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**Title : Eddies in the Tropical Atlantic Ocean and their seasonal variability**

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**Key points:**

- Detected eddies using altimetry data present amplitudes, radii and kinergy around 1-5cm, 30- 100km and  $50-100\text{cm}^2.\text{s}^{-2}$  in the TAO.
- Seasonal cycle of eddy properties has the highest amplitude in the NBC retroflection and in the western part of NECC.
- Barotropic instabilities are the main mechanism related to eddy generation in the western part of NECC.

36 **Abstract:**

37           We study mesoscale eddy characteristics in the Tropical Atlantic Ocean, using 23 years  
38 of daily altimetry sea level anomalies. Eddies are mainly generated in the eastern boundary up-  
39 wellings and in the Brazil current region. They have westward propagating speed reaching 20 cm  
40  $s^{-1}$  in equatorial area, decreasing with latitudes. They present typical amplitudes of around 1-5 cm.  
41 The largest and most energetic eddies are observed in the equatorial region, in particular in the  
42 retroflection of the North Brazil Current (NBC). The seasonal cycle of the main eddy characteristics  
43 shows a marked seasonal cycle along the NBC retroflection and along the western part of the North  
44 Equatorial Countercurrent (NECC). We propose a criterion using altimetry to analyse the mecha-  
45 nism responsible for eddy generation. In the NECC, we argue that eddy generation is mainly due to  
46 barotropic instability of mean surface currents whereas other mechanisms must be invoked for the  
47 NBC.

48  
49 **Plain Language Summary**

50  
51           Mesoscale eddies in the ocean are numerous quasi-circular structures having typical  
52 spatial scale from 10 to 100 km. They can be formed for example by instability of the large-scale  
53 currents. Eddies play a key role in the ocean. Indeed, the kinetic energy of ocean circulation is dom-  
54 inated by mesoscale eddies, which play also a significant role in the transport of water masses, heat,  
55 and biogeochemical properties (e.g. nutrients) in the ocean. They have a signature in sea surface  
56 height measured by satellite altimeters. In this work, we use satellite sea level anomalies over 23  
57 years in the Tropical Atlantic Ocean to analyze eddy properties (size, amplitude, kinetic energy, vor-  
58 ticity) at the basin scale and their seasonal variability. Although they are more developed in the sub-  
59 tropical gyres, eddies with largest radii and higher eddy kinetic energy are found in the equatorial  
60 region, with the strongest seasonal cycle in the North Brazil Current retroflection. We used a crite-  
61 rion based on altimetry products to study the processes involved. In the North Equatorial Counter-  
62 current, eastern part of the North Brazil current retroflection, eddy genesis is due to barotropic in-  
63 stabilities whereas inside the retroflection area other processes are suspected.

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## 72 1. Introduction

73 The development of altimetry has fostered a more advanced understanding of the ocean  
74 circulation and revealed that mesoscale eddies are a key component of ocean dynamics that contain  
75 most of the ocean kinetic energy (e.g. [Fu et al., 2010](#)). Mesoscale eddies are quasi-circular oceanic  
76 structures, in rotation, with spatial scales of the order of a few tens to several hundred kilometers.  
77 Cyclonic and anticyclonic eddies (CE and AE, respectively) have lifespans from days to months and  
78 can travel several hundreds to thousands of kilometers across ocean basins (e.g. [Chelton et al.,](#)  
79 [2011a](#)). Although they can form and dissipate almost everywhere in the ocean ([Fu et al., 2010](#)),  
80 long-lived eddies are preferentially formed in the eastern part of the ocean basins or along energetic  
81 large-scale currents (e.g. [Chelton et al., 2011a](#)). During their formation stage, mesoscale eddies trap  
82 water-mass characteristics in their core and thus play an important role in the redistribution of  
83 physical and biogeochemical properties in the global ocean. Both through horizontal and vertical  
84 mechanisms, they can also strongly impact the primary production (e.g. [Dadou et al., 1996](#);  
85 [Chelton et al., 2011b](#); [McGillicuddy et al., 2016](#); [Rousselet et al., 2016](#)) and higher trophic levels  
86 ([Logerwell and Smith, 2001](#); [Domokos et al., 2007](#)).

87 The formation of vortices can be due to several processes, including barotropic and  
88 baroclinic instabilities of large-scale currents. In the tropical Atlantic Ocean, both the Canary and  
89 Benguela Eastern Boundary Upwelling Systems (EBUS) are hotspots for the generation of  
90 mesoscale eddies (e.g. [Chaigneau et al., 2009](#); [Gutknecht et al., 2013](#); [Pegliasco et al., 2015](#))  
91 through several instability mechanisms such as interaction of the large-scale circulation with  
92 islands, topographic features, coastline geometry or strong local wind shear (e.g. [Aristégui et al.,](#)  
93 [1994](#); [Chaigneau et al., 2009](#); [Djakouré et al., 2014](#)). In-situ data revealed that 40-60% of the  
94 eddies formed in the eastern Atlantic EBUS are subsurface intensified with a vertical extent down to  
95 800 m depth ([Pegliasco et al., 2015](#)). Energetic eddies are also generated in the Agulhas  
96 retroflexion and propagate westward across the south Atlantic (e.g. [Penven et al., 2001](#); [Laxenaire](#)  
97 [et al., 2018](#)). In the western part of the Atlantic, the generation of large isolated warm-core vortices  
98 exceeding 450km in diameter occurs in the retroflexion of the North Brazil Current (NBC)  
99 propagating toward the Caribbean Sea (e.g. [Goni and Johns, 2003](#); [Fratantoni and Richardson,](#)  
100 [2006](#); [Garraffo et al., 2003](#)). Likewise, the equatorial Atlantic is also the site of tropical instability  
101 waves (TIW) (e.g. [Caltabiano et al., 2005](#); [Athié and Marin, 2008](#)) that are formed by the  
102 horizontal and vertical shears of the zonal current systems especially between the North Equatorial  
103 Counter Current (NECC) and the South Equatorial Current (SEC), and between the SEC and the  
104 Equatorial Undercurrent (EUC) (e.g. [von Schuckmann et al., 2008](#)). These TIW are also associated  
105 with coherent structures called tropical instability vortices (TIV) having typical radii of ~ 300-  
106 500km and confined in the upper thermocline ([Flament et al., 1996](#); [Willett et al., 2006](#); [Dutrieux et](#)

107 *al.*, 2008).

108 All of these studies focused in particular areas, especially in coastal areas (eastern and  
109 western boundary), so that the description of mesoscale eddy properties and their seasonal  
110 variability at the scale of the tropical Atlantic Ocean (TAO) is not known. The purpose of the  
111 present study is to highlight the main physical characteristics (size, lifetime, kinetic energy,  
112 amplitude, etc.) and formation mechanisms of the eddies in the TAO as well as their seasonal  
113 variability.

114

## 115 2. Data and methods

116

### 117 2.1 Altimetry data: sea level anomaly and geostrophic current

118 The main dataset used in this study is the Salto/Duacs gridded product of Sea Level  
119 Anomalies (SLA) and geostrophic currents distributed by the Copernicus Marine Environment  
120 Monitoring Service (CMEMS, <http://marine.copernicus.eu/>). The SLA product was computed  
121 relative to a 20-year (1993-2012) mean. (See for details [Duacs/AVISO+, 2014](#); [Pujol et al., 2016](#)).  
122 This product is based on Sea Surface Height (SSH) measurements from multi-mission altimeters  
123 since 1992 optimally interpolated daily onto a  $0.25^\circ \times 0.25^\circ$  longitude/latitude grid ([Ducet et al.,](#)  
124 [2000](#); [Le Traon et al., 1998](#)). In our study, we used SLA and geostrophic currents in the Tropical  
125 Atlantic Ocean (TAO:  $70^\circ\text{W}$ - $16^\circ\text{E}$ ;  $30^\circ\text{N}$ - $30^\circ\text{S}$ ) for the time period extending from January 1993 to  
126 December 2015.

127

### 128 2.2 Eddy detection and tracking algorithm

129 Mesoscale eddies were identified on the daily SLA maps, using the eddy detection  
130 algorithm developed by [Chaigneau et al., \(2008; 2009\)](#). Eddy centers correspond to local extrema  
131 in SLA (maxima for AE and minima for CE) whereas eddy edges correspond to the outermost  
132 closed SLA contour around each detected eddy center. An eddy is considered as valid if it contains  
133 at least 4 connected grid points, which approximately corresponds to a minimal radius of  $\sim 20$  km,  
134 given the resolution of the altimetric product. For each identified eddy, several properties can be  
135 inferred such as its amplitude (A), its equivalent radius (R), or its mean eddy kinetic energy (EKE,  
136 computed from geostrophic currents). Eddy life cycles are investigated along eddy trajectories  
137 constructed using the algorithm developed by [Pegliasco et al., \(2015\)](#). In this study, we only  
138 retained coherent and long-lived eddies having a lifetime higher than 30 days and a median  
139 amplitude and radius greater than 1 cm and 30 km, respectively.

140

141 In order to investigate the mechanisms involved in the eddy generation and their  
characteristics, the relative vorticity ( $\zeta$ ) of the large-scale flow were computed from the gradients of

142 the geostrophic components ( $u, v$ ) in Cartesian coordinates ( $x, y$ ) as in [Chaigneau et al., \(2008\)](#) :

143 
$$\zeta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \quad (1)$$

144 A barotropic instability criterion based on the gradient of the vorticity of the mean  
145 current is used. Indeed, [Rayleigh \(1880\)](#) showed that for parallel sheared currents, a necessary  
146 condition for barotropic instability is that the gradient of the vorticity field changes sign. Similar  
147 results were obtained for more complex steady currents, provided the gradient of the vorticity field  
148 is computed perpendicularly to the local current, which is the preferential direction for the growth  
149 of perturbations ([Drazin and Howard, 1966](#); [Arnold, 1965](#)). In the present geostrophic context, the  
150 local gradient of vorticity ( $C$ ) is computed as:

151 
$$C = \nabla(f + \zeta) \cdot \vec{n} \quad (2)$$

152 where  $f$  is the Coriolis parameter,  $\vec{n} = \vec{\nabla}\psi / (\|\vec{\nabla}\psi\|)$  is the unit vector perpendicular to geostrophic  
153 streamlines and  $\psi = (-g/f) \cdot SLA$  is the streamfunction.

154 Barotropic instability is associated with a change in the sign of  $C$  and is thus likely to occur in  
155 regions with weak values of  $C$ .

156

### 157 **3 Results**

#### 158 **3.1 Mean eddy properties in the Tropical Atlantic Ocean**

159 In the TAO, more than 32,000 vortices were detected and tracked over the study period  
160 consisting of ~52% of CE and ~48% of AE. [Figure 1a](#) shows the total number of eddy per square  
161 degree that were detected in daily SLA maps between 1993 and 2015. A higher number of eddies  
162 was observed in the eastern part of the TAO particularly in the Canary and Benguela EBUS where  
163 up to 3,000 eddies per square degree were identified as well as in the western boundary along the  
164 Brazilian Current (BC) and around 20°S and 20°N in the South and North Atlantic gyres. In  
165 contrast, a weaker number of eddies was observed in the equatorial region between 12°N and 12°S,  
166 as also noted in previous studies (e.g. [Chelton et al., 2011a](#); [Fu et al., 2010](#)). There is no clear  
167 geographical preference for CE and AE in the TAO (not shown) as also observed in the global  
168 ocean (e.g. [Chelton et al., 2011a](#)).

169 The spatial distribution of eddy properties in the TAO shows that eddies have  
170 amplitudes of 1 to 6cm ([Figure 1b](#)) and more than 40% of these long-lived eddies have an  
171 amplitude of ~2cm. The largest amplitudes are observed i) along the western boundary currents, ii)  
172 south of 25°S mainly associated with anticyclonic Aghulas rings that are formed at the Aghulas  
173 retroflection and propagate westward across the south Atlantic ocean (e.g. [Laxenaire et al., 2018](#)).

174 Although most eddies have typical radii between 60 and 90 km ([Figure 1.c](#)), individual  
175 eddies can exhibit radii up to 150 km in the equatorial region (12°S-12°N). Poleward of ±12°, radii

176 decrease in agreement with the theoretical Rossby deformation radii (*Chelton et al., 1998*). However  
177 at mid-latitudes ( $\sim 30^\circ$ ), the observed eddy radii are almost twice the 1<sup>st</sup> baroclinic Rossby radius of  
178 deformation, probably due to non-linear processes or eddy coalescence (*Chaigneau et al., 2009; Fu*  
179 *et al., 2010*). The largest eddies are observed in the western TAO along the northeastern Brazilian  
180 coast, due to the shedding of large eddies by the NBC retroflection (*Goni and Johns, 2003;*  
181 *Frantantoni and Richardson, 2006; Garraffo et al., 2003*).

182           On average, eddies in the TAO are characterized by relatively weak EKE of less than  
183  $150 \text{ cm}^2 \cdot \text{s}^{-2}$  (*Figure 1d*). However, for the most energetic eddies, located between  $2^\circ\text{N}$  and  $6^\circ\text{N}$   
184 especially in the western part of the basin near the NBC retroflection and along the northern  
185 Brazilian coast, EKE is up to  $500 \text{ cm}^2 \cdot \text{s}^{-2}$ . In the Southern Hemisphere, energetic structures are  
186 located along the south eastern Brazilian coast from  $24^\circ\text{S}$  to  $30^\circ\text{S}$ . Another area with moderate EKE  
187 of  $\sim 200 \text{ cm}^2 \cdot \text{s}^{-2}$  is located in the northern part of the Guinea Gulf along the Guinea current off the  
188 African coast. Note that the patch of relatively high EKE values centered at  $15^\circ\text{W}$  and  $10^\circ\text{N}$  is  
189 spurious and likely due to the interference of the altimeters with the Bijagós Archipelago and the  
190 surrounding region characterized by a shallow bathymetry ( $< 200 \text{ m}$  depth).

### 191 **3.2 Eddy generation, propagation and lifespan**

192           Eddies are mainly generated in the EBUS (*Figure 2a*) and in the western boundary  
193 along the BC where the interaction with the topography and the Brazilian coastline is a favorable  
194 condition for eddy genesis (*Soutelino et al., 2011*). Also, an additional area of favorable eddy  
195 genesis appears in the North Atlantic subtropical gyre between  $12^\circ\text{N}$  and  $30^\circ\text{N}$ . No counterpart  
196 exists for the South Atlantic subtropical gyre. The longest-lived eddies are those generated in the  
197 subtropical gyres, especially in the Southern Hemisphere where on eddies live 150 days (*Figure 2d*).  
198 Statistics show that the mean eddy lifespan in the TAO is of 100 days whereas  $\sim 40\%$  of the eddies  
199 have a lifetime of less than 50 days. Due to the  $\beta$ -effect, almost all the TAO eddies propagate  
200 westward (*Cushman Roisin, 1994*). Equatorial eddies move faster than off equatorial eddies with  
201 propagation speeds of  $15\text{-}30 \text{ cm} \cdot \text{s}^{-1}$  (*Figure 2d*).

202           Based on the results seen in *Figure 1a*, we further divide the TAO in 3 subregions to  
203 examine the mean temporal evolution of eddy properties during their life-cycle: the northern region  
204 ( $12^\circ\text{N}\text{-}30^\circ\text{N}$ ), the equatorial region ( $12^\circ\text{S}\text{-}12^\circ\text{N}$ ) and the southern region ( $12^\circ\text{S}\text{-}30^\circ\text{S}$ ). In general,  
205 mesoscale eddies show a growing phase during which their amplitudes, EKE and radii strongly  
206 increase. This growing phase occurs during the first 20% of their lifetime. Although the maximum  
207 values of the eddy characteristics are reached at half of the eddy lifespan, eddy properties show a  
208 plateau-like structure between 20% and 80% of their life-cycle where only slight changes are  
209 observed. During the last 20% of their life-cycle they exhibit a decaying phase during which their

210 amplitudes, EKE and radii strongly decrease. On average, eddy amplitudes change from  $\sim 0.5$  cm to  
211  $\sim 3$  cm in all three regions (Figure 2b), and eddy radii from 30 km to 70 km in the northern and  
212 southern regions, and up to  $\sim 100$  km within the central region (Figure 2e). EKE shows almost the  
213 same evolution with very weak maximum values lower than  $100 \text{ cm}^2 \text{ s}^{-2}$  in the two off equatorial  
214 regions and  $\sim 500 \text{ cm}^2 \text{ s}^{-2}$  in the equatorial region (Figure 2.c).

215 During their lifespan, eddy normalized vorticity, which corresponds to the ratio of eddy  
216 relative vorticity to the local planetary vorticity  $f$ , is less than 1 and almost constant, in all three  
217 regions though 10 times higher in the equatorial region (Figure 2f). Very weak values of  $\sim 0.07$   
218 suggest that mesoscale eddies are in geostrophic equilibrium in the off-equatorial regions. In  
219 contrast, normalized vorticity values of 0.4-0.5 suggest that ageostrophic motions might be an  
220 important component of the eddy dynamics in the equatorial region between  $12^\circ\text{N}$  and  $12^\circ\text{S}$ .

221

### 222 3.3 Eddy seasonal variability

223 The seasonal cycles of eddy properties were computed in  $2^\circ \times 2^\circ$  boxes from the 23-  
224 year period of SLA data (Figure 3). The amplitude of these seasonal cycles was determined for each  
225 eddy property as the difference between the maximum and minimum of the 12 monthly averages. In  
226 general, for each eddy property, the seasonal cycle amplitude is enhanced in i) the western part of  
227 TAO, ii) along the  $3\text{-}8^\circ\text{S}$  latitude band, and/or iii) south of  $24^\circ\text{S}$  (Figure 3). However, the most  
228 striking features are the maximum amplitudes observed in the region ( $30^\circ\text{W}\text{-}54^\circ\text{W}$ ;  $2^\circ\text{N}\text{-}10^\circ\text{N}$ )  
229 delimited by red boxes in Figure 3. In this region, which embeds the NBC retroflexion and the  
230 western part of the NECC, the seasonal cycle amplitude reaches 1,5 cm for eddy amplitude, 25 km  
231 for eddy radius and  $200 \text{ cm}^2 \text{ s}^{-2}$  for EKE representing  $\sim 60\%$ ,  $\sim 33\%$  and  $\sim 50\%$  of the mean values,  
232 respectively. The NBC retroflexion and the eastward flowing NECC exhibit a strong seasonal  
233 variability (Johns *et al.*, 1990; Garraffo *et al.*, 2003; Fonseca *et al.*, 2004) and are associated with  
234 regular eddy shedding (Johns *et al.*, 1990 Goni and Johns, 2001; Garraffo *et al.*, 2003). We thus  
235 now focus on this particular region.

236 Figure 3d-e show the number of AE and CE trajectories that were generated locally  
237 over the 23-year period and passing through each  $1^\circ \times 1^\circ$  pixel. We further delimited 2 subregions :  
238 NECC box and NBC box (numbered 1 and 2 respectively on Figure 3d-e). Indeed, more than 85%  
239 of both AE and CE generated in NECC box have a northwestward propagation and do not propagate  
240 through the NBC retroflexion area (Figure 3d-e). Those generated within the NBC box propagate  
241 northwestward along the Brazilian coast as previously observed (e.g. Goni and Johns, 2003;  
242 Fratantoni and Richardson, 2006). Both boxes exhibit a marked seasonal cycle for eddy properties,  
243 but their amplitude and phase strongly differ from one to the other. In the NECC box, AE and CE  
244 show similar seasonal variations, with maximum values in winter (December-February) and



245 minimum values in late spring/early summer except for radii whose minimum values are observed  
246 in August-September (Figure 4 a,b and d). Normalized eddy relative vorticity shows minimum  
247 values during spring (April-May) and maximum values in early fall (September-October) in the  
248 NECC box (Figure 4c). In the NBC box, CE do not show a significant variability in amplitude,  
249 radius, EKE and vorticity, while minimum values for AE are reached in early spring. The relatively  
250 high values of normalized vorticity in that box suggest that eddies are much more ageostrophic  
251 within the NBC retroflexion.

252 The number of new eddies generated over the study period exhibits a strong seasonal  
253 cycle with a minimum of 1 eddy per year generated during spring (April-May) and a maximum of 3  
254 during late summer (August- September) within the NECC box. In contrast, in the NBC box, the  
255 seasonal cycle of eddy generation is less clear, except for CE which tend to be preferentially formed  
256 in late spring and early summer (Figure 4e-f).

257 Figure 4e-f also display the monthly variations of large-scale relative vorticity,  
258 computed from the geostrophic currents climatology. It shows in both boxes a clear annual cycle  
259 and a weak semi-annual variability with two minima during spring and fall and two maxima in early  
260 winter and early summer. This variation is associated with variations of zonal equatorial currents  
261 especially the NECC, the northern branch of the SEC (nSEC) and with the variation of the NBC  
262 retroflexion (e.g. *Garraffo et al., 2003; Fonseca et al., 2004*). Similar seasonal variability was  
263 obtained for current shear and strain using both geostrophic and total surface current climatology  
264 from drifters data (not shown).

265 To further investigate the mechanism that drives eddy generation, we computed the  
266 vorticity gradient of the mean climatological currents using equation (2). The eddy generation  
267 positions were superimposed on maps of this quantity for every month. Figure 5a shows the result  
268 for January. In the NECC box, it is striking that most eddies are generated in regions where vorticity  
269 gradient changes sign and is therefore close to 0. This is further underlined in Figure 5b, which  
270 shows that most of eddies form in regions of weak vorticity gradient ( $\sim 55\%$  between  $\pm 0.2 \cdot 10^{-10} \text{ m}^{-1} \cdot \text{s}^{-1}$   
271 and  $75\%$  between  $\pm 0.3 \cdot 10^{-10} \text{ m}^{-1} \cdot \text{s}^{-1}$  within the NECC box). This indicates that barotropic  
272 instability, associated with the horizontal shear of the surface currents, is probably the main  
273 mechanism of eddy generation along the NECC. In contrast, despite an annual variability of the  
274 current vorticity in the NBC box, eddy formation sites show no clear tendency here (Figures 5a-b  
275 show that only 25% of eddy generation occur between  $\pm 0.2 \cdot 10^{-10} \text{ m}^{-1} \cdot \text{s}^{-1}$ ). Also note vorticity is  
276 negative over most of the NBC box. Thus, unlike in the NECC box, barotropic instability cannot  
277 explain eddy generation in the NBC box and other mechanisms are necessarily involved. *Johns et*  
278 *al., (1990)* suggested that eddy-shedding in the retroflexion is more likely related to a local  
279 instability process. According to *Silveira et al., (2000)*, the mechanism could be baroclinic

280 instability. Alternatively, wave reflection (*Ma 1996; Castelao 2011*) or processes related to the flow  
281 force of retroflecting current (*Nof and Pichevin 1996*) have been invoked for the generation of  
282 eddies in the NBC retroflection area.

283

#### 284 **4 Conclusions**

285 We applied an automatic eddy detection and tracking algorithm on 23 years of daily  
286 altimetry SLA to characterize mesoscale eddies in the TAO (30°N- 30°S). More than 32,000 eddy  
287 trajectories were identified and vortices are mainly generated both in the eastern part of the Atlantic  
288 ocean, especially in the two EBUS (Canary and Benguela/Angola) and in the western boundary  
289 along the Brazil current. The detected eddies present typical amplitudes, radii and EKE of around 2-  
290 5 cm, 30-100 km and 50-100 cm<sup>2</sup> s<sup>-2</sup>, respectively. The most energetic eddies are observed in the  
291 equatorial region, in particular in the retroflection of the North Brazil Current. They propagate  
292 westward almost zonally during several weeks, with velocities reaching 20 cm s<sup>-1</sup> in the equatorial  
293 band, and less than 5 cm s<sup>-1</sup> at higher latitudes. On average, mesoscale eddies show i) a growing  
294 phase during the first 20% of their lifecycle during which their amplitude, radius and EKE strongly  
295 increase; ii) a mature phase between 20% and 80% of their life cycle during which they maintain  
296 their characteristics; iii) a decaying phase during the last 20% of their lifecycle during which their  
297 properties decrease and they dissipate.

298 The seasonal cycle of the main eddy characteristics shows marked seasonal variations  
299 in specific regions of the TAO, and in particular in the NBC retroflection and along the western part  
300 of the NECC. In these regions, the seasonal variability of the eddy amplitudes, radii and EKE  
301 account for about 60%, 35% and 50% of their mean values, respectively. The more significant result  
302 is that along the NECC, east of the NBC retroflection, mesoscale eddies are likely generated by  
303 barotropic instabilities due to horizontal shear of the large-scale currents. In contrast, in the NBC  
304 retroflection region, other processes, such as baroclinic instabilities, have to be involved in eddy  
305 generation. These processes, related to the vertical structure of the stratification and currents, can  
306 not be assessed with altimetry data alone. Future studies based on a combination of satellite  
307 measurements and in-situ data or on high-resolution modelling should be conducted to determine  
308 the physical mechanisms responsible for the eddy generation in the NBC retroflection.

309

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320

321

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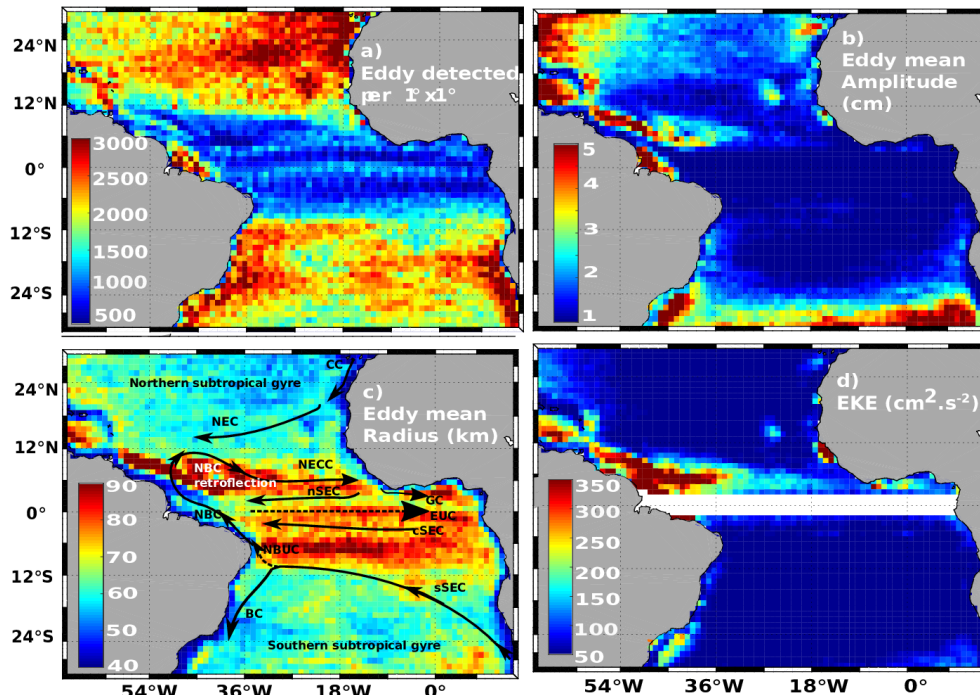
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**Figure 1 – Mean eddy properties over the 1993-2015 period: a) total number of detected eddies, b) eddy amplitude (cm), c) eddy radius (km) and (d) eddy kinetic energy ( $\text{cm}^2 \text{s}^{-2}$ ). Main currents are superimposed on figure 1c: Brazil current (BC), North Brazil Undercurrent (NBUc), North Brazil Current (NBC), Guinea Current (GC), southern, central and northern branch of South Equatorial Current (sSEC, cSEC, nSEC), North Equatorial Current (NEC), North Equatorial Countercurrent (NECC), Equatorial Undercurrent (EUC).**

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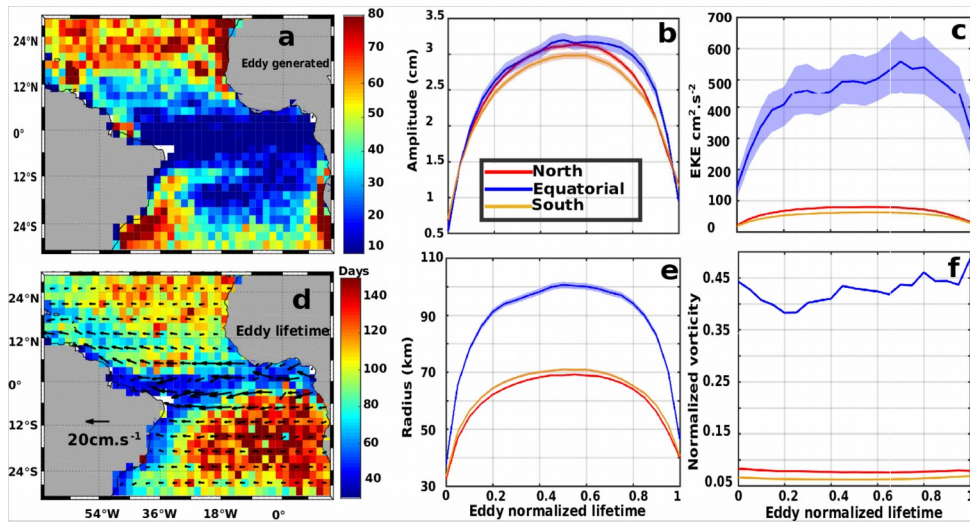


Figure 2: (a) Number of eddies generated per 2°x2° bin, and (d) eddy lifetime at birth locations (days). Arrows indicate eddy propagation speeds in cm s<sup>-1</sup>. Ensemble mean (solid lines) and standard error (shading areas) of eddy (b) amplitude, (c) kinetic energy (EKE), (e) radii and (f) normalized vorticity as a function of lifetime for the long-lived eddies.



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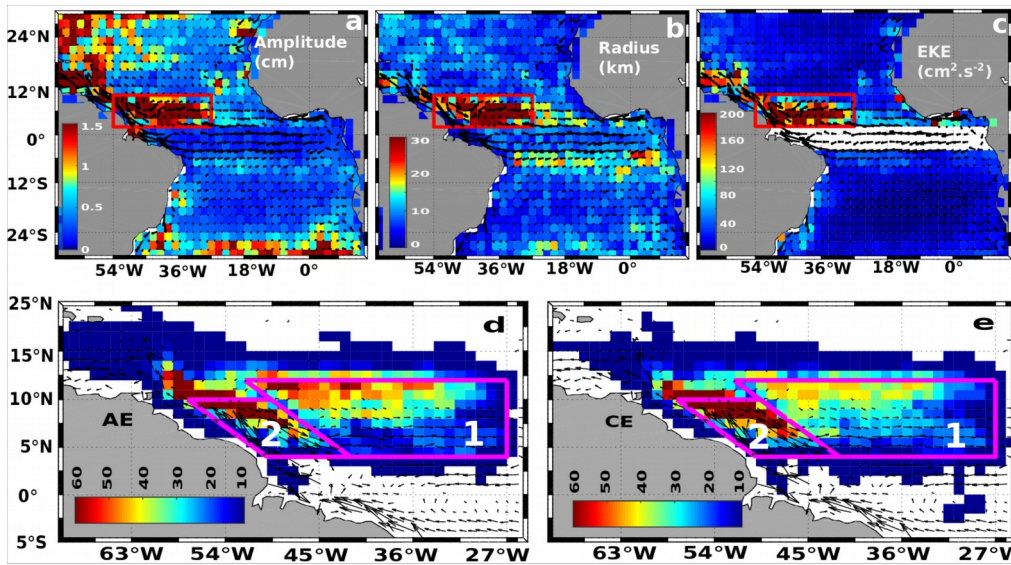
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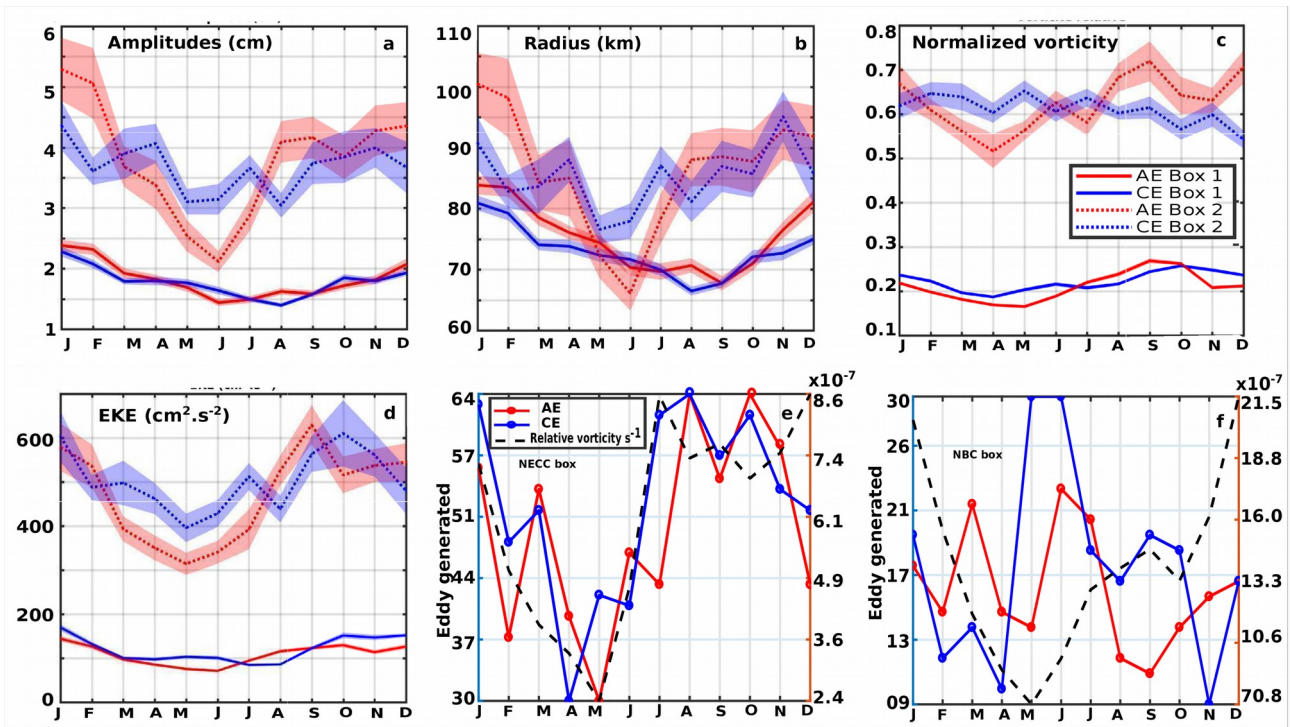
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**Figure 3 – Amplitude of the seasonal cycle of the a) eddy amplitudes (cm), b) eddy radii (km), c) EKE ( $\text{cm}^2 \text{s}^{-2}$ ). d-e) Number of AE and CE trajectories that cross each  $1^\circ \times 1^\circ$  pixel. Black arrows represent the mean large-scale currents obtained from near-surface drifters. NECC and NBC boxes are also represented (respectively labeled 1 and 2).**



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554 **Figure 4 – Seasonal cycle of eddy properties. (a) amplitude (cm), (b) radius (km), (c)**  
 555 **normalized vorticity, (d) EKE (cm<sup>2</sup> s<sup>-2</sup>) for AE (red lines) and CE (blue lines) in NECC (solid**  
 556 **lines- Box 1) and NBC (dotted lines- Box 2) boxes shown in Figure 3. (e, f) Monthly**  
 557 **cumulative eddy generated and seasonal cycle of the relative vorticity of geostrophic current**  
 558 **within NECC (Box 1) and NBC boxes (Box 2) shown in Figure 3. Shading areas are standard**  
 559 **errors evaluated using Student's test with 95% significance level.**

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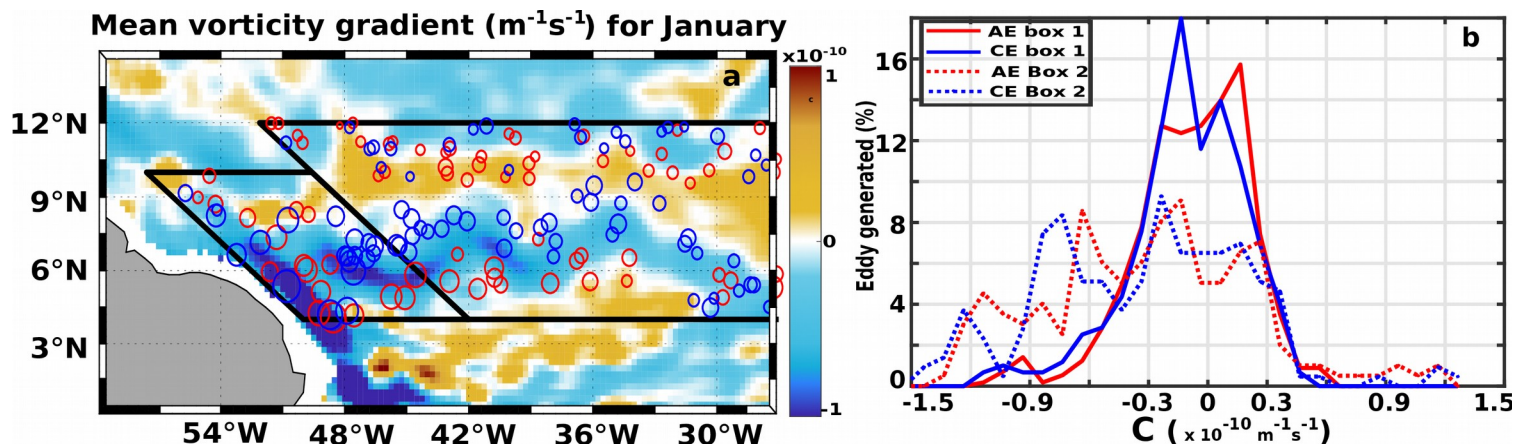
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 573 **Figure 5: (a) Mean vorticity gradient of the large-scale currents in January (color shading)**  
 574 **and location of the long-lived eddies generated in January between 1993 and 2015 (blue and**  
 575 **red circles for CE and AE, respectively). The size of circles is proportional to the mean eddy**  
 576 **relative vorticity. (b) Distributions of the percentage of eddies as a function of the gradient of**  
 577 **the large-scale relative vorticity ( $\text{m}^{-1} \text{s}^{-2}$ ) at the eddy generation sites for all eddies generated**  
 578 **between 1993 and 2015.**

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