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RESEARCH LETTER

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Key Points:

- Tropical cyclones occur in the region of massive proliferation of *Sargassum* since 2011
- High winds in tropical cyclones induce decrease of *Sargassum* coverage
- No recovery of *Sargassum* after cyclone crossing

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Impact of Tropical Cyclones on Pelagic *Sargassum*

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Abstract The strong proliferation of holopelagic *Sargassum* in the Tropical Atlantic from 2011, raises many questions on the environmental factors controlling their growth and decay at interannual, seasonal, and intraseasonal scales. In this work, we specifically investigate the response of the *Sargassum* aggregations to high wind events such as those found in Tropical Cyclones (TCs). The evolution of *Sargassum* coverage obtained from MODIS observations in the north tropical Atlantic Ocean (from 0 to 30°N and from 0 to 100°W) was analyzed under 86 historical paths of TCs and tropical storms from 2011 to 2020 that crossed *Sargassum* aggregations. Our results show on average a 40% drop in *Sargassum* coverage under TC trajectories, which can exceed 60% for the most intense TCs. We associate this drop with a sinking of *Sargassum* toward the deep ocean. Our estimates suggest that TCs contribute to the seasonal decay of *Sargassum* biomass from August to November.

Plain Language Summary The massive development of holopelagic *Sargassum* spp. in the north tropical Atlantic Ocean from 2011 to present causes annual stranding in millions of tons on the coasts of the Tropical Atlantic. The causes for this proliferation are still uncertain and may involve a combination of environmental factors. Both in areas where the presence of *Sargassum* is known for a long time, such as the Sargasso Sea and the Gulf of Mexico, and in new areas of proliferation, such as the Caribbean and the Central Atlantic, *Sargassum* are subject to Tropical Cyclones (TCs). In this work, we specifically investigate the response of the *Sargassum* aggregations to high wind events such as those found in TCs. By combining satellite observations and TC tracks from 2011 to 2020, this study shows that high winds produce massive decrease of *Sargassum* coverage as detected by satellite, which can reach 60% for the most energetic TCs. So TCs may contribute to shape the seasonal cycle of *Sargassum* coverage, and in particular its decay from July to October.

1. Introduction

The massive development of holopelagic *Sargassum* spp. in the north tropical Atlantic Ocean from 2011 to present causes annual stranding in millions of tons on the coasts of the Lesser Antilles, Central America, Brazil and West Africa (e.g., Langin, 2018; Smetacek & Zingone, 2013; Wang & Hu, 2016; Wang et al., 2019). The causes for this proliferation are still uncertain (Johns et al., 2020; Jouanno, Benschila et al., 2021; Jouanno, Moquet et al., 2021; Oviatt et al., 2019; Wang et al., 2019) and may involve a combination of environmental factors. Both in areas where the presence of *Sargassum* is known for a long time, such as the Sargasso Sea and the Gulf of Mexico, and in new areas of proliferation, such as the Caribbean and the Central Atlantic, *Sargassum* are subject to Tropical Cyclones (TCs).

Sargassum algae have characteristics that make them prone to be influenced by TCs. Their buoyancy makes them evolve almost exclusively at the surface (Butler, 1983), that is, in the zone most exposed to the mechanical energy of the TCs.

On one side, TCs could favor *Sargassum* growth and proliferation. The strong turbulence may induce fragmentation of those algae and increase their abundance, since pelagic *Sargassum* species are known to reproduce asexually by fragmentation (Awasthi, 2007; Rogers, 2011). Because they bring nutrient-rich subsurface waters within the mixed-layer, TCs are known to increase the productivity at the ocean surface. This is revealed by increased concentration of chlorophyll-a in the wake of TCs (Avila-Alonso et al., 2021; Babin et al., 2004; Menkes et al., 2016). Although this effect on the primary productivity appears to be relatively weak in the open ocean, because of a deep nitracline, as suggested in Menkes et al. (2016), we cannot discard at this stage a possible

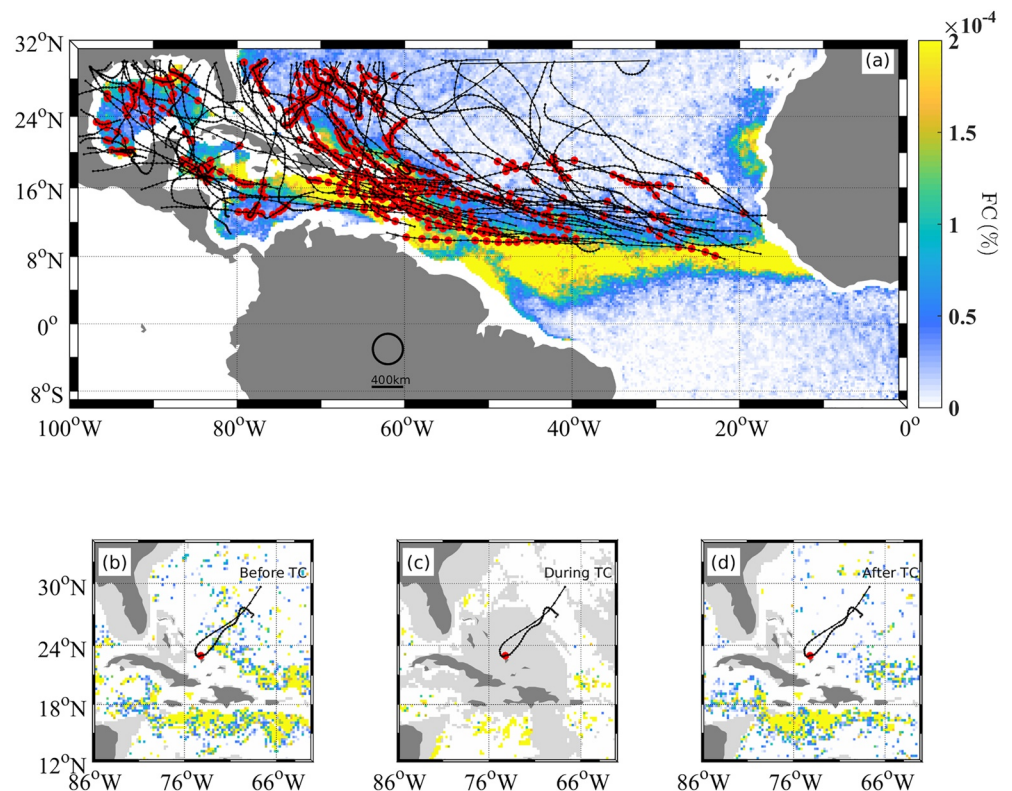


Figure 1. (a) Mean *Sargassum* Fractional Coverage (color) in the Tropical Atlantic during the hurricane season (from June to November) computed from MODIS from 2011 to 2020 at 25 km resolution. Tropical cyclones (TCs) trajectories from IBTrACS are indicated (black lines), together with the TCs positions used in the composite analysis (red points). Average *Sargassum* FC of a region under influence of TC Joaquin in 2015 that was active from 28 September 2015 to 7 October 2015 for different periods: (b) pre-storm (from September 21 to 28, 2015), (c) storm (1 October 2015, day of passage of the hurricane), and (d) post-storm (from October 4 to 11, 2015) conditions.

influence on *Sargassum* growth. On another side TCs may induce a loss of *Sargassum* from the ocean surface. Indeed, the position of the *Sargassum* at the ocean surface is maintained by their pneumatocysts (small bladders filled with gas), which could detach under strong turbulence or collapse under high pressure conditions. Johnson and Richardson (1977) suggest that the fragmentation of weed clumps due to wave action with the subsequent sinking of the older more heavily encrusted portions of the algae is one mechanism of *Sargassum* loss from the ocean surface. Circulation induced by wave-current interactions (Langmuir cells) are known to organize *Sargassum* at the surface (Langmuir, 1938) but also to induce cyclic submergence of the algae (Woodcock, 1993). From scaling and pressure chamber experiments, Johnson and Richardson (1977) suggest that Langmuir circulations may be able to transport *Sargassum* at depth long enough for the pressure to damage the pneumatocysts, causing an irreversible buoyancy loss and their sinking toward the deep ocean. This mechanism could explain the large amounts of *Sargassum* observed at the sea floor (Baker et al., 2018; Schoener & Rowe, 1970). The very high wind conditions induced by TCs may exacerbate all those different processes and could cause the sinking of important amounts of *Sargassum* toward the ocean floor.

The objective of this work is to draw on 10 years of daily remote sensing observations of *Sargassum* in the north tropical Atlantic to understand their evolution in the wake of TCs and tropical storms. This aims at providing insights on how *Sargassum* respond to high wind conditions, and more broadly to clarify the factors that may favor the large decrease of the *Sargassum* during the second half of the year (Wang et al., 2019). This question of the factors controlling the mortality is still poorly known and thus weakly constrained in *Sargassum* models (e.g., Brooks et al., 2018; Jouanno, Benschila et al., 2021, Jouanno, Moquet et al., 2021).

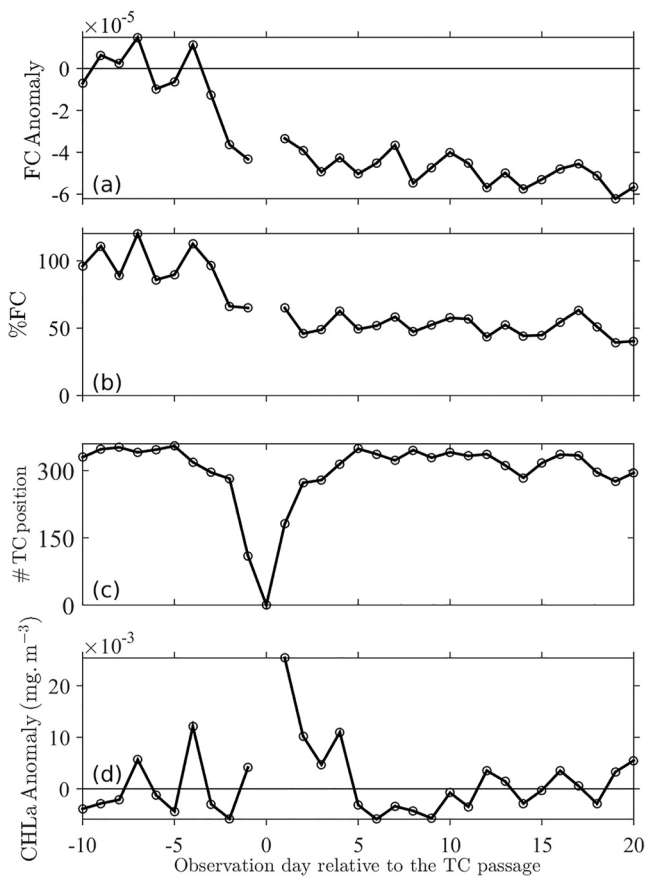


Figure 2. Composite evolution of (a) The anomalies of *Sargassum* FC with respect to the pre-storm conditions, (b) Percentage of *Sargassum* FC with respect to the pre-storm conditions, (c) The numbers of TC positions used to compute these composite values, (d) chl-a anomalies with respect to the mean chl-a pre-storm conditions. All the variables were averaged within a radius of 200 km (centered on the positions indicated in Figure 1), for each day from 10 days before to 20 days after the TC passage.

2. Data and Methods

The detection of holopelagic *Sargassum* is based on the Alternative Floating Algae Index (AFAI; Wang & Hu, 2016), and modified as in Berline et al. (2020). The AFAI is computed using data at 1 km resolution from the Moderate Resolution Imaging Spectroradiometer (MODIS) on board NASA's Aqua and Terra satellites, and converted to Fractional Coverage of *Sargassum* (hereinafter FC, representative of the fraction of a surface covered by *Sargassum*). The 1 km daily composites of FC from 2011 to 2020 were down-scaled on a regular grid of 0.25° (~25 km) horizontal resolution for faster processing. Historical position and intensity of the tropical Atlantic TCs are given each 3 hr by the International Best Track Archive for Climate Stewardship (IBTrACS; Knapp et al., 2010). Surface chlorophyll observations are from CMEMS GlobColour multi-satellite merged daily product with a spatial resolution of 0.25°. These observations are used to quantify the impact of the TCs, and indirectly infer whether the TCs contribute to a nutrient supply with impact on the primary productivity. The observations close to the coast and on the shelf (depth < 500 m) were not considered in our analysis and thus masked. This choice to consider only the open ocean response was motivated by the fact that detection of *Sargassum* near the coast is often undermined by other processes.

The response of *Sargassum* and chlorophyll to high wind events was analyzed over the north tropical Atlantic (8–30°N and 0–100°W) between 2011 and 2020, focusing on the June–November period for which TCs are more active. To do so, *Sargassum* FC and chlorophyll were daily averaged over a radius of 200 km centered on the TCs positions, from 10 days before the TC passage to 20 days after. Such a methodology is similar to the one used by others to analyze the phytoplankton or temperature response in the wake of the TCs (Avila-Alonso et al., 2019, 2021; Hernandez et al., 2016; Menkes et al., 2016; Vincent, Lengaigne, Madec et al., 2012; Vincent, Lengaigne, Vialard et al., 2012). To avoid too much overlap of averaging areas, we only used positions from the IBCTrAC database every 6 hr. We considered cases with a significant mean FC value in the pre-storm period (above 10^{-5} , averaged within the 200 km radius, between days –10 and –3 before the passage of the TCs). To limit false positive detections of *Sargassum* and suspicious

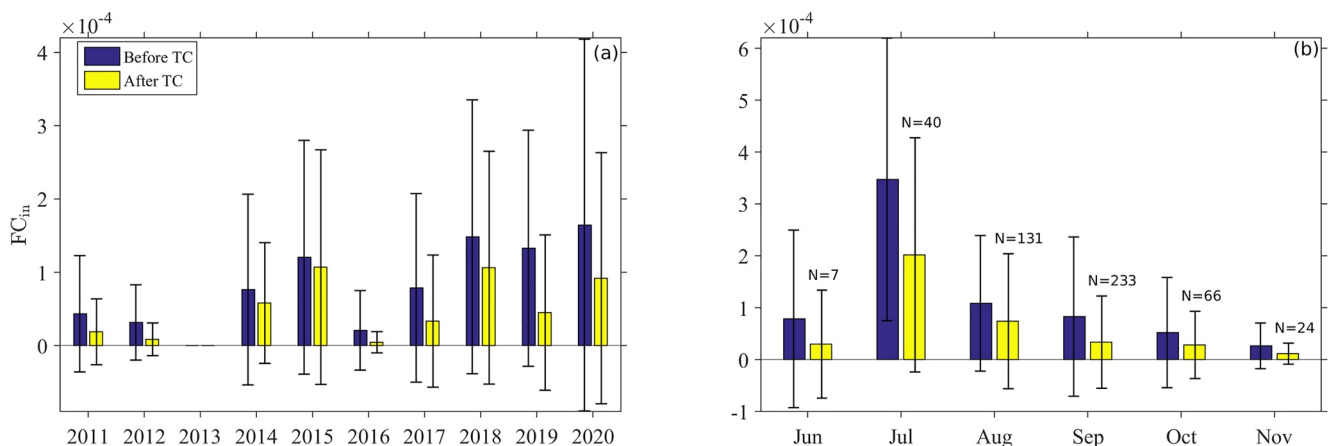


Figure 3. Average *Sargassum* FC during pre-storm (–10 to –3 days) and post-storm conditions (+3 to +20 days) for each year from 2011 to 2020 (a) and for each month from June to November (b). In (b), the number of composites used to compute each monthly mean is indicated. The error-bar is indicated by the vertical black-line, and represented the average *Sargassum* FC and its standard deviation.

Table 1
Annual Number of TCs in the Tropical Atlantic From the IBTrACS Database, and Number of TCs That Crossed Important Amounts of Sargassum and Were Included in the Analysis

Year	Tropical Atlantic TCs	TCs that crossed important amounts Sargassum
2011	19	13
2012	19	9
2013	14	-
2014	8	6
2015	11	6
2016	15	7
2017	17	10
2018	17	8
2019	18	9
2020	30	18

extreme values, we removed TC areal average with percentage of cloudiness above 50% and or with very high average FC values ($>10^{-3}$). In addition, time series showing high variance (standard deviation of FC twice larger than the pre-storm mean FC value) were not considered. In total, 501 TC positions (from 86 different TC events) were considered for the period 2011–2020.

3. Results

The average distribution of Sargassum from 2011 to 2020 during the North Atlantic hurricane season (June–November) is shown in Figure 1a. TCs trajectory and the positions used to compute the composite evolution of both surface chlorophyll and Sargassum FC are also indicated. The mean distribution of Sargassum is in agreement with basin scale observations by Wang et al. (2019) or Gower and King (2020). Figure 1a illustrates that during that period Sargassum aggregations are under the influence of TCs. This co-occurrence happens predominantly in the region surrounding the Lesser Antilles and the Sargasso Sea, and to a lesser extent in the central tropical Atlantic and in the Gulf of Mexico. As an example, average Sargassum FC before and after the passage of cyclone Joaquin in 2015 is shown in Figures 1b–1d, illustrating how the average distribution of FC after Joaquin's passage is reduced compared to the pre-cyclone state.

Daily values of Sargassum FC of all TC events are averaged for each day relative to the passage of the TCs to produce the composite evolution of Sargassum FC around the TCs passage, from 10 days before to 20 days after. The composite evolution of the Sargassum FC around the TCs passage is shown in Figure 2. The FC anomalies are calculated with respect to the mean value taken from the pre-storm observations. The evolution of FC shows on average a drop of 3.5×10^{-5} in terms of Sargassum surface coverage. Considering a surface density of 3.34 kg m^{-2} (Wang et al., 2018), this corresponds in average to a local loss of 15,000 tons of Sargassum within a radius of 200 km centered on the TC position. Note that the Sargassum coverage starts to decrease 2 days before the passage of the hurricanes; this is due to slowly propagating TCs that are accounted in the average. Moreover, the observability of Sargassum is reduced near the date of the TC passage because of cloudiness (Figure 2c).

Since Sargassum coverage shows strong seasonal and interannual variations, the average FC drop in Figure 2a may be biased by situations with strong Sargassum coverage. So, we also show the evolution of the Sargassum FC normalized with respect to the pre-storm Sargassum FC. In this way, we give the same weight to each event in our composite. That reveals that TCs cause a Sargassum loss of $\sim 50\%$ on average (Figure 2b).

The average Sargassum response to TCs for each year from 2011 to 2020 is shown in Figure 3. The number of TCs tracks considered per year is given in Table 1. The drop in Sargassum coverage caused by TCs occurred every year but with different amplitudes. The picture that emerges is those years with intense TC activity (e.g., 2017–2020) caused larger loss compared to years with lower activity (e.g., 2014–2015). To investigate whether hurricane intensity can modulate loss, differences in Sargassum coverage between pre- and post-storm observations are given in Figure 4 as a function of TC category. Although it shows a broad variance in the Sargassum response, it also indicates an overall increase in response for major hurricanes (3–5) compared to moderate hurricanes (1 and 2) and tropical storms. Not surprisingly, the general picture is that stronger winds favor higher losses.

At the seasonal scale, monthly FC in pre- and post-storms conditions illustrates that the largest TC-induced decrease of Sargassum coverage occurs in September (Figure 3b), which is the month with the largest number of TCs. That seasonal pattern also emphasizes the fact that hurricanes pass through

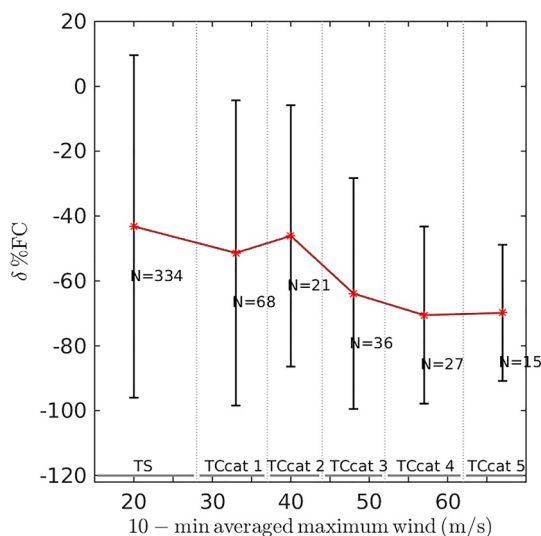


Figure 4. Sargassum FC change as a function of the averaged maximum wind associated to the Tropical Cyclones (TCs) categories. Change is computed as the % difference between post-storm (+3 to +20 days) and pre-storm conditions (−10 to −3 days). The error bars show the average Sargassum FC and its standard deviation (black vertical-line).

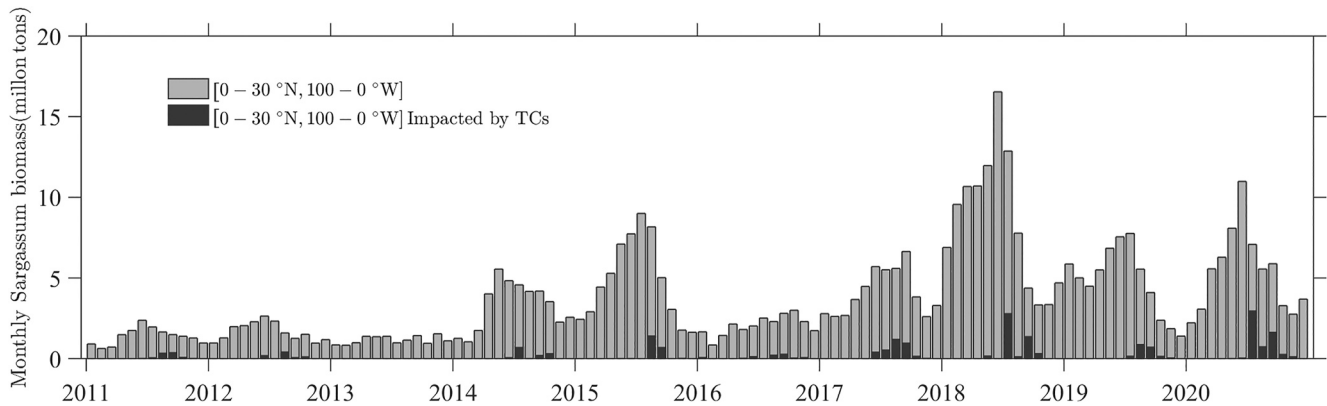


Figure 5. Monthly *Sargassum* biomass (in gray) in the tropical Atlantic basin ($0\text{--}30^{\circ}\text{N}$, $100\text{--}100^{\circ}\text{W}$, $\sim 7.37 \times 10^8 \text{ km}^2$) and monthly *Sargassum* biomass of the fraction that was under the influence of the high TC winds (in black). The area of influence of the Tropical Cyclones (TCs) winds for a given month is computed considering each TC imprint on the ocean, considering all the TCs positions each 3 hr and a 200 km radius of influence. The biomass was estimated from the FC by considering a density of *Sargassum* of 3.34 kg m^{-2} (Wang et al., 2018).

Sargassum aggregations during a period when *Sargassum* abundance is decreasing, and thus could accelerate or contribute to that decrease.

The analysis of chl-*a* response to TCs sheds light on a possible nutrient supply, in response to mixing and upward advection of subsurface waters, that could benefit the *Sargassum*. We used the evolution of chl-*a* concentrations as a proxy for the evolution of the primary production and indirectly as an indication of a nutrient supply. On average, the maximum chl-*a* anomalies occurred 1 day after TCs with a maximum of $+0.02 \text{ mg m}^{-3}$. These increased chl-*a* concentrations persist for the next 4 days after the passage of the TCs, in good agreement with previous studies (e.g., Avila-Alonso et al., 2021; Babin et al., 2004; Menkes et al., 2016). This is indicative that TCs induce a fertilization of the upper ocean which may also fuel *Sargassum* growth. Nevertheless, it appears that this contribution, which we are unable to quantify at this stage, cannot offset the loss of *Sargassum*. Indeed, there is no indication in Figures 2a and 2b that *Sargassum* FC recovers in the weeks following the passage of the TCs.

4. Discussion and Conclusion

By combining satellite observations and TC tracks from 2011 to 2020, this study shows that high winds produce massive decrease of *Sargassum* coverage as detected by satellite, which can reach 60% for the most energetic TCs. At this stage, the processes involved in this decrease remain uncertain. Satellite-detected *Sargassum* coverage is sensitive to the existing cloud coverage rate under the TCs. Cloud coverage increases from $\sim 25\%$ days prior to the TC passage to $\sim 100\%$ by the time the TC passes, as observed in the number of TC positions (Figure 2c).

TCs cross the *Sargassum* aggregations during a period of the year where the *Sargassum* biomass is declining, so one possibility would be that clumps are older and more brittle than younger ones, so its bladders could be more sensible to the turbulence caused by the TCs. Surface wave breaking, deep Langmuir circulations, submesoscale vertical motion, direct wind action on *Sargassum* outcropping at the surface, all may act to detach or damage the bladders and cause the sinking of the algae. The decrease of FC may also be caused by the “dilution” of *Sargassum* aggregations under TC, dropping below the detection limit (FC = 0.2% for 1 km MODIS pixels according to Wang & Hu, 2016).

After the TC passages, we did not observe *Sargassum* recovery although some signs of a nutrient supply to the mixed-layer are revealed by increased chl-*a*. This may be due to the relatively slow growth rate of *Sargassum* (maximum of 0.1 d^{-1} , Lapointe et al., 2014). Moreover, nutrients supplied to the surface ocean in response to the passage of TCs could be more opportunistically consumed by phytoplankton beforehand.

In order to provide an estimate of the seasonal impact of the TCs on the seasonal decrease of tropical Atlantic *Sargassum* total biomass, we computed for each month from 2011 to 2020 the *Sargassum* biomass that had been under influence of the cyclonic winds, and compared it with the total biomass (Figure 5). This time series

suggests that at a seasonal scale the amount of *Sargassum* under the influence of TCs is relatively important and can reach ~25% during some months (e.g., during July 2018 we estimate that about 2.5 million tons of *Sargassum* have been subject to TC winds). So TCs may contribute to shape the seasonal cycle of *Sargassum* coverage, and in particular its decay from July to October.

At a basin or global scale, Atlantic pelagic *Sargassum*'s role in carbon fixation and sequestration to the deep ocean is certainly insignificant compared to the role of phytoplankton (Hu et al., 2021). However, as discussed by Baker et al. (2018), the large-scale sedimentation of *Sargassum* could form an important trophic link between surface and benthic production. Our study suggests that TCs may be active players in those fluxes.

Data Availability Statement

The *Sargassum* fractional coverage database was processed by AERIS/ICARE Data and Services Center at the University of Lille, in collaboration with the MIO (<http://org.doi.org/10.12770/8fe1cdcb-f4ea-4c81-8543-50f0b-39b4eca>). GlobColour data (<http://globcolour.info>) used in this study has been developed, validated, and distributed by ACRI-ST, France. TC tracks were obtained from the International Best Track Archive for Climate Steward (IBTrACS) database (<https://www.ncdc.noaa.gov/ibtracs>; last access 10/2021).

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