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Sargassum accumulation and transport by mesoscale eddies

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Abstract. The proliferation of pelagic *Sargassum* spp. (Sargassum) in the tropical Atlantic has significant ecological and socio-economic impacts. While large-scale ocean circulation patterns influence the basin scale distribution of *Sargassum*, the role of mesoscale eddies in their local accumulation and transport was not quantitatively assessed so far. This study investigates the relationship between mesoscale eddies and *Sargassum* dynamics using satellite observations. By analyzing 13 years of remote sensing observations, we demonstrate that both cyclonic and anticyclonic long-lived mesoscale eddies can trap and transport Sargassum. However, results show that in cyclonic eddies *Sargassum* cover is higher and tends to accumulate during their lifetime while within anticyclonic eddies the Sargassum cover is usually weaker and tend to decrease. These findings align with recent studies highlighting the role of eddies in shaping the distribution of floating debris and provide an important observational basis for the development of *Sargassum* drift models.

1 Introduction

Prior to 2010, the two holopelagic *Sargassum* species, *Sargassum natans* and *Sargassum fluitans* (*Sargassum* hereafter), were primarily found in the Sargasso Sea and the northwestern tropical Atlantic (Gower and King 2008). However, since 2010, these two pelagic *Sargassum* species have expanded their presence to the Tropical Atlantic (< 20° N), from the coasts of the Lesser Antilles, Central America, Brazil, to West Africa (Gower et al. 2013, Wang et al., 2019). This expansion has led to stranding events and large accumulations, resulting in significant economic and environmental damage on the coast areas of the tropical Atlantic (e.g., Rodríguez-Martínez et al. 2024, Van Tussenbroek et al. 2017, Hendy et al., 2021, Antonio-Martínez et al., 2020, Rosellón-Druker et al. 2023).

Sargassum remains afloat in the upper layer of the ocean due to its gas-filled bladders and is therefore in constant interaction with surface currents and wind. The upper ocean dynamical continuum is involved in the formation of *Sargassum* accumulations over a highly variable range of scales (see illustrations in Ody et al. 2019), from aggregations with length scale of a few tens of meters typically driven by Langmuir dynamics (Langmuir 1938) to scales that can reach hundreds of kilometers (Gower et al. 2013, Zhong et al. 2012), characteristics of mesoscale and submesoscale frontal dynamics. While the convergence zone due to mesoscale and submesoscale frontal dynamics is thought to drive the aggregations (Zhong et al. 2012), there is uncertainty about the ability of cyclonic or anticyclonic mesoscale eddies to accumulate and transport Sargassum. Theoretical and experimental developments by Provenzale (1999) suggest that only cyclones should retain floating particles. However, development of the Maxey-Raley equations to account for wind drag or elastic forces has shown antagonistic effects of these different components on the ability of cyclonic or anticyclonic eddies to attract or expel floating

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particles (Beron-Vera et al. 2021). Observations also show different behaviors. For example, limited in situ observations have revealed cases of microplastic accumulation in anticyclones (Brach et al. 2018). Instead, Vic et al. (2022) with a systematic, quantitative study, have shown a tendency for drifters to accumulate in cyclones in the North Atlantic. Thus, there is considerable uncertainty about how mesoscale eddies drive the distribution of floating objects. This is expected to depend on the nature of the object considered, and in particular its buoyancy or its wind resistance.

With respect to Sargassum, a few case studies have shown that mesoscale eddies can be transporters of Sargassum. For example, Andrade-Canto et al. (2022) shows the transport of *Sargassum* by a large eddy in the Caribbean Sea, and more recently Sun et al. (2024) presents some illustrative cases of accumulation in eddies. However, there has been no systematic assessment of the transport and organization of *Sargassum* by these eddies. We fill this gap through a systematic analysis of *Sargassum* distribution by combining eddy tracking techniques from altimetry (Chaigneau et al. 2009, Pegliasco et al. 2015, Sosa-Gutierrez et al. 2020) and long-term *Sargassum* detection from MODIS ocean color sensor (Descloitres et al. 2021) for the last 13 years.

2 *Sargassum* and eddy detection methods

Sargassum aggregations were detected by computing the Alternative Floating Algae Index (AFAI; Wang and Hu 2016) from ocean color acquisitions by the Moderate Resolution Imaging Spectroradiometer (MODIS), which operates aboard the Aqua and Terra satellites. The AFAI, computed using the processing chain described in Descloitres et al. (2021), was converted to Fractional Cover (FC), which represents the percentage of an analysis pixel covered by Sargassum. Daily detections at 1 km provided by the SAREDA database (*Sargassum* Evolving Distributions in the Atlantic, Descloitres et al., 2021) were aggregated on a regular grid of 0.25° (~25 km) horizontal resolution. These daily MODIS images have significant cloud coverage compared to multi-sensor products (e.g., Sun et al., 2024) but have the advantage of being a homogeneous series over the last 13 years. They have already allowed the tracking of high-frequency decay in the lee of tropical cyclones (Sosa-Gutierrez et al. 2022). They therefore seem well suited to the mesoscale compositing proposed in the present study. *Sargassum* biomass is obtained from *Sargassum* cover by considering an average density of 3.34 kg m^{-2} for pure *Sargassum* patches as estimated by Wang et al. (2018).

Mesoscale cyclonic and anticyclonic eddies in the Tropical Atlantic were identified from 2011 to 2023 using daily Absolute Dynamic Topography (ADT) maps at a horizontal resolution of 25 km, which are distributed by the Copernicus Marine and Environment Monitoring Service (CMEMS; https://www.copernicus.eu/en). The mesoscale eddies were detected using a method described by Chaigneau et al. (2009), with a slight modification of the methodology outlined by Sosa-Gutierrez et al. (2020). While the original method identifies the outermost closed contour of Sea Level Anomalies (SLA) for each anticyclonic and cyclonic eddy center (SLA maxima and minima, respectively) as eddy edges, the modification involves considering the outermost closed SLA where the averaged azimuthal velocity is maximum at the periphery of the eddy. The eddy-tracking algorithm, described in Pegliasco et al. (2015), involves calculating the paths of eddies by intersecting them with daily maps. For this study, only mesoscale eddies with radii larger than 40 km and lifetime greater than 30 days were retained.

An illustration of 7-day averaged *Sargassum* cover centered on June 28, 2021, together with superimposed eddy detections for the same day, is given in Figure 1. This figure illustrates that the *Sargassum* distribution is strongly structured by mesoscale eddies. To provide a systematic and quantitative view of this organization by mesoscale eddies, we composited

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the *Sargassum* coverage by selecting eddies under the following conditions: i) the detected eddy last at least 30 days, ii) during its lifetime the eddy has more than 25% of unclouded ocean color observations, iii) *Sargassum* presence is detected at least once during the eddy lifetime. This results in 471 trajectories of anticyclonic eddies (AE) and 628 trajectories of cyclonic eddies (CE) between 2011 and 2023 (Figure 2a and b, respectively). The trajectory analysis shows that AEs are predominantly found in the path of the western boundary current from the North Brazil Current (NBC) to the Loop Current, in agreement with known distribution of large anticyclonic eddies in this region (e.g. Richardson 2005, Jouanno et al. 2008). In contrast, CEs are more homogenously distributed in the central Atlantic and Caribbean Sea. The mean lifetime of AEs that captured *Sargassum* was 69 ± 40 days (mean ± standard deviation) and 65± 37 for CE; the longest-lived AE lasted 277 days and 269 days for a CE, respectively (Figure 2c-d).

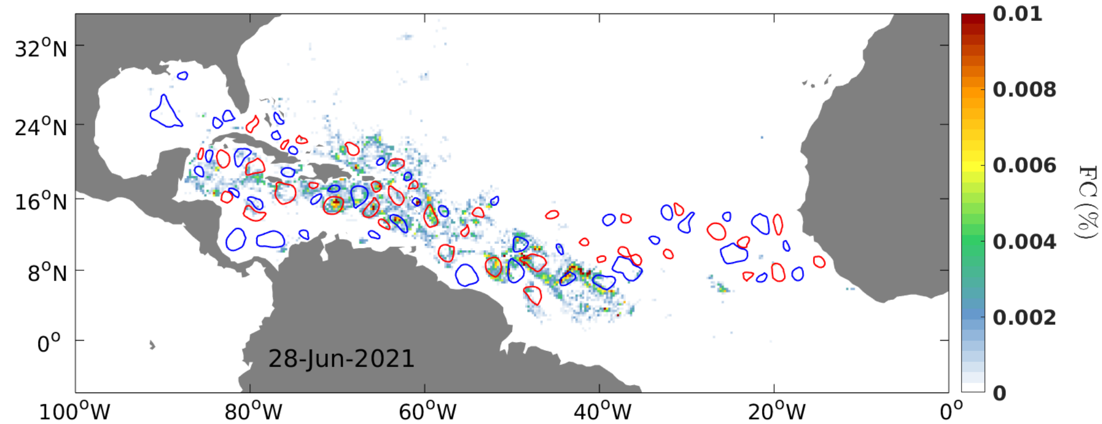

Figure 1: Distribution of *Sargassum* cover (%) obtained from MODIS and mesoscale eddy contours detected with AVISO ADT product for day June 28, 2021. *Sargassum* biomass was averaged over a 7-day period centered on day June 28 and coarsen to 0.25° regular grid. Red contours represent anticyclonic eddies, and blue contours represent cyclonic eddies.

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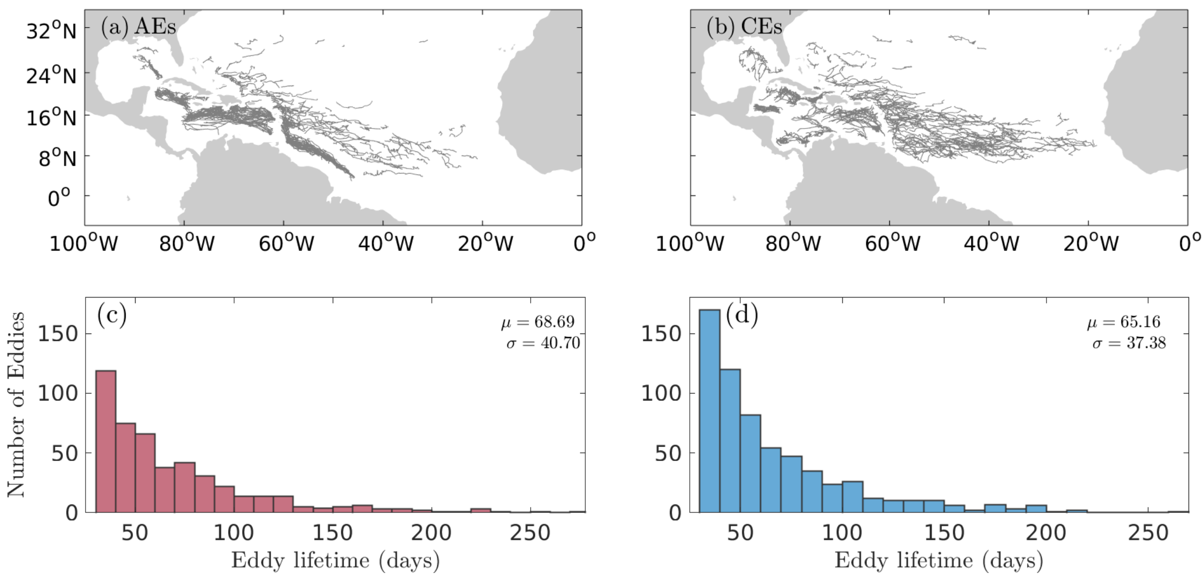

Figure 2: Eddy tracks for the period 2011-2023 with (a) trajectories of AEs and (b) trajectories of CEs that last at least 30 days and have seen Sargassum during their lifetime. (c) and (d) show histograms of the total number of AEs (red) and CEs (blue) with respect to eddy lifetime (in days).

The *Sargassum* cover within CEs and AEs and their neighborhood was averaged for each day within the period 2011-2023 for the entire Tropical Atlantic (10°W-90°W, 5°N-30°N) and in two regions where mesoscale activity and *Sargassum* presence are significant: the Caribbean Sea (61°W-90°W, 10°N-23°N), and the Central Atlantic (10°W 50°W, 5°N-15°N). To construct the composite distribution, each eddy was normalized by its radius, where radius of ±1 corresponds to the eddy periphery, 0 corresponds to the eddy center, and radius larger than +1 or lower than -1 corresponds to the region surrounding the eddy (Figure 3). This normalization allowed to account for eddies of different sizes. To verify that our compositing methodology does not introduce a bias that would favor detections of eddies with increased *Sargassum* cover, we performed a null hypothesis test by compositing the *Sargassum* distribution with the same criteria but using the eddy contours for the previous year. The results are shown in Figure 4 and confirm that the eddy trapping observed in Figure 3 and discussed below is not a bias of the methodology.

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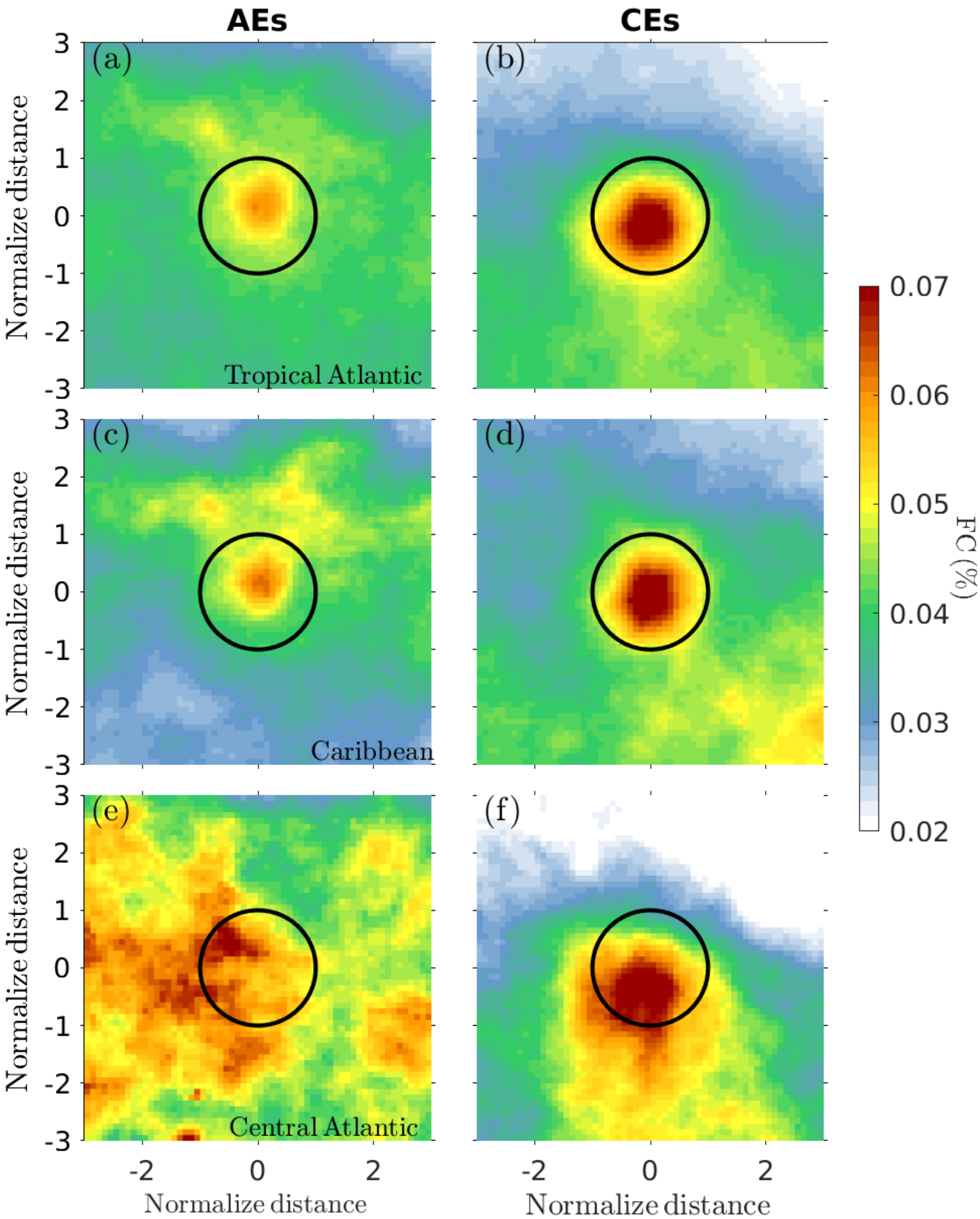

105 **Figure 3: Normalized composite averages of *Sargassum* cover (%; color) for AEs and CEs, for the following regions Tropical Atlantic (top), Caribbean (middle), and Central Atlantic (bottom). The black circle represents an idealized contour of the eddy periphery.**

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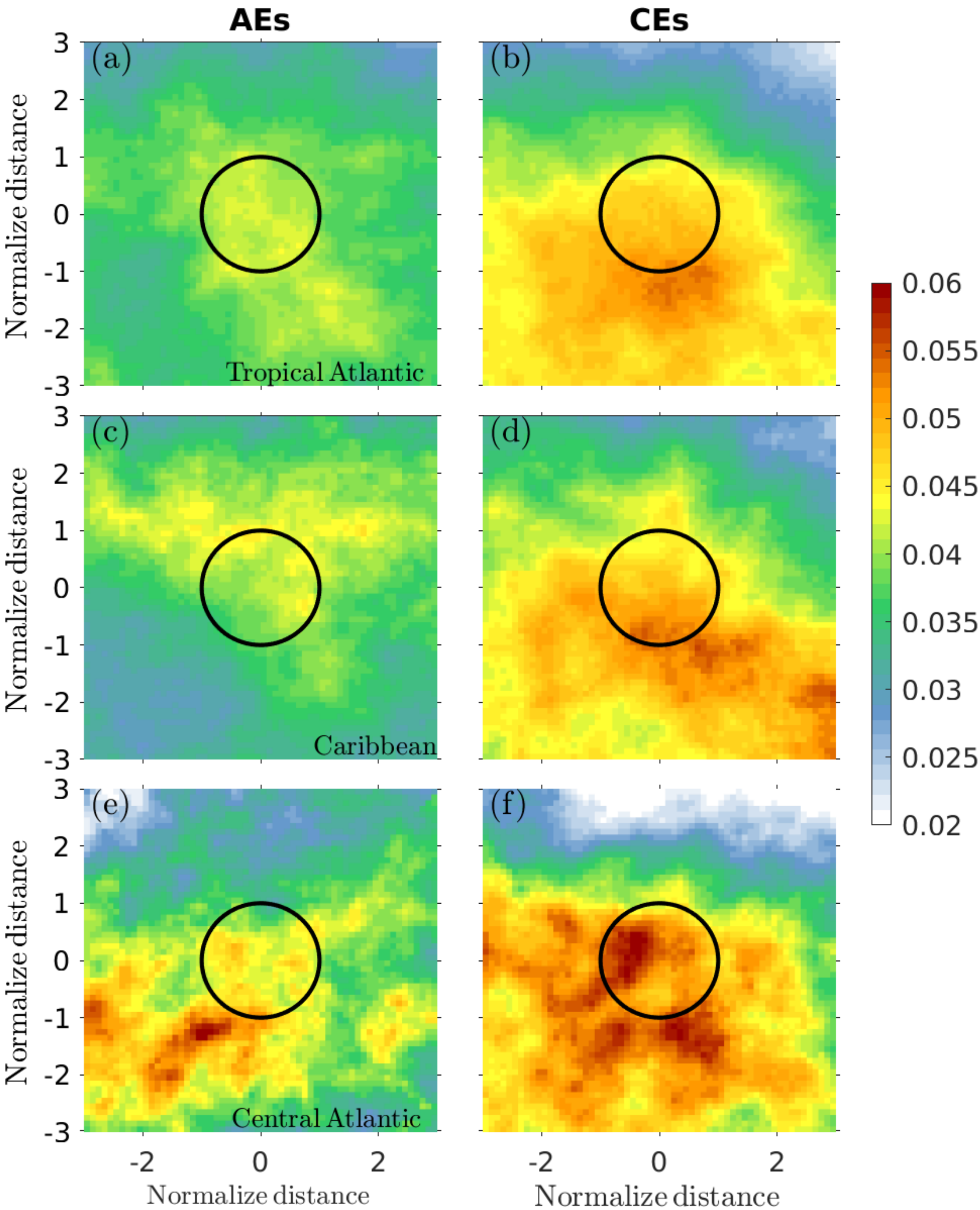

110 **Figure 4. Same as Figure 3, but the *Sargassum* cover observed for a given day have been composited using eddy detections from the previous year. The same selection criteria were used as in Figure 3. This is a null hypothesis that allows to verify that the selection of the eddy cases for the compositing (e.g. that only eddies where *Sargassum* was observed are considered) does not induce a bias in favor of *Sargassum* accumulation inside the eddies.**

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3 *Results*

The *Sargassum* cover composited for AEs and CEs in the Tropical Atlantic is shown in Figure. 3ab. It reveals that both anticyclones and cyclones accumulate *Sargassum* in their core, but with much greater accumulation of *Sargassum* in cyclones (Figure 3b) than in anticyclones (Figure 3a). There are regional differences in this distribution. In the Caribbean, for example, the contrast between AEs and CEs is pronounced (Figure 3c-d and 5d), whereas in the central Atlantic (Figure 3ef and 5g) it is much less pronounced with much more spread distribution for CEs, and no evidence for accumulation in AEs.

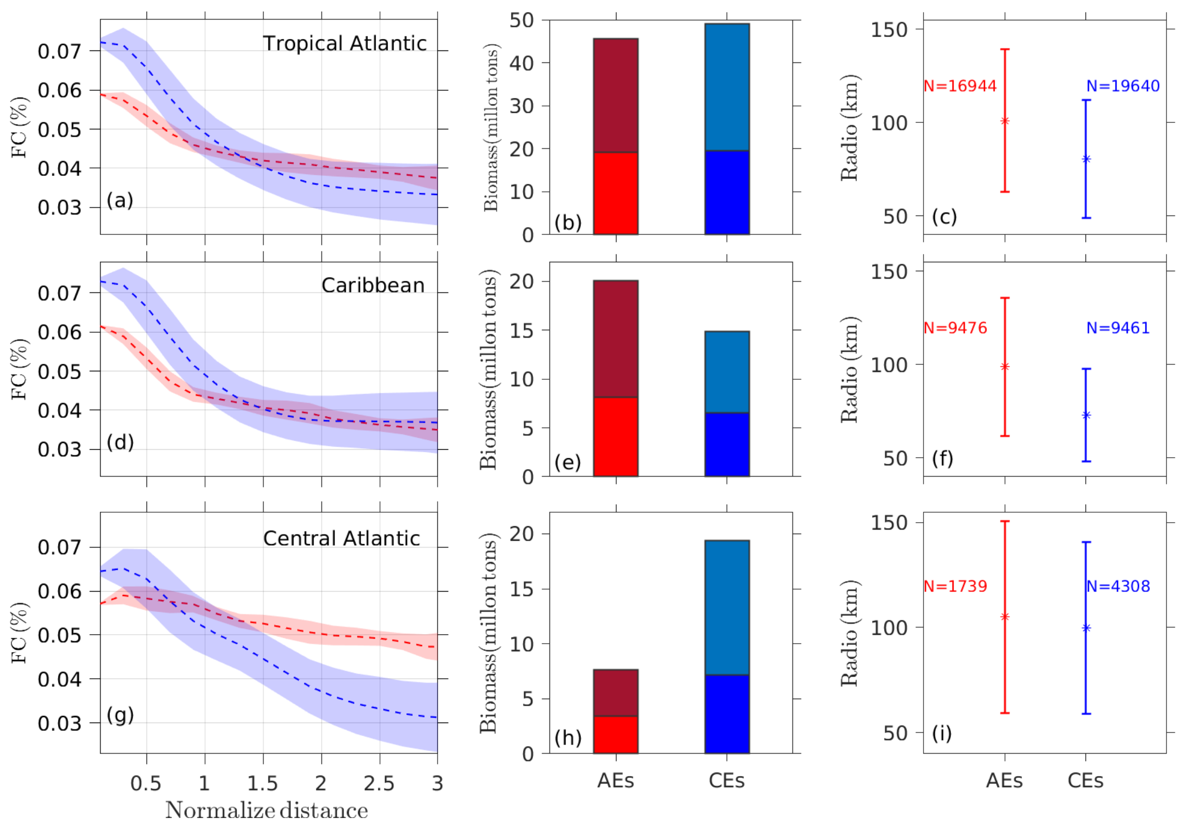

Figure 5: (a, d, g) Sargassum cover averaged within concentric radii (represented as normalize distance), the innermost radius was R = 0.1, with an interval of 0.2, until reaching radius =3 (red and blue lines correspond to AE and CE, respectively), and the red and blue shading represent one standard deviation to AE and CE. (b, e, h) Sargassum biomass within the all AEs and CEs (dark red and blue bars) compared with the Sargassum biomass in eddies propagating for at least 30 days (light red and blue bars). (c, f, i) Radius distribution (±1 standard deviation) of all eddies that contributed to build the composite, where N represents the number of eddies used for the calculation of the composites.

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In terms of biomass, the AEs and CEs transport similar amount of *Sargassum* at the basin scale (Figure 5b) but again with significant regional differences (Figure 5e-h). In the Caribbean, despite greater accumulation of *Sargassum* by cyclonic eddies, the anticyclones contain more *Sargassum* on average. This is explained by the difference in size between the two types of eddies in this region, with anticyclones being much larger than cyclones (Figure 5f). In the central Atlantic, there are many more cyclonic eddies (Figure 5i), which favors a higher biomass in cyclonic eddies. These regional differences are well illustrated in Figure 6ab, which shows a large *Sargassum* content in the AEs of the North Brazil Current, the NBC rings pathways, and the north Caribbean. The high *Sargassum* content transported by cyclonic eddies around 10°N correspond to the shear zone between the North Equatorial Current and the North Equatorial Countercurrent (Figure 6ab).

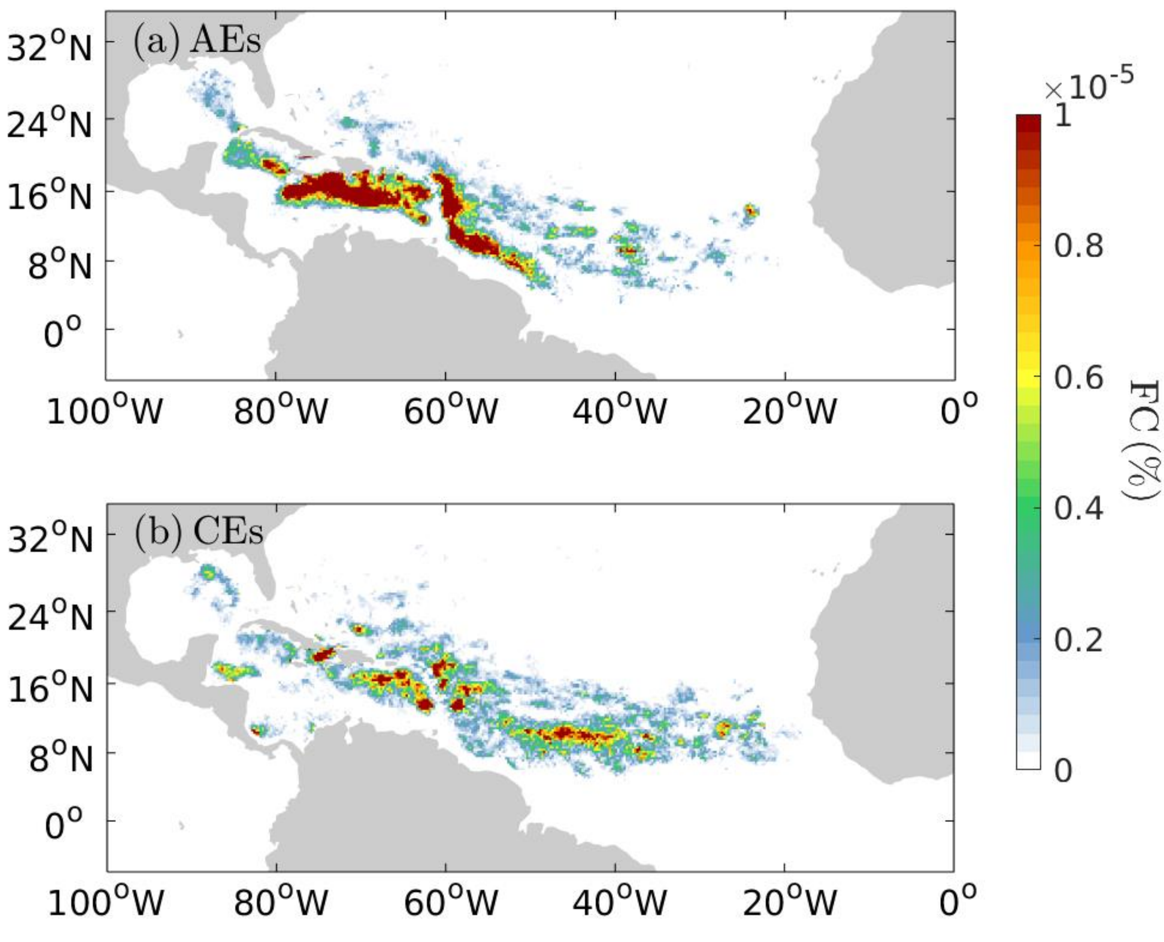

Figure 6. The *Sargassum* cover (%) within AEs and CEs during the period from 2011 to 2023.

The distribution of the *Sargassum* varies along the eddy life cycle as revealed by the evolution of the *Sargassum* cover with respect to the normalized lifetime of the eddies (Figure 7). It shows that CEs increase their *Sargassum* cover along time for all the region considered, while the *Sargassum* cover within AEs show a tendency to decrease along time, especially for the

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Caribbean Sea. It is worth noting, that the occurrence of AEs in the Central Atlantic is low (Figure 2) and therefore may contribute to a much noisier signal than in the Caribbean (Figure 7b).

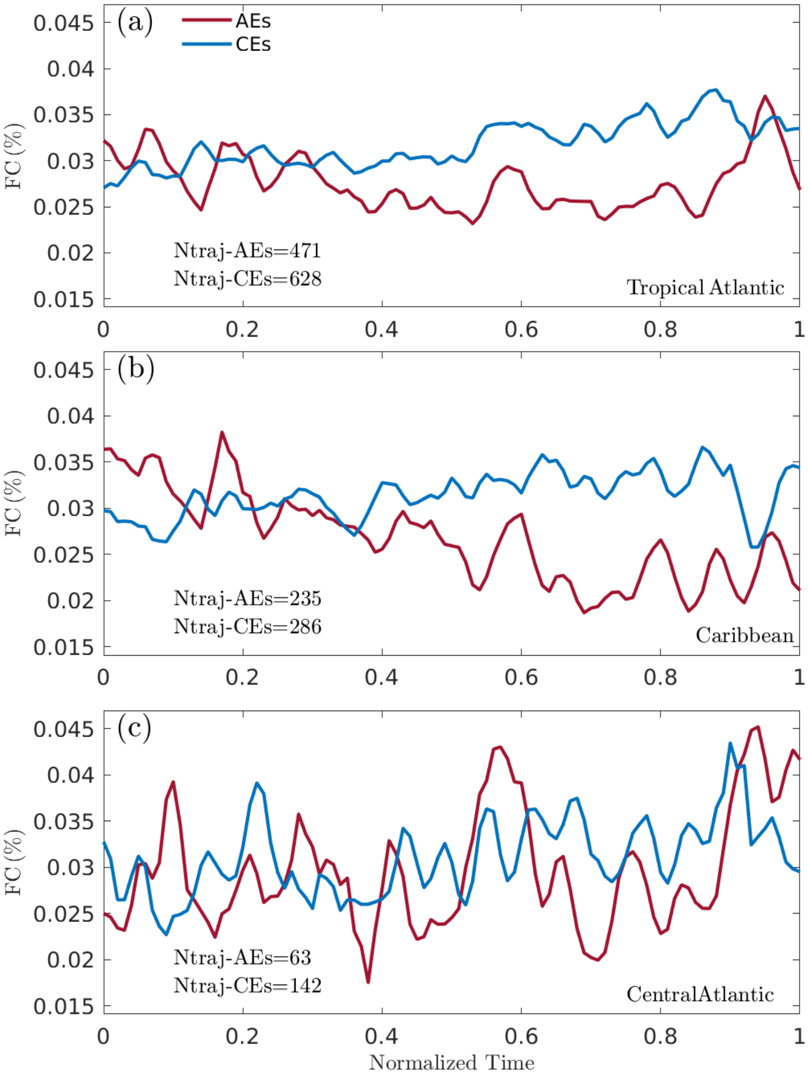

Figure 7: (a) Average temporal evolution of *Sargassum* cover as a function of the normalized eddy lifetime (AEs and CEs, indicated by red and blue lines, respectively). Ntraj-AEs and Ntraj-CEs are the number of trajectories considered for the different regions.

Figure 8a shows the mean monthly biomass of *Sargassum* aggregated across the tropical Atlantic (5-30°N and 0-100°W), showing a clear seasonal cycle characterized by a growth phase from January to July, followed by a decline phase from September to December. In addition, estimates of *Sargassum* biomass within the AEs and CEs are shown (Figure 8a). This provides insight into the periods when the retention of *Sargassum* biomass within the eddies was significant. Figure 8b

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illustrates the monthly percentage of *Sargassum* biomass contained within the AEs and CEs relative to the total biomass. The accumulation of *Sargassum* biomass by these eddies can be significant, reaching up to 20% in certain months. For example, in June 2018, this amount was equivalent to an estimated biomass of approximately 3 million tons (Mt) of Sargassum.

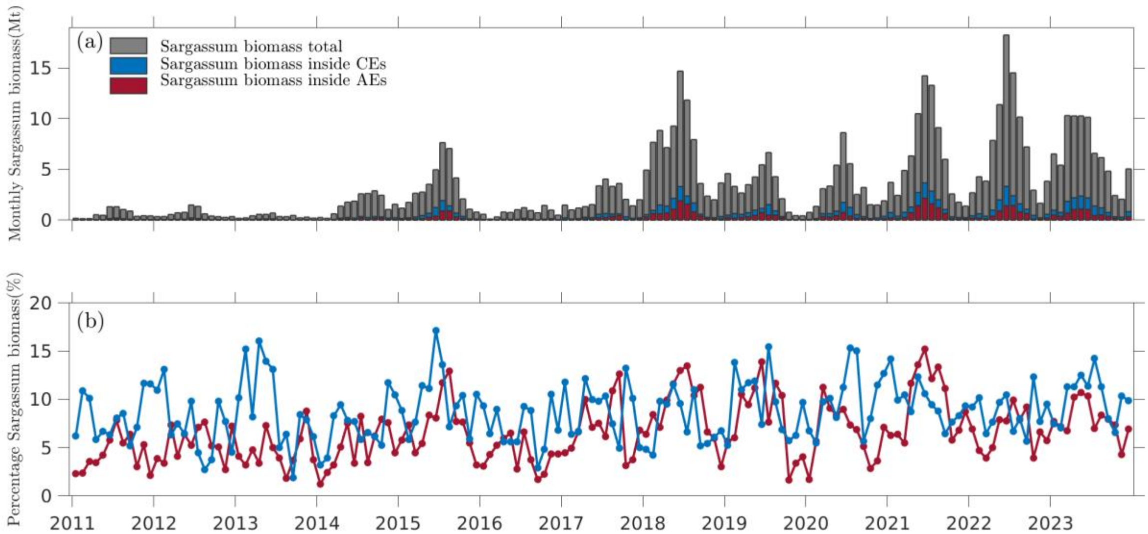

Figure 8: (a) The total monthly biomass of *Sargassum* in the tropical Atlantic (gray bars, 5-30°N and 0-100°W), and within the AEs and CEs (red and blue bars, respectively). (b) The monthly percentage of *Sargassum* biomass retained within the AEs and CEs relative to the total biomass (indicated by red and blue lines, respectively).

4 Conclusion and Discussion

This research provides new insights into the important role played by oceanic mesoscale eddies in structuring *Sargassum* biomass in the tropical Atlantic and fill a gap in our understanding of *Sargassum* organization by the ocean dynamical continuum, between the fine scale aggregation processes (Langmuir 1938, Zhong et al. 2012) and the large-scale distribution (Wang et al. 2019, Jouanno et al. 2023).

Using ADT satellite imagery, we applied an eddy detection and tracking methodology (Chaigneau et al., 2009; Pegliasco et al., 2015) to analyze the distribution of *Sargassum* detections from 2011 to 2023. By combining these observational datasets, we have shown that both mesoscale cyclonic and anticyclonic eddies can trap and transport Sargassum. This suggests that these eddies serve as effective *Sargassum* transporters and may act as connectors along the eddy propagation pathway.

Our composite analysis of *Sargassum* cover within mesoscale eddies consistently shows a preference for *Sargassum* accumulation within CEs over AEs in the tropical Atlantic, with on average 15% higher *Sargassum* cover in CEs. Although using a drogued drifter dataset, this is consistent with recent findings by Vic et al. (2022), who show a 24% higher accumulation of floating surface material in CEs compared to AEs in the North Atlantic using drifting buoy and model data sets. The tendency to accumulate or not in cyclonic and anticyclonic eddies has been shown to depend on theoretical choices and complexity of drift models (Provenzale, 1999, Beron Vera et al. 2021), so our findings should have important implications for motivating future drift model developments.

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Results also suggest that the trapping is much more effective in the Caribbean than in the Central Atlantic, as revealed by sharpest contrast of *Sargassum* cover between the interior and exterior in the Caribbean. One hypothesis is that there is a much less energetic mesoscale activity in the Central Atlantic compared to the Caribbean: weak eddy circulation and the drift associated with the trade winds may reduce the capacity of the eddies to accumulate Sargassum.

These results raise the question of how mesoscale activity could influence the growth and decay of *Sargassum* by modulating nutrient availability. It has been documented that processes such as Ekman pumping and eddy pumping act by increasing nutrients in the euphotic layer in cyclones and decreasing nutrients in the euphotic layer in anticyclones (Gaube et al., 2014, McGillicuddy, 2016). In addition to contrasted surface radial velocity properties between AEs and CEs, this could contribute to the contrasted time evolution of the distribution highlighted in Figure 7 and could modulate overall growth at the basin scale. This should receive further attention in the future.

Code and data availability. All code and processed data needed to reproduce the main results and figures in this paper have been made available via Zenodo (https://zenodo.org/records/14816717)

Author contributions. ERS, JJ and LB conceived the study, ERS and JJ wrote the manuscript, ERS, analysed the data, JJ acquired funding and managed the project. All authors reviewed and edited the draft version.

Competing interests. The contact authors have stated that none of of the authors have conflicting interests

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Open Research. The remote sensing ADT observations are available on Global Ocean Gridded L 4 Sea Surface Heights And Derived Variables Reprocessed 1993 Ongoing | Copernicus Marine Service and the *Sargassum* cover is available at https://www.odatis-ocean.fr.

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