Long-lived Mesoscale Eddies in the Northeastern Atlantic Ocean: Demography, Geometric Properties and Transport

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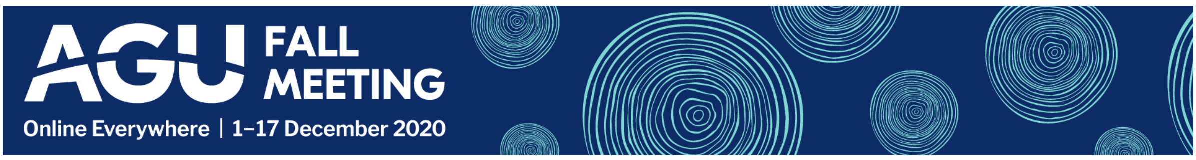


1.- INTRODUCTION

In the northeastern Atlantic Ocean, the eastward-flowing Azores Current converges towards the southwestward-flowing Canary Current, following the African coastline and leading the **Eastern Boundary Current System of the North Atlantic Subtropical Gyre**.

Based on satellite altimetry measurements (1992-2006) and *in situ* observations (1998, 2002), **Sangrà et al. (2009) described for the first time the Canary Eddy Corridor** in the northeastern Atlantic Ocean (22.1ºN - 29.1ºN) **as a zonal long-lived mesoscale eddy corridor**.

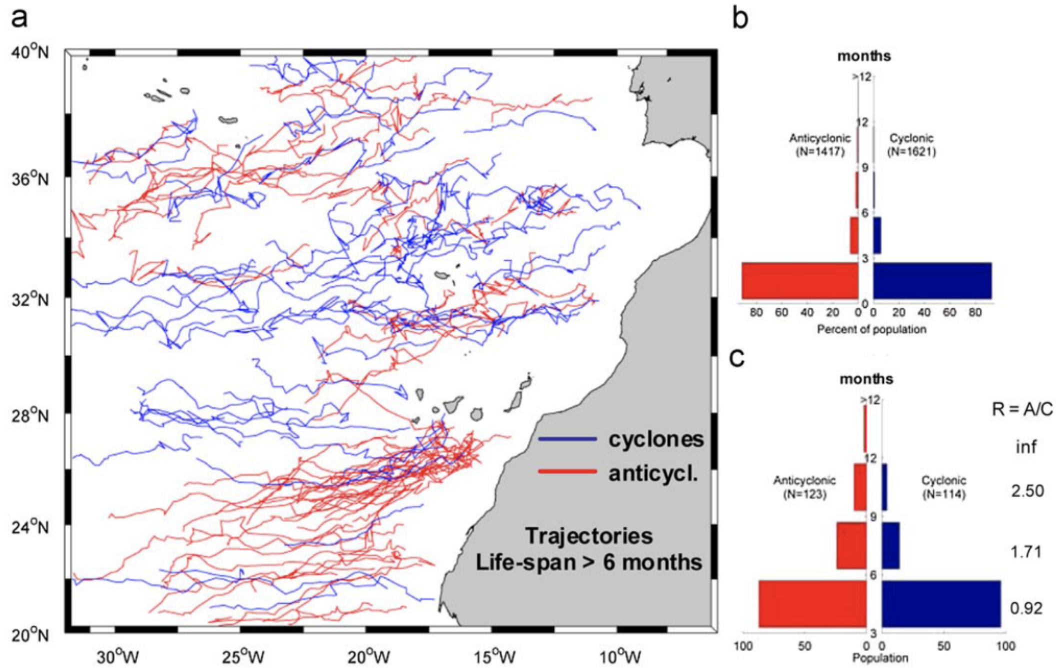


Figure 1. Westward propagating eddy trajectories lasting over 6 months, as obtained with the Okubo–Weiss technique from 14 years (1992–2006) of merged altimeter data, showing the Canary Eddy Corridor extending from 22.1 N to 29.1 N. Eastward propagating eddies and near-stationary eddies (westward propagation of less than three degrees) were filtered out. This affects only the eddy field of the Azores front that was depressed (b) age pyramid for all eddies in the Canary Eddy Corridor region, and (c) age pyramid for long-lived eddies (lifespan 43 months) in the Canary Eddy Corridor region. The ratio R between the number of anticyclones and cyclones increases with eddy age. From *Sangrá et al 2009*.

In this work, **we extend the study area and redefine five zonal corridors that expand from 12ºN to 40ºN**. The aim is to assess the potential role of these eddy corridors as **zonal conveyors of mass and ocean properties**.

2.- DATA & METHODS

The analyses are performed in terms of the **eddy demography**, **geometric properties and transport**.

To this aim we use two products: 1) **altimeter data** provided by CMEMS (Global Ocean Gridded L4 Sea Surface Heights and Derived Variables Reprocessed; *Duacs/AVISO, 2014*); and, 2) an **altimeter-based dataset of global mesoscale ocean eddies** covering the period 1992-2018 (*User Guide, 2017*). The methodology for eddy identification and tracking was firstly described in *Schlax and Chelton (2016)*.

Based on the altimeter data, the **annual mean Eddy Kinetic Energy (EKE) in Figure 2 reveals the turbulence structure of the Eastern Boundary Current System**, highlighting five areas of relatively high EKE. These areas are suggestive of **eddy generation sites (or eddy corridors)** and are used, in the following, to construct five boxes for further analysis.

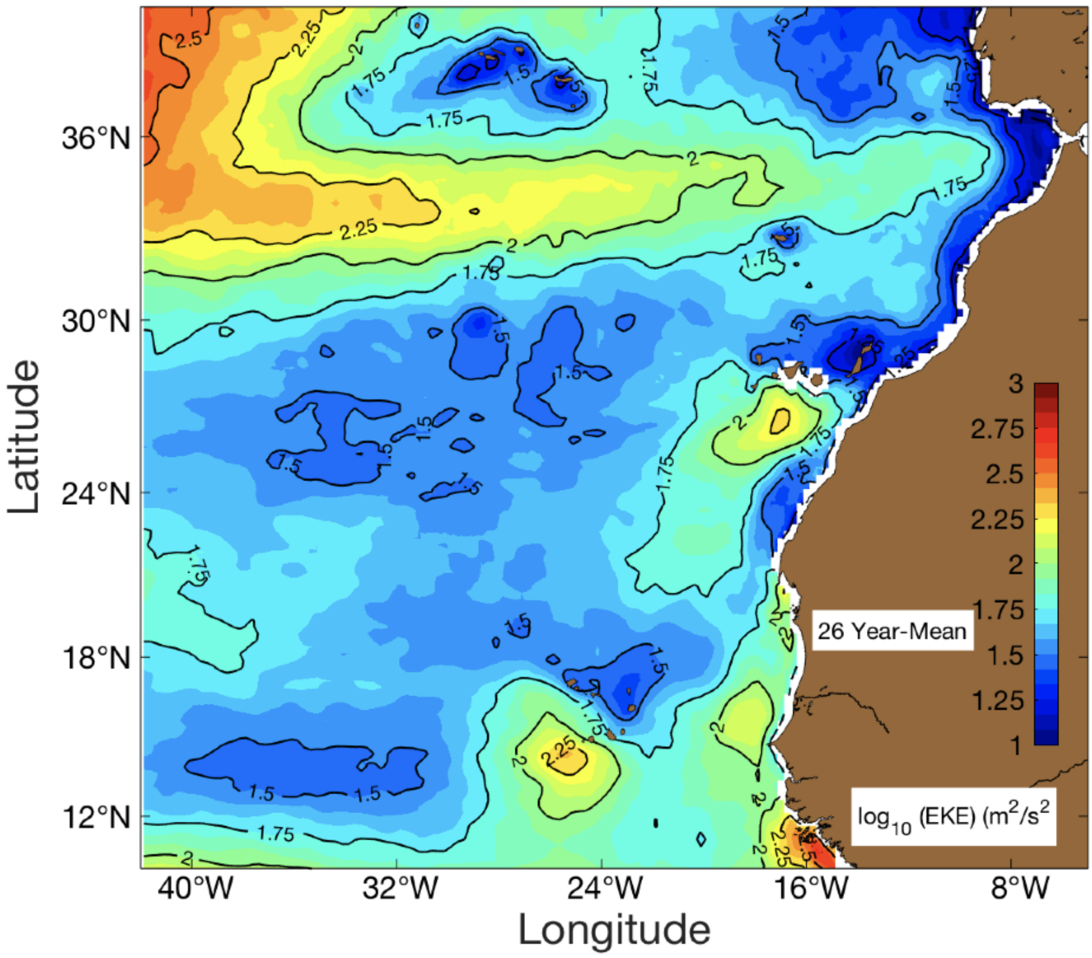
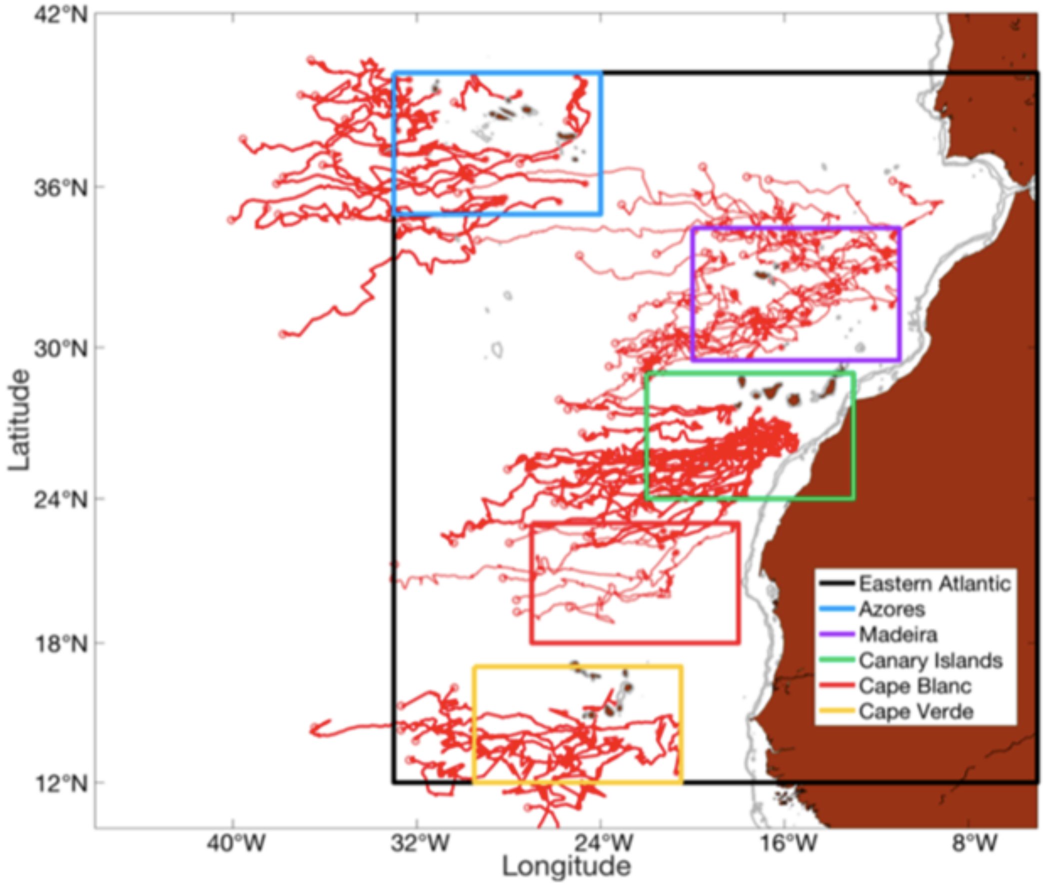


Figure 2. Horizontal map of the Eddy Kinetic Energy (EKE) in the northeastern Atlantic Ocean. Areas of high EKE indicate regions of potential eddy generation.

3.- DEMOGRAPHY

Figure 3 shows the **eddy trajectories of long-lived eddies** for the five corridors of study (see legend).



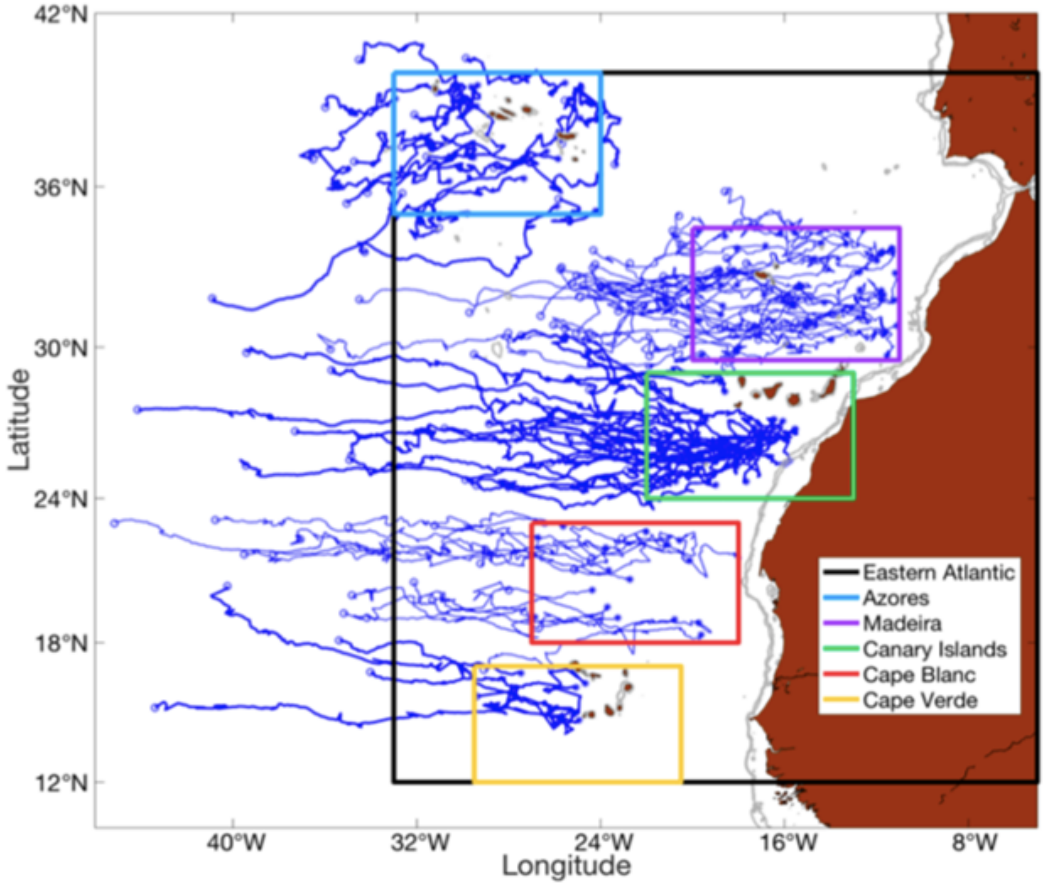


Figure 3. (a) Anticyclonic and (b) cyclonic eddy trajectories lasting > 6 months. The colored boxes show the different eddy corridors of study (see legend).

Main demographic features are summarized below, supported by satellite-based observations, in **Table 1**.

- **Anticyclonic eddies (AEs) are the most frequent type of short-lived eddies** (<3 months) everywhere but in the Azores Front Corridor.

- **Cyclonic eddies (CEs) are the most frequent type of long-lived eddies** (>6 months) everywhere but in the Cape Verde Corridor and the Azores Front Corridor, where AEs and CEs are of a similar number.

- Departing all corridors from similar numbers of short-lived eddies (240-310), we observe that **at low latitudes the generation of long-lived eddies decreases significantly** to about 5-18 eddies on record (Cape Blanc and Cape Verde Corridors).

Area	Latitude	AEs.	CEs	Ratio R = ACs/CCs
Azores	35–40°N	214 | 74 | 22	251 | 70 | 22	0.85 | 1.06 | 1
Madeira	29.5–34.5° N	251 | 76 | 44	243 | 94 | 51	1.03 | 0.81 | 0.86
Canary Islands	24–29°N	223 | 61 | 30	219 | 62 | 33	1.02 | 0.98 | 0.91
Cape Blanc	18–23°N	308 | 55 | 6	298 | 59 | 18	1.03 | 0.93 | 0.33
Cape Verde	12–17°N	256 | 29 | 8	239 | 49 | 5	1.07 | 0.59 | 1.6

Table 1: Summary table of the eddy demography by corridors. Three age population groups are considered, according to their lifetime in months: short-lived eddies (<3 months); long-lived eddies I (3-6 months); long-lived eddies II (>6 months).

4.- GEOMETRIC PROPERTIES

Zonally, results agree well with theory and show **recurrent patterns** about their geometric eddy properties. **Main features are summarized below**, supported by satellite-based observations in **Tables 2-4.**

A.- In all Eddy Ages

A.1.- **Eddy radius and propagation speeds increase with latitude**, according to theory. Both eddy types **propagate** west at approximately the **phase speed of nondispersive baroclinic Rossby waves** according to their latitude

A.2.- Within a given eddy age group, there are **no significant zonal differences in what regards to amplitudes (and rotational speeds)**

B.- Short-lived eddies (<3 months) **vs Long-lived eddies** (3-6 months; >6 months)

B.1.- **Short-lived eddies** display on average **smaller radius** than long-lived eddies do

B.2.- **Short-lived eddies** display on average **slightly smaller (and weaker) amplitudes (and rotational speeds)** than long-lived eddies do

B.3.- **Eddy propagation speeds** are similar for eddies of the same corridor **independently of the eddy age**

AEs	**Amplitude** (cm)	**Radius** (km)	**Rot. Speed** (cm s^{-1})	**Prop. Speed** (cm s^{-1})
Azores	3±1 (5)	62±13 (86)	11±2 (14)	5±27 (6)
Madeira	3±1 (4)	68±14 (93)	10±2 (12)	6±30 (6)
Canary I.	4±1 (5)	63±12 (89)	14±2 (18)	7±34 (7)
Cape Blanc	3±1 (4)	81±19 (119)	11±2 (14)	10±45 (10)
Cape Verde	3±1 (5)	95±25 (145)	14±3 (19)	13±67 (15)
CEs	**Amplitude** (cm)	**Radius** (km)	**Rot. Speed** (m s^{-1})	**Prop. Speed** (km day^{-1})
Azores	3±1 (5)	62±13 (86)	11±2 (14)	5±29 (6)
Madeira	3±1 (5)	65±13 (90)	11±2 (13)	6±30 (6)
Canary I.	3±1 (4)	66±14 (95)	12±2 (16)	8±36 (8)
Cape Blanc	3±1 (4)	83±20 (123)	11±2 (14)	11±49 (10)
Cape Verde	3±1 (5)	94±24 (146)	15±3 (20)	13±64 (14)

Table 2: Anticyclonic/cyclonic eddy geometric properties for eddies with a lifetime < 3 months.

AEs	**Amplitude** (cm)	**Radius** (km)	**Rot. Speed** (cm s^{-1})	**Prop. Speed** (cm s^{-1})
Azores	5±2 (8)	72±17 (109)	13±2 (17)	5±38 (6)
Madeira	4±1 (6)	78±20 (118)	11±2 (14)	6±43 (7)
Canary I.	5±1 (8)	71±17 (112)	15±3 (22)	7±44 (7)
Cape Blanc	4±1 (6)	89±24 (143)	13±3 (18)	9±57 (10)
Cape Verde	4±1 (6)	102±31 (183)	15±4 (22)	14±81 (17)
CEs	**Amplitude** (cm)	**Radius** (km)	**Rot. Speed** (m s^{-1})	**Prop. Speed** (km day^{-1})
Azores	4±2 (8)	75±18 (113)	12±2 (17)	5±42 (7)
Madeira	4±1 (7)	72±17 (109)	12±2 (16)	6±43 (7)
Canary I.	4±1 (6)	73±17 (115)	13±2 (18)	7±43 (7)
Cape Blanc	3±1 (5)	93±24 (151)	11±2 (15)	10±58 (11)
Cape Verde	4±1 (7)	101±28 (170)	16±4 (24)	13±82 (15)

Table 3: Anticyclonic/cyclonic eddy geometric properties for eddies with a lifetime betwenn 3–6 months.

AEs	**Amplitude** (cm)	**Radius** (km)	**Rot. Speed** (cm s^{-1})	**Prop. Speed** (cm s^{-1})
Azores	7±2 (13)	83±22 (134)	16±3 (23)	5±48 (6)
Madeira	5±2 (9)	86±22 (136)	12±3 (18)	5±47 (6)
Canary I.	7±2 (12)	70±15 (117)	20±5 (31)	7±61 (7)
Cape Blanc	5±2 (8)	88±22 (150)	15±3 (22)	8±66 (10)
Cape Verde	4±2 (8)	115±38 (210)	16±5 (27)	14±97 (16)
CEs	**Amplitude** (cm)	**Radius** (km)	**Rot. Speed** (m s^{-1})	**Prop. Speed** (km day^{-1})
Azores	6±2 (11)	80±23 (131)	14±3 (20)	5±50 (7)
Madeira	6±2 (10)	82±20 (127)	14±3 (19)	5±44 (6)
Canary I.	5±2 (9)	85±22 (141)	14±3 (21)	7±48 (7)
Cape Blanc	4±1 (7)	94±27 (165)	12±2 (18)	9±65 (9)
Cape Verde	5±1 (8)	105±32 (194)	17±5 (28)	11±86 (14)

Table 4: Anticyclonic/cyclonic eddy geometric properties for eddies with a lifetime > 6 months.

5.- TRANSPORT CAPABILITIES

Main findings are summarized below, supported on observations in **Tables 5-7**.

A.- <u>In all Eddy Ages</u>

- According to theory, **AEs always propagate with a slight deflection towards the equator**; however, **CEs only do consistently towards the pole along the low latitude corridors** (Cape Blanc and Cape Verde)

B.- <u>Short-lived eddies</u> (<3 months)

- **Mid and low latitude eddies** (Canary I., Cape Blanc and Cape Verde) **travel the farthest away due to faster propagation speeds** given that they have similar lifetimes and track stabilities

C.- <u>Long-lived eddies</u> (3-6 months, >6 months)

C.1- **Low latitude CEs** (Cape Blanc and Cape Verde) **propagate the farthest away due to a combination of longer lifetimes and higher track stabilities**, although AEs also reach on occasions as far as more than 1000 km of traveled distance

C2.- **Only AEs from the Azores Front seem more stable than CEs** having a longer lifetime, traveled distance and track stability

AEs	Lifetime (days)	Distance (km)	Track Stability	Deflection Angle
Azores	48±17 (89)	93±59 (381)	0.48±0.23 (0.98)	191±63 (358)
Madeira	48±16 (89)	97±52 (260)	0.44±0.20 (0.95)	182±63 (346)
Canary I.	49±17 (89)	138±82 (441)	0.47±0.21 (0.94)	190±45 (356)
Cape Blanc	47±16 (88)	173±97 (581)	0.48±0.21 (0.96)	181±46 (347)
Cape Verde	47±16 (89)	199±120 (766)	0.41±0.22 (0.93)	182±60 (353)
CEs	**Lifetime** (days)	**Distance** (km)	**Track Stability**	**Deflection Angle**
Azores	49±17 (88)	111±72 (331)	0.51±0.23 (0.95)	193±55 (343)
Madeira	49±17 (89)	106±64 (346)	0.48±0.21 (0.95)	186±50 (341)
Canary I.	51±18 (89)	146±84 (449)	0.46±0.20 (0.95)	186±42 (354)
Cape Blanc	49±16 (89)	185±101 (627)	0.46±0.21 (0.94)	178±47 (339)
Cape Verde	48±15 (87)	229±121 (798)	0.46±0.21 (0.98)	178±42 (305)

Table 5: Anticyclonic/cyclonic eddy traveling properties for eddies with a lifetime <3 months.

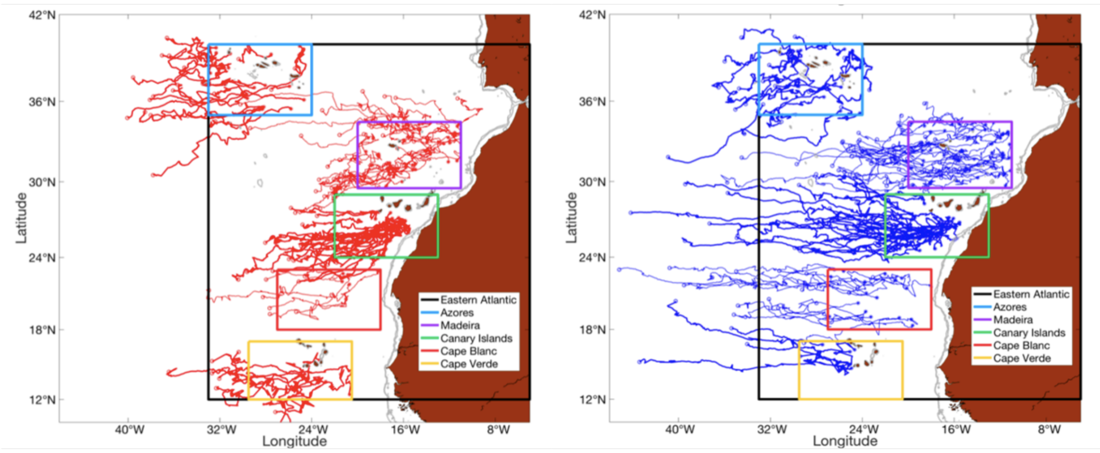
AEs	**Lifetime** (days)	**Distance** (km)	**Track Stability**	**Deflection Angle**
Azores	122±25 (176)	248±127 (610)	0.49±0.22 (0.90)	197±44 (350)
Madeira	123±24 (171)	216±105 (528)	0.38±0.17 (0.77)	195±40 (328)
Canary I.	127±26 (179)	375±123 (701)	0.50±0.14 (0.92)	194±20 (250)
Cape Blanc	122±23 (179)	422±175 (885)	0.47±0.17 (0.82)	188±22 (271)
Cape Verde	115±26 (179)	475±187 (853)	0.35±0.15 (0.74)	189±48 (300)
CEs	**Lifetime** (days)	**Distance** (km)	**Track Stability**	**Deflection Angle**
Azores	125±26 (179)	233±122 (590)	0.42±0.19 (0.84)	202±37 (334)
Madeira	125±24 (179)	269±114 (554)	0.45±0.16 (0.78)	187±23 (261)
Canary I.	125±25 (175)	342±124 (607)	0.47±0.15 (0.81)	181±21 (221)
Cape Blanc	117±23 (178)	473±172 (1085)	0.48±0.14 (0.79)	178±18 (225)
Cape Verde	121±23 (174)	643±275 (1365)	0.48±0.17 (0.84)	179±21 (271)

Table 6: Anticyclonic/cyclonic eddy traveling properties for eddies with a lifetime between 3–6 months.

AEs	**Lifetime** (days)	**Distance** (km)	**Track Stability**	**Deflection Angle**
Azores	289±91 (481)	542±285 (1083)	0.45±0.19 (0.70)	190±21 (253)
Madeira	279±100 (676)	479±254 (1273)	0.40±0.16 (0.72)	184±25 (221)
Canary I.	245±65 (488)	736±210 (1248)	0.54±0.10 (0.78)	197±13 (231)
Cape Blanc.	225±46 (315)	830±214 (1256)	0.53±0.08 (0.62)	193±10 (207)
Cape Verde.	234±40 (303)	920±237 (1281)	0.36±0.13 (0.57)	182±16 (211)
CEs	**Lifetime** (days)	**Distance** (km)	**Track Stability**	**Deflection Angle**
Azores	268±89 (463)	419±267 (1191)	0.35±0.15 (0.60)	198±31 (286)
Madeira	297±155 (985)	635±387 (2314)	0.53±0.15 (0.79)	183±14 (227)
Canary I.	318±156 (693)	1044±538 (2329)	0.59±0.12 (0.91)	175±11 (199)
Cape Blanc	269±85 (474)	1098±420 (1890)	0.55±0.12 (0.78)	179±5 (189)
Cape Verde	229±44 (304)	1200±535 (1952)	0.55±0.20 (0.68)	173±11 (187)

Table 7: Anticyclonic/cyclonic eddy traveling properties for eddies with a lifetime $\geq$ 6 months.

SUMMARY FIGURE: EDDY CORRIDORS OF THE NE ATLANTIC OCEAN



6.- CONCLUDING REMARKS

The annual-mean of EKE (log scale) in combination with an extended period of eddy tracks enable an **updated view of the eddy corridors of the NE Subtropical and Tropical Atlantic Ocean**, where these distribute following zonal pathways from 40ºN to 12ºN

Main sites of long-lived eddy generation take place along the **Azores Front** and all along the **African coastline**

6.1- **CEs are the most frequent type of long-lived eddies**, propagating the farthest away due to **longer lifetimes** and **higher track stabilities**

6.2- Both AEs and CEs reach on occasions as far as 1000 km away from their generation site, supporting their **potential as transporters of ocean properties to remote places**

6.3- Generally, **mid and low latitude eddies** encompass the **best combination to transport ocean properties to remote places** in terms of **eddy radius (size) and long traveled distances,** driven by relatively high propagation speeds

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ABSTRACT

In the northeastern Atlantic Ocean, the eastward-flowing Azores Current converges towards the southwestward-flowing Canary Current, following the African coastline and leading the Eastern Boundary Current System of the North Atlantic Subtropical Gyre. Based on satellite altimetry measurements (1992-2006) and *in situ* observations (1998, 2002), Sangrà et al. (2009) described for the first time the Canary Eddy Corridor in the northeastern Atlantic Ocean (22.1ºN - 29.1ºN) as a zonal long-lived mesoscale eddy corridor.

In this work, we extend the study area and redefine five zonal corridors that expand from 12ºN to 40ºN. The aim is to assess the potential role of these eddy corridors as zonal conveyors of mass and ocean properties. To ease its identification, we name these corridors following their generation sites: Cape Verde, Cape Blanc, Canary Islands, Madeira, and the Azores Front. We do this using an altimeter-based dataset of global mesoscale ocean eddies (1992-2018). The analyses are performed in terms of the eddy demography and eddy geometric properties.

Generally, we find that cyclonic eddies (CEs) are the most frequent type of long-lived eddies (> 6 months) everywhere but in the Cape Verde Corridor and the Azores Front Corridor, where anticyclonic eddies (AEs) and CEs are of similar number. On average, CEs propagate the farthest away due to the combination of longer lifetimes and higher track stabilities, although AEs also reach on occasions as far as 1000 km away from their generation site.

Zonally, results agree well with theory and show recurrent patterns about their geometric eddy properties, where both anticyclonic (AEs) and cyclonic (CEs) eddies display significant differences. Both eddy types increase (decrease) its radius and decrease (increase) its amplitude and rotational speeds when their corridor locates at lower (higher) latitudes. Also, observed eddies propagate west at approximately the phase speed of nondispersive baroclinic Rossby waves, according to their latitude.

These results highlight the implications of the geographical location (latitude) of the eddy corridors, suggesting that low latitude eddy corridors may generate the best candidates to convey ocean properties to remote places while these candidates are significantly less frequent than eddies of higher latitude corridors.