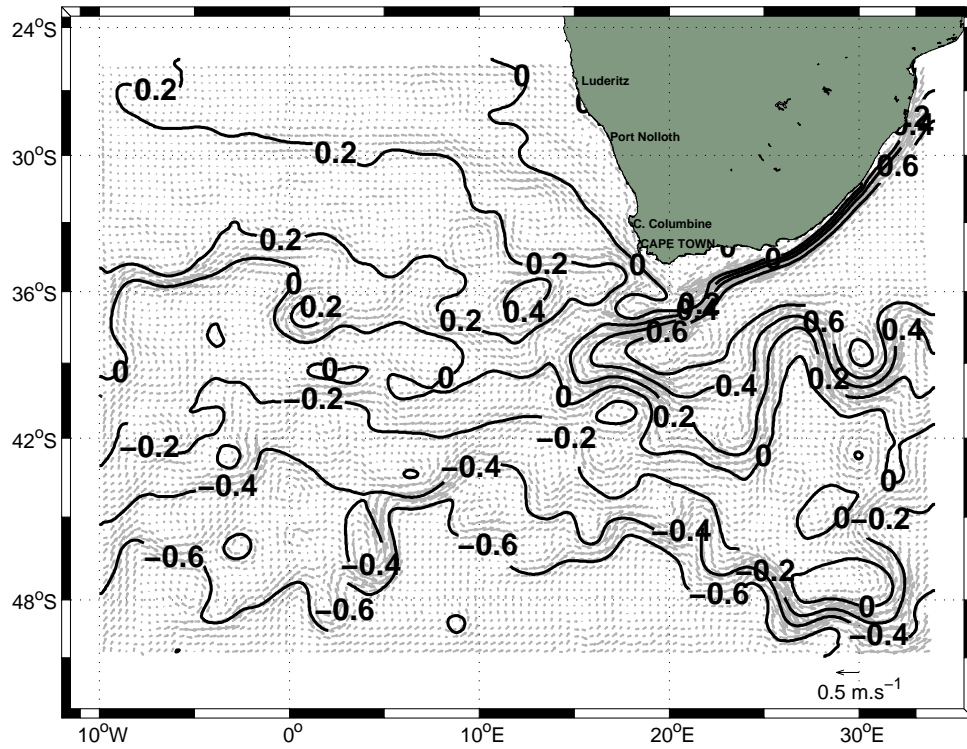
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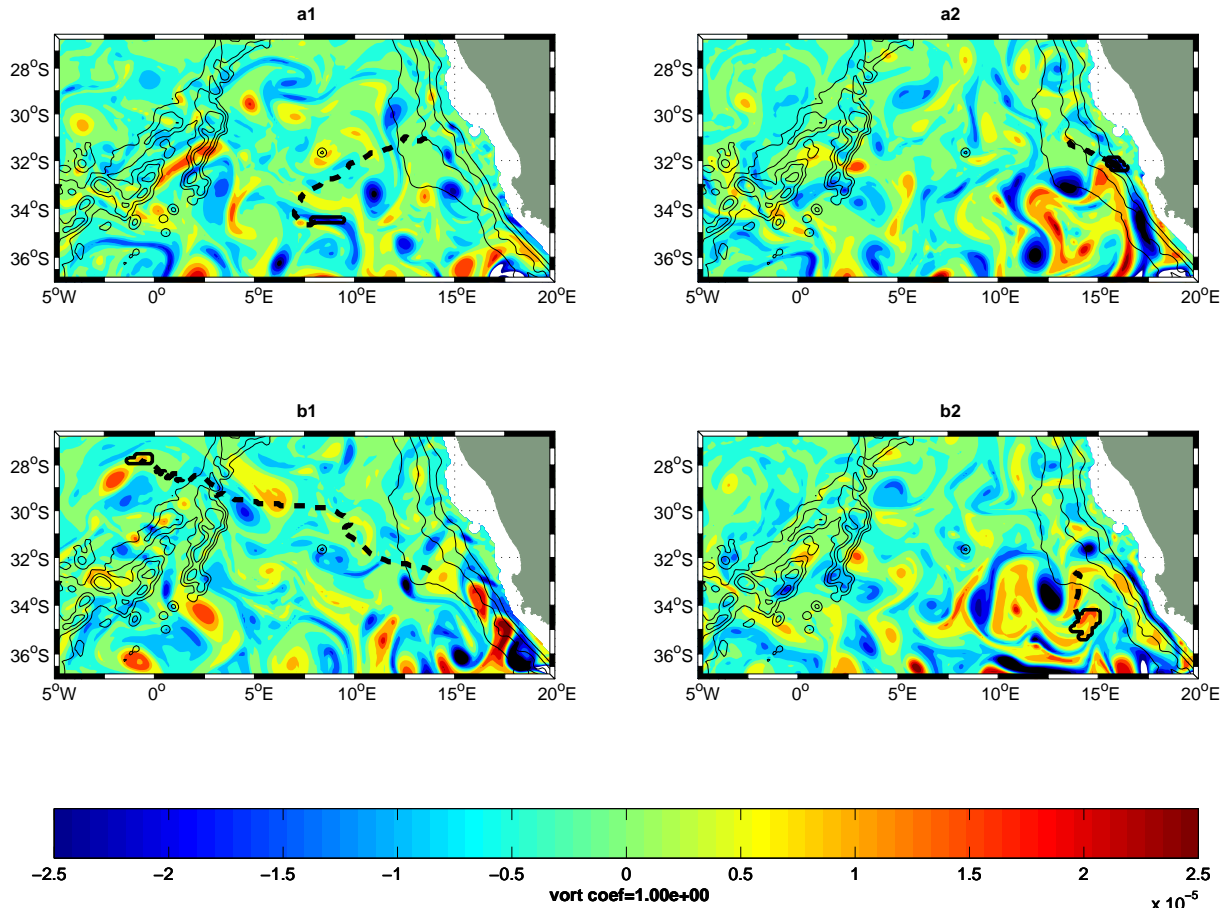


**Figure 1.** Model domain and bathymetry [m]. The trajectories of three anticyclones (solid lines) and one cyclone (dashed line) are drawn in black. Cross symbols and letters indicate the beginning and end of each trajectory, respectively. P=Panoramix, I=Idefix, O=Obelix, A=Asterix, see section 3 for nomenclature.



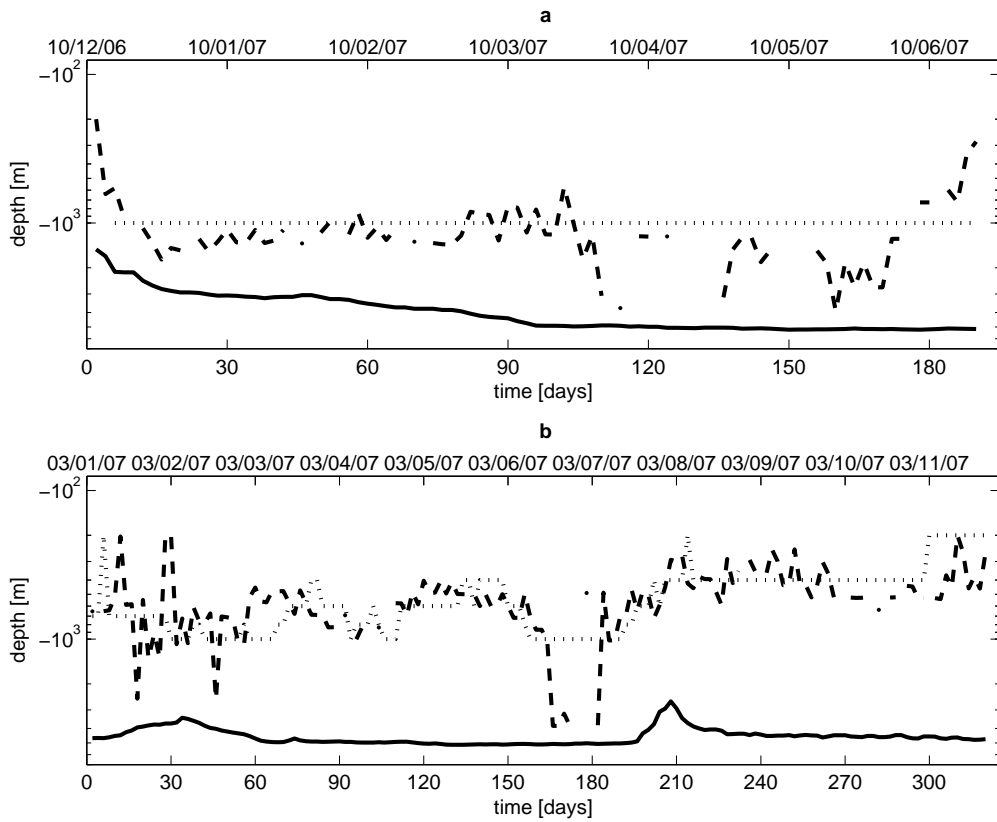
**Figure 2.** Model-climatology. Contour lines and arrows show the SSH anomaly [m] and barotropic current [ $\text{m s}^{-1}$ ], respectively.

**Figure 3.** Wavelet analysis. Shaded colors represent (a) relative vorticity [ $s^{-1}$ ], (b) SSH anomaly [m], (c) temperature [ $^{\circ}C$ ], (d) salinity [psu], (e) potential vorticity [ $m^{-1}s^{-1}$ ] and (f) Okubo-Weiss criterion [ $s^{-1}$ ]. All fields are calculated on day 11 / month 3 / year 7 and, except SSH, at depth -200 m. The black square shows the  $256 \times 256$  gridpoint domain of the wavelet analysis applied on relative vorticity, and the identified eddies are contoured in black. Letters A, O, I and P indicate anticyclones Asterix, Obelix and Idefix and cyclone Panoramix, respectively.

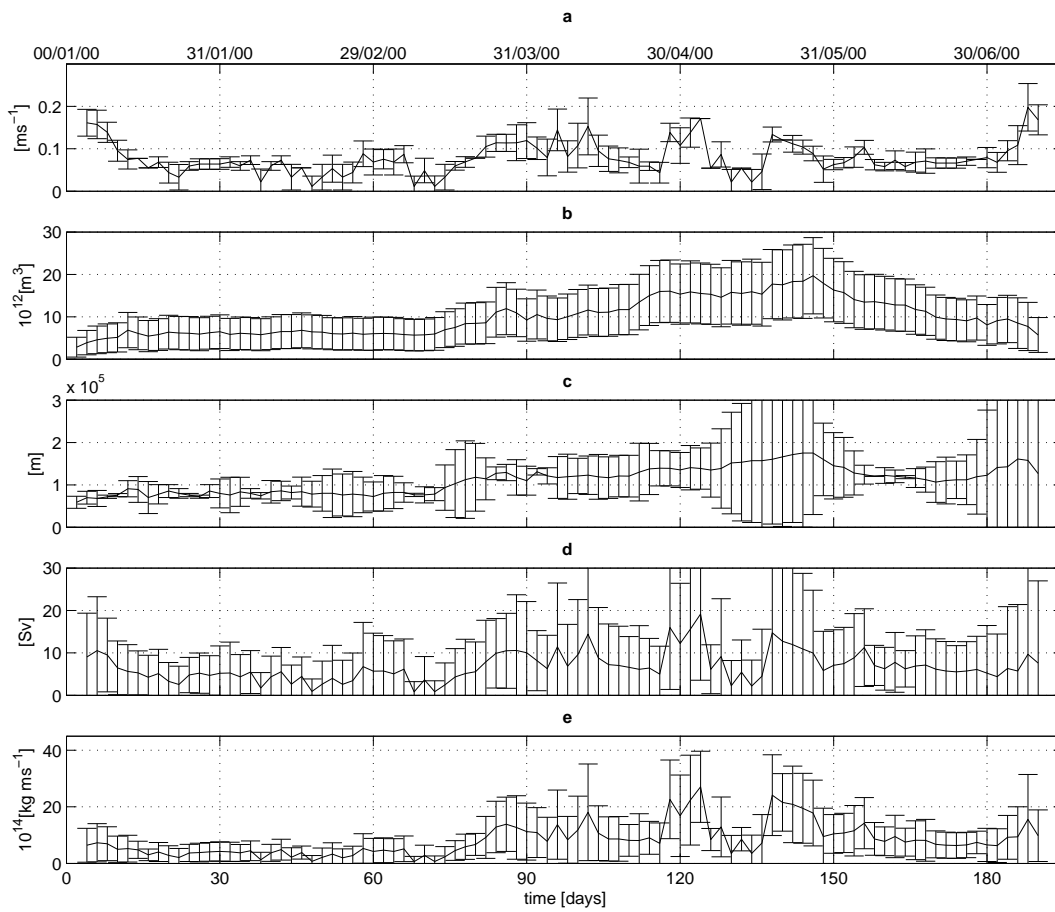


**Figure 4.** “Death” (left panels) and “birth” (right panels) of cyclone Panoramix (upper panels) and anticyclone Idefix (lower panels). Eddy patterns are shown by black and thick solid lines. Forward (left panels) and backward in time (right panels) trajectory segments are drawn with black and thick dashed lines. Bathymetry is shown in black and thin solid contours (-1000, -2000, -3000, -4000 m). Relative vorticity [ $s^{-1}$ ] is shown in color at times (a1) day 14 / month 5 / year 7, (a2) 10/11/6, (b1) 11/10/7 and (b2) 3/12/6.





**Figure 5.** Vertical tracking. Time series of the deepest vertical tracking level,  $iz_L$ , reached by the wavelet analysis (dotted line), the maximum depth at which Flierl's criterion can be defined (dashed line) and bathymetry below the eddy center (solid line). For (a) cyclone Panoramix and (b) anticyclone Idefix.



**Figure 6.** (a) Translational velocity, (b) volume, (c) diameter, (d) instantaneous transport and (e) instantaneous momentum of cyclone Panoramix.

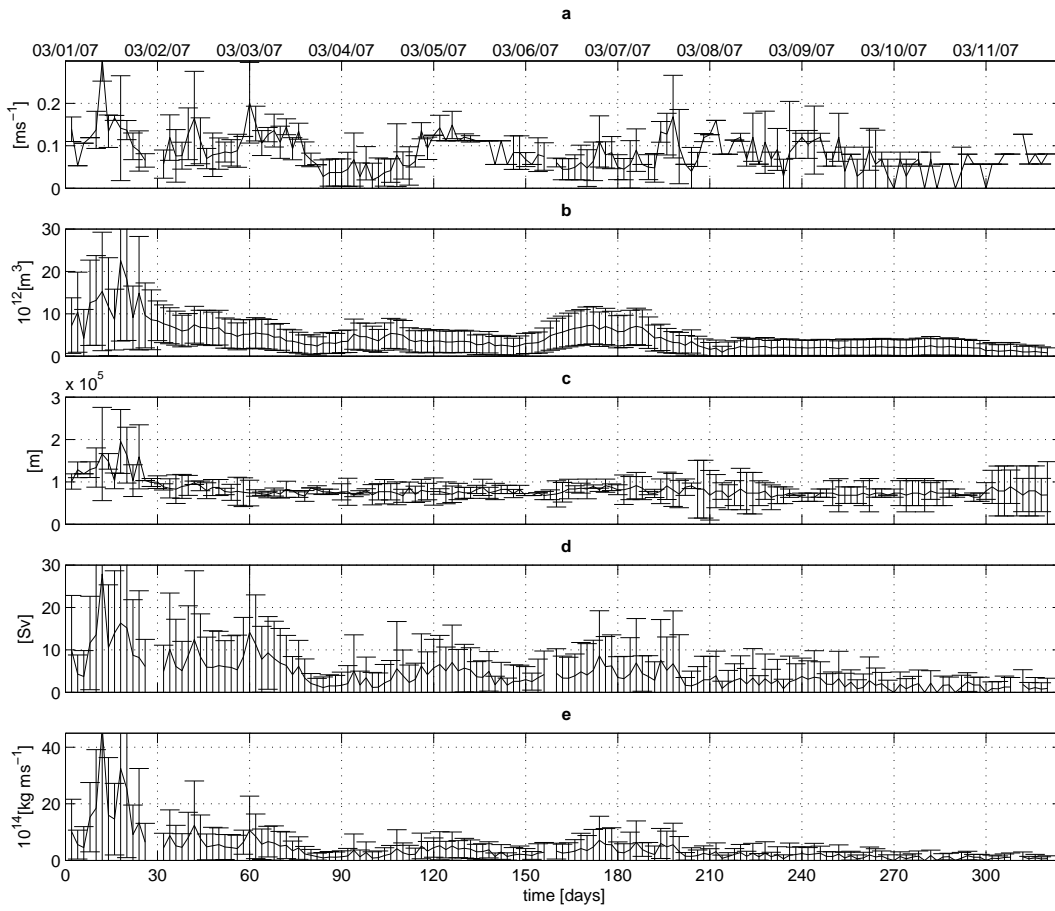


Figure 7. Same as Fig. 6, but for anticyclone Idefix.

eddy name	PANORAMIX	IDEFIX	OBELIX	ASTERIX
tracking duration [days]	190	320	110	150
$\bar{v}$ [ $\text{ms}^{-1}$ ]	0.079	0.083	0.127	0.115
$\bar{V}$ $10^{12}[\text{m}^3]$	10	4	14	12
$\bar{D}$ [km]	111	81	156	128
$\overline{Tinst}$ [Sv]	6.8	4.3	5.7	5.9
$\overline{Minst}$ $10^{14}[\text{kg ms}^{-1}]$	8.2	4.0	5.3	6.1

**Table 1.** Time-averaged eddy parameters