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1 Evolution of the riverine nutrient export to the Tropical  
2 Atlantic over the last 15 years: is there a link with  
3 *Sargassum* proliferation?

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21 **The Tropical Atlantic is facing a massive proliferation of *Sargassum* since 2011, with**  
22 **severe environmental and socioeconomic impacts. As a contribution to this proliferation,**  
23 **an increase in nutrient inputs from the tropical rivers, in response to climate and land use**  
24 **changes or increasing urbanization, has been often suggested and widely reported in the**  
25 **scientific and public literature. Here we discuss whether changes in river nutrient inputs**  
26 **could contribute to *Sargassum* proliferation in the recent years or drive its seasonal cycle.**  
27 **Using long-term *in situ* and satellite measurements of discharge, dissolved and particulate**  
28 **nutrients of the three world largest rivers (Amazon, Orinoco, Congo), we do not find clear**  
29 **evidences that nutrient fluxes may have massively increased over the last 15 years.**  
30 **Moreover, focusing on year 2017, we estimate that along the year only 10% of the**  
31 ***Sargassum* biomass occurred in regions under river plume influence. While deforestation**

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2  
3 32 **and pollution are a reality of great concern, our results corroborate recent findings that**  
4  
5 33 **hydrological changes are not the first order drivers of *Sargassum* proliferation. Besides,**  
6  
7 34 **satellite observations suggest that the major Atlantic river plumes suffered a decrease of**  
8  
9 35 **phytoplankton biomass in the last two decades. Reconciling these observations requires a**  
10  
11 36 **better understanding of the nutrient sources that sustain *Sargassum* and phytoplankton**  
12  
13 37 **growth in the region.**

### 14 15 38 **Context**

16  
17 39 Before 2010, holopelagic *Sargassum* spp. were preferentially found in the Sargasso Sea and in  
18  
19 40 the Gulf of Mexico. They now develop in large quantities on the southern part of the North  
20  
21 41 Atlantic between 0 and 10°N forming a '*Sargassum* belt' stranding in millions of tons on the  
22  
23 42 coasts of the Lesser Antilles, Central America, Brazil and West Africa. (e.g., Smetacek and  
24  
25 43 Zingone 2013, Wang and Hu 2016, Langin 2018, Wang et al. 2019).

26  
27 45 Satellite imagery pointed to the presence of large amounts of *Sargassum* in areas under seasonal  
28  
29 46 influence of the Amazon plume (Gower et al. 2013, Sissini et al. 2017, Oviatt et al. 2019, Wang  
30  
31 47 et al. 2019) raising the hypothesis that river nutrient fluxes might play a role in this proliferation  
32  
33 48 (Langin 2019, Wang et al. 2019, Oviatt et al. 2019). A possible influence of the Congo has also  
34  
35 49 been invoked in several studies (Djakouré et al. 2017, Oviatt et al. 2019). A recent study by  
36  
37 50 Johns et al. (2020), however, did not find strong evidence to support this hypothesis as there  
38  
39 51 appears to be a spatiotemporal mismatch between *Sargassum* occurrence and these riverine  
40  
41 52 sources of nutrients. Given the importance of this question and the present discrepancies in the  
42  
43 53 scientific literature we find it important to examine to which extent the riverine source of  
44  
45 54 nutrients may contribute to the proliferation of pelagic *Sargassum*. Indeed, several elements  
46  
47 55 give support to a possible influence of the riverine sources of nutrients. First, rivers export  
48  
49 56 nitrogen and phosphorus, which are key limiting nutrients required for *Sargassum* growth  
50  
51 57 (Lapointe 1986, 1995). Specifically, the Amazon also contains important concentrations of  
52  
53 58 dissolved organic substrates that could be an important source of nutrient for *Sargassum* growth  
54  
55 59 as reviewed in Oviatt et al. (2019). Second, the Tropical Atlantic receives the fresh and nutrient  
56  
57 60 rich waters of the three largest rivers on the planet - in terms of flow (Amazon, 209 000 m<sup>3</sup> s<sup>-1</sup>,  
58  
59 61 Congo, 42 000 m<sup>3</sup> s<sup>-1</sup> and Orinoco, 35 000 m<sup>3</sup> s<sup>-1</sup>), which alone represent 21% of the total global  
60  
61 62 riverine flow (Milliman and Farnsworth, 2011). Their low-saline and productive plumes extend  
62  
63 63 thousands of kilometers far offshore (Muller-Karger et al. 1988, Signorini et al. 1999). Third,  
64  
65 64 the watersheds undergo strong climatic and anthropogenic pressures that are thought to have

1  
2  
3 65 the potential to modify oceanic biogeochemical systems. For instance, Seitzinger et al. (2010)  
4 66 estimated that the total river input of nitrogen to the coastal seas has approximately doubled  
5 67 since the 70s, with South America representing ~20% of the global increase. The Amazon basin  
6 68 already shows some signs of a transition to a disturbance-dominated regime in response to  
7 69 agricultural expansion and climate variability (Davidson et al. 2012). The region experiences a  
8 70 strong anthropogenic pressure associated with a rapid urbanization (Richards and VanWey,  
9 71 2015), intense hydropower dam construction (Latrubesse et al. 2017), and increase of mining  
10 72 and oil extraction contamination (e.g. Moquet et al., 2014). The overall consequences of these  
11 73 changes in terms of nutrient budget remain uncertain since they can act as a source or a sink of  
12 74 nutrients.

13 75 In this context, the long-term evolution of the continental nutrient export to the Tropical  
14 76 Atlantic is investigated on the basis of *in situ* observations of the major dissolved and particulate  
15 77 nutrients exported by the three main rivers of the basin (Amazon, Orinoco and Congo). Satellite  
16 78 estimates of chlorophyll provide an independent set of observations to monitor the long-term  
17 79 changes of biological activity in the large river plumes. Finally, the large-scale seasonal  
18 80 distribution of *Sargassum* for year 2017 is confronted to numerical experiments of river plume  
19 81 dispersal. We focused on this year because basin scale *Sargassum* fractional coverage  
20 82 observations from MODIS were available (Berline et al. 2020), with concurrent observations  
21 83 carried out during two cruises in the Tropical Atlantic (Ody et al. 2019). Year 2017 was the  
22 84 third most important year of the decade in terms of quantity of *Sargassum* (as inferred from  
23 85 time series in Wang et al. 2019), with a seasonal pattern that closely mirrors the averaged  
24 86 seasonal pattern from Wang et al. (2019).

### 25 87 **River nutrient fluxes**

26 88 The productivity of the *Sargassum* is enhanced by N (nitrogen) and P (phosphorus) availability  
27 89 (Lapointe, 1995). At global scale, the rivers carry N to oceanic coastal zone in dissolved and  
28 90 particulate forms in almost equal proportion (Joo et al., 2013) while P is mainly exported as  
29 91 particulate form (90-95% of the total P flux to the ocean; Ruttenberg, 2004). About 25-45% of  
30 92 the particulate P (Ruttenberg, 2004) and a significant proportion of particulate N are reactive in  
31 93 the sea water and bioavailable for marine organisms including the seaweed. The dissolved and  
32 94 particulate N and P fluxes measured or estimated at the seaward-most stations for the Amazon,  
33 95 Orinoco, and Congo basins are shown in Figure 1 for the last two decades. These data were  
34 96 collected by the SO-HYBAM observatory and are presented together with riverine flux  
35 97 calculation methods in the supplementary material.

98

99 For the three rivers, the largest input of N is provided by the dissolved organic matter. Dissolved  
100 organic nitrate delivered by the Amazon is thought to become bioavailable in the offshore  
101 fraction of the plume through bacterial and photochemical transformations (Medeiros et al.  
102 2015). For the Amazon, this flux appears to regularly increase from 2004, apart from maxima  
103 in years 2007 and 2008. Observations for the Orinoco suggest a doubling of this flux over the  
104 last 15 years (Figure 1). The particulate fluxes of N, estimated from remote sensing, is also  
105 expected to contribute to nutrient supply through desorption of the shelf (Demaster and Aller  
106 2000). It is stable for the three rivers. The dissolved inorganic N flux, computed from  $\text{NO}_3^-$  in  
107 situ measurements, show larger values during the last decade for the three rivers (Figure 1a-c).  
108 Before 2013, values above the detection limit (0.01 mg/l) were of similar magnitude than  
109 independent Amazon (Richey et al. 2009, Ward et al. 2015, Doherty et al. 2017), Orinoco  
110 (Lewis and Saunders, 1989) and Congo (Descy et al., 2016) water analyses. They did not show  
111 a marked evolution over this period. From the years 2013-2014, the average concentration of  
112  $\text{NO}_3^-$  has increased for the three rivers. On the one hand, the scatter of the measured  
113 concentrations is so high that it is difficult to determine how significant the  $\text{NO}_3^-$  increase really  
114 is. On the other hand, the more frequent recording of high  $\text{NO}_3^-$  fluxes is of concern and suggests  
115 a potential evolution of the dissolved  $\text{NO}_3^-$  export that needs to be investigated. However, it  
116 should be noted that the marked changes in terms of  $\text{NO}_3^-$  for the different rivers occurred 2-3  
117 years after the first massive proliferation of 2011.

118

119 In the Amazon river, the largest amount of P is delivered in particulate form (Figure 1g). The  
120 importance of the particulate P is in line with observations by Berner and Rao (1994) who  
121 conclude that the solubilization of P from bacterial decomposition of river-transported organic  
122 matter and desorption from ferric oxide/hydroxide may result in an effective flux of reactive P  
123 about three times greater than that carried only in dissolved form. This particulate flux shows a  
124 slight decrease over the last two decades, while the inorganic and organic dissolved fluxes  
125 remained stable. The P fluxes for the Orinoco and Congo are one order of magnitude smaller  
126 than those of the Amazon.

127

128 So, observations show different long-term trends of inorganic, organic and particulate fluxes of  
129 N and P. No direct and clear relationship with *Sargassum* growth can be drawn, neither in terms  
130 of long-term evolution, nor in terms of interannual variability (e.g. no major peak of nutrient  
131 fluxes was observed during the record *Sargassum* years 2015 and 2018, and there is no clear

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2  
3 132 relation with the basin scale *Sargassum* biomass time series from Wang et al. 2019). Large  
4  
5 133 uncertainties remain in the nutrient fluxes estimation and the fate of these nutrients in the open  
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7 134 ocean, but these results already question whether the order of magnitude of the observed trends  
8  
9 135 and variability are large enough to contribute to the inter-annual variability of the oceanic  
10  
11 136 biological response.

12 137

### 13 138 **Link with changes in plume productivity and *Sargassum* distribution**

14  
15 139 The diversity of the nutrient trends and the lack of knowledge on the lability of the dissolved  
16  
17 140 and particulate riverine material render uncertain the assessment of the long-term evolution of  
18  
19 141 the riverine fertilization of the ocean. As an independent marker of possible changes in the  
20  
21 142 nutrient export by the large tropical Atlantic rivers, the long-term evolution of surface  
22  
23 143 chlorophyll estimated from satellite ocean color is now analyzed. Chlorophyll is the main  
24  
25 144 pigment in phytoplankton and here we use chlorophyll as a proxy of phytoplankton biomass.  
26  
27 145 As it has been evidenced for the Mississippi in the northern Gulf of Mexico (Lohrenz et al.  
28  
29 146 1997, Rabalais et al. 2002, Wysocki et al. 2016), we expect that fluctuations in riverine nutrients  
30  
31 147 alter the dynamics of phytoplankton growth and thus phytoplankton biomass in the large  
32  
33 148 tropical river plumes. The difference between the “*Sargassum* period” (2011-2018) and the  
34  
35 149 years before (2003-2010) reveals an overall decrease of the chlorophyll concentration in the  
36  
37 150 tropical Atlantic (Figure 2b). This decline is sharper in the Amazon, Orinoco, and Congo plume  
38  
39 151 regions. Since Chlorophyll retrieval from space is subject to large discrepancies between the  
40  
41 152 different available products, we compared five monthly chlorophyll products from three  
42  
43 153 different groups (GlobColour, NOAA, and CCI). For the three rivers considered, four out of  
44  
45 154 the five different products show a consistent decrease of Chlorophyll concentration in the plume  
46  
47 155 areas (Figure S5).

48  
49 156 The basin scale decrease of chlorophyll evidenced in Figure 2b is in line with the study by  
50  
51 157 Gregg and Rousseau (2019) that suggested that global net ocean primary production has  
52  
53 158 experienced a small but significant decline in the 18-year satellite records from 1998 to 2015,  
54  
55 159 in response to shallowing surface mixed layer depth, decreasing nitrate supply and changes in  
56  
57 160 the phytoplankton communities. Chlorophyll concentrations in river plumes exhibit a larger  
58  
59 161 decrease. The underlying cause of these changes in the chlorophyll content of the plumes is  
60  
162 difficult to ascertain from observations only. It is worth mentioning that 1) colored detrital  
163 material contributes to total light attenuation in the blue region of the spectrum where  
164 chlorophyll-a also absorbs strongly (Fournier et al. 2015) which could lead to large errors in

1  
2  
3 165 ocean color retrievals, 2) the response of the productive plumes may not only depend on the  
4  
5 166 riverine nutrient flux but on other variables such as temperature, stratification, turbidity, or dust  
6  
7 167 deposition. But this decrease, whether it is caused by a decrease of plume productivity or  
8  
9 168 weaker discharge of dissolved colored material (which is not observed in SO-HYBAM  
10  
11 169 observations of organic and particulate nutrient fluxes, Figure 1) is difficult to reconcile with  
12  
13 170 the hypothesis of an overall increase in fertilization by tropical rivers in recent years. A better  
14  
15 171 understanding of the river plume biogeochemistry is required, together with analysis of possible  
16  
17 172 competing growth dynamics between phytoplankton and *Sargassum*.

18 173 The seasonal distribution of *Sargassum* for year 2017 is shown in Figure 3 together with the  
19  
20 174 chlorophyll concentrations. The *Sargassum* bloom during the first 6 months of the year occurs  
21  
22 175 preferentially in the Intertropical Convergence Zone (ITCZ; located between the equator and  
23  
24 176 10°N), where chlorophyll is relatively high compared to the surrounding subtropical  
25  
26 177 oligotrophic area. To our knowledge, the causes of the high chlorophyll level have not been  
27  
28 178 identified, but could be the result of diatoms-diazotroph assemblages (Subramanian et al. 2008,  
29  
30 179 Schlosser et al. 2014), atmospheric deposition of dust (Yu et al. 2015), or biomass burning  
31  
32 180 emissions (Barkley et al. 2019). Yet, the presence of relatively high chlorophyll concentration  
33  
34 181 indicates nutrient availability that may participate to sustain *Sargassum* growth.

35 182 Interestingly, we remark that during September-October, when the North Brazil Current  
36  
37 183 retroflects and transports the Amazon riverine freshwater to the east, the abundance of  
38  
39 184 *Sargassum* in the plume area between 60°W and 40°W, is drastically reduced relative to the  
40  
41 185 two previous months. The North Brazil Current is mainly fed by waters originating from the  
42  
43 186 equatorial area and the southern Tropical Atlantic (Johns et al. 1998) where no massive  
44  
45 187 proliferation of *Sargassum* was observed in the previous months. Our interpretation is that the  
46  
47 188 weak abundance of *Sargassum* in the plume at this time is mainly controlled by advection of  
48  
49 189 low *Sargassum* water in the region. The low salinity of the plume could also limit the  
50  
51 190 proliferation of *Sargassum* there. Indeed, culture experiments of *Sargassum natans* and  
52  
53 191 *Sargassum fluitans* described in Hanisak and Samuel (1987) revealed some dependence of their  
54  
55 192 growth rate to salinity. A reduction in salinity from 36 to 30 caused a reduction in the growth  
56  
57 193 rates by almost half, and no growth was observed for salinity below 18. This effect may likely  
58  
59 194 limit the fertilizing effect of the nutrient rich river plumes.

58 195 The river plume dispersion numerical experiment (Figure 3) also reveals that the central  
59  
60 196 Atlantic is not under the influence of the Amazon plume during the first half of the year. The



1  
2  
3 197 largest coincidence between the plume and *Sargassum* distribution occurs in June-July-August  
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5 198 (Figure 4), when the Amazon plume extends toward the Lesser Antilles. This is in line with the  
6  
7 199 analysis by Gouveia et al. (2019) that showed that the Amazon plume fingerprints on oceanic  
8  
9 200 primary productivity spatio-temporal variability are restricted to the western Tropical Atlantic.  
10  
11 201 The first 6 months of the year appear to be crucial for the occurrence of *Sargassum* along the  
12  
13 202 south American and Caribbean coasts a few months later (Wang and Hu 2017, Putman et al.  
14  
15 203 2018, Wang et al. 2019, Berline et al. 2020). Even if Amazon river fertilization could contribute  
16  
17 204 to the seasonal growth in the portion of western tropical Atlantic under seasonal influence of  
18  
19 205 the Amazon plume (an area between 60°W and 40°W and between 0° and 20°N), this analysis  
20  
21 206 further suggests that it does not drive the large-scale seasonal bloom. At the annual scale, we  
22  
23 207 found that only 9% of the *Sargassum* biomass occurred in the river plume area in 2017, with  
24  
25 208 occurrence below 5% from September to May and peak at 23% in July when the plume is well  
26  
27 209 extended toward the Lesser Antilles. It is even more unlikely that the Congo and Orinoco rivers  
28  
29 210 could contribute to the large-scale bloom due to the limited imprint of the plumes on the  
30  
31 211 chlorophyll distribution and remoteness of the river plumes from the main *Sargassum* bloom  
32  
33 212 areas.

34  
35 213

36 214 As a conclusion, while increasing inputs of nitrogen and phosphorus in the watershed from  
37  
38 215 human activity, predominantly from land-based activities, are thought to have the potential to  
39  
40 216 significantly increase the nutrient fluxes toward the ocean and have been proposed as  
41  
42 217 contributors of the *Sargassum* proliferation, this analysis suggests that riverine fertilization is  
43  
44 218 unlikely a key controlling factor of both seasonal and interannual variability of the *Sargassum*  
45  
46 219 biomass. In agreement with recent findings by Johns et al, (2020), it fails to explain the  
47  
48 220 *Sargassum* distribution shift that occurred after 2010. Instead, Johns et al. (2020) proposed that  
49  
50 221 an extreme negative phase of the North Atlantic Oscillation triggered the 2011 event and that  
51  
52 222 vertical mixing dynamics below the ITCZ sustains *Sargassum* growth in the Central Tropical  
53  
54 223 Atlantic. This is in line with the enhanced chlorophyll concentrations observed below the ITCZ  
55  
56 224 (Figure 4). However, the forcing processes sustaining the productivity there remain to be  
57  
58 225 clarified. This study also reminds us that advection is instrumental in controlling the seasonal  
59  
60 226 distribution of *Sargassum*, as already revealed by several studies (Brooks et al. 2018, Wang et  
227  
228 al. 2019, Berline et al. 2020). Although much progress has been made recently on how  
*Sargassum* advection responds to currents and winds (Berline et al. 2020, Putman et al. 2020,

1  
2  
3 229 Miron et al. 2020), this issue has yet to be fully evaluated and understood. That key aspects of  
4  
5 230 growth and movement are missing from for our ability to understand and forecast  
6  
7 231 spatiotemporal variability in the distribution of pelagic *Sargassum*.

## 9 232 **Methods**

10  
11 233 Methods and associated references are available in the supplementary material.

## 13 14 234 **Acknowledgment**

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28 241 providing hydrogeochemistry Amazon river data.

## 29 30 243 **Authors contributions**

31  
32 244 All authors contributed to the interpretation of the results and writing of the manuscript. J.J. and  
33  
34 245 J.S.M. designed the study. J.J. implemented the numerical simulations, and conducted the  
35  
36 246 comparison with observations. G.M.M and F.M. participated to the long-term hydrological  
37  
38 247 measurements. J.S.M, W.S. and J.M.M. performed the hydrological analysis. L.B. and W.P.  
39  
40 248 produced the basin scale *Sargassum* observations. M.H.R. contributed to the ocean color  
41  
42 249 analysis.

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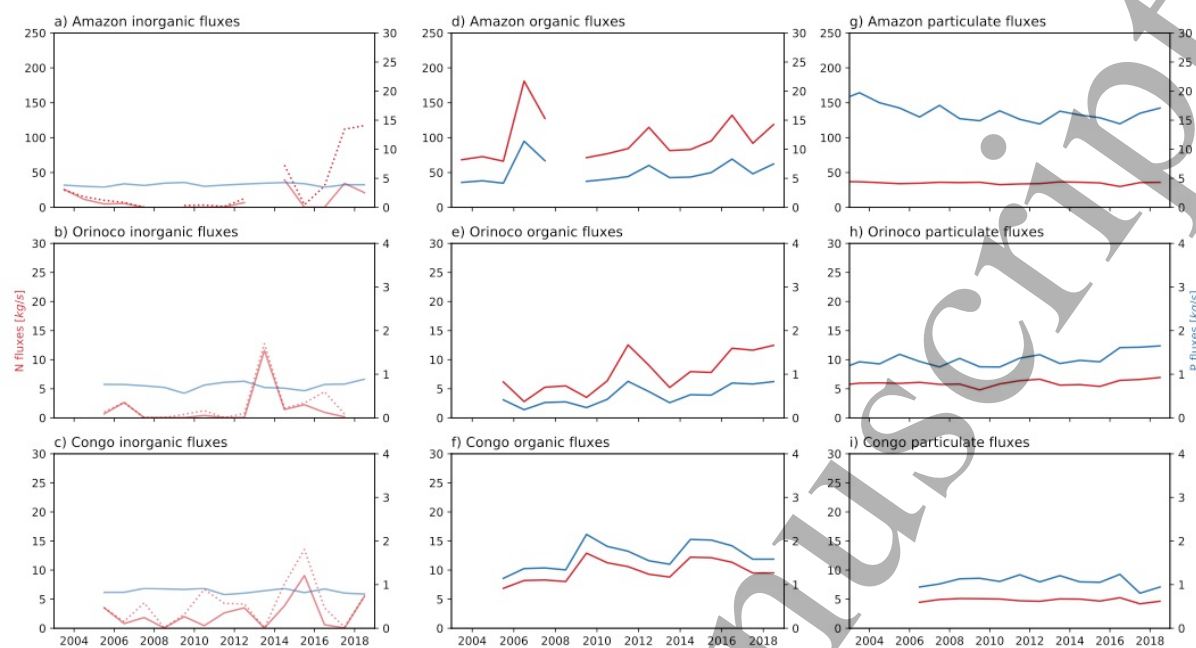
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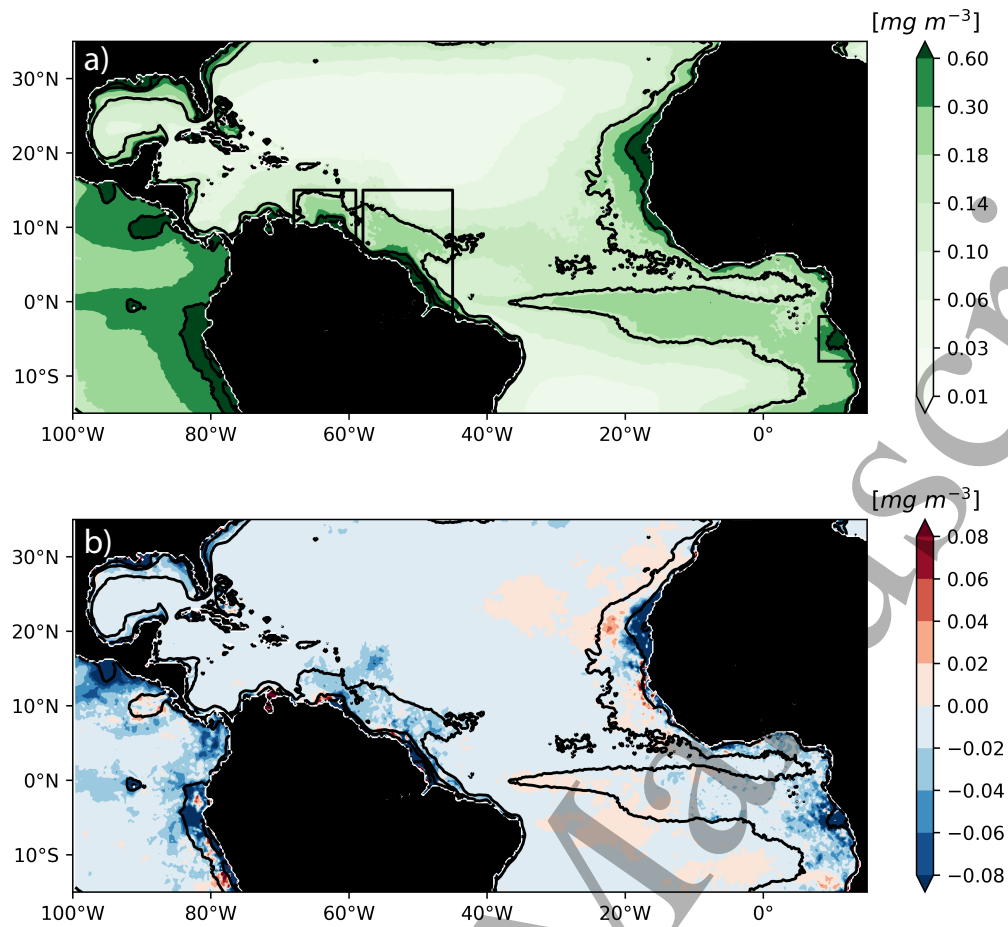
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403 **Figure 1.** Interannual variations of dissolved inorganic N (red) and P (blue) fluxes (left  
 404 column), dissolved organic N and P fluxes (central column) and particulate N and P fluxes  
 405 (right column). Data are from 2003 to 2018 and include the three largest rivers of the Tropical  
 406 Atlantic: a,d,g) the Amazon at Óbidos station, b,e,h) the Orinoco at Ciudad Bolivar station and  
 407 c,f,i) the Congo at Brazzaville station. Fluxes were computed from different data sources (in-  
 408 situ, satellite, literature) and details are given in supplementary material. In a-c, the annual mean  
 409 N flux has been computed considering all the available Hybam monthly measured NO<sub>3</sub>-  
 410 concentrations (dashed line) but also removing the 10% extreme values for each year  
 411 (continuous line).

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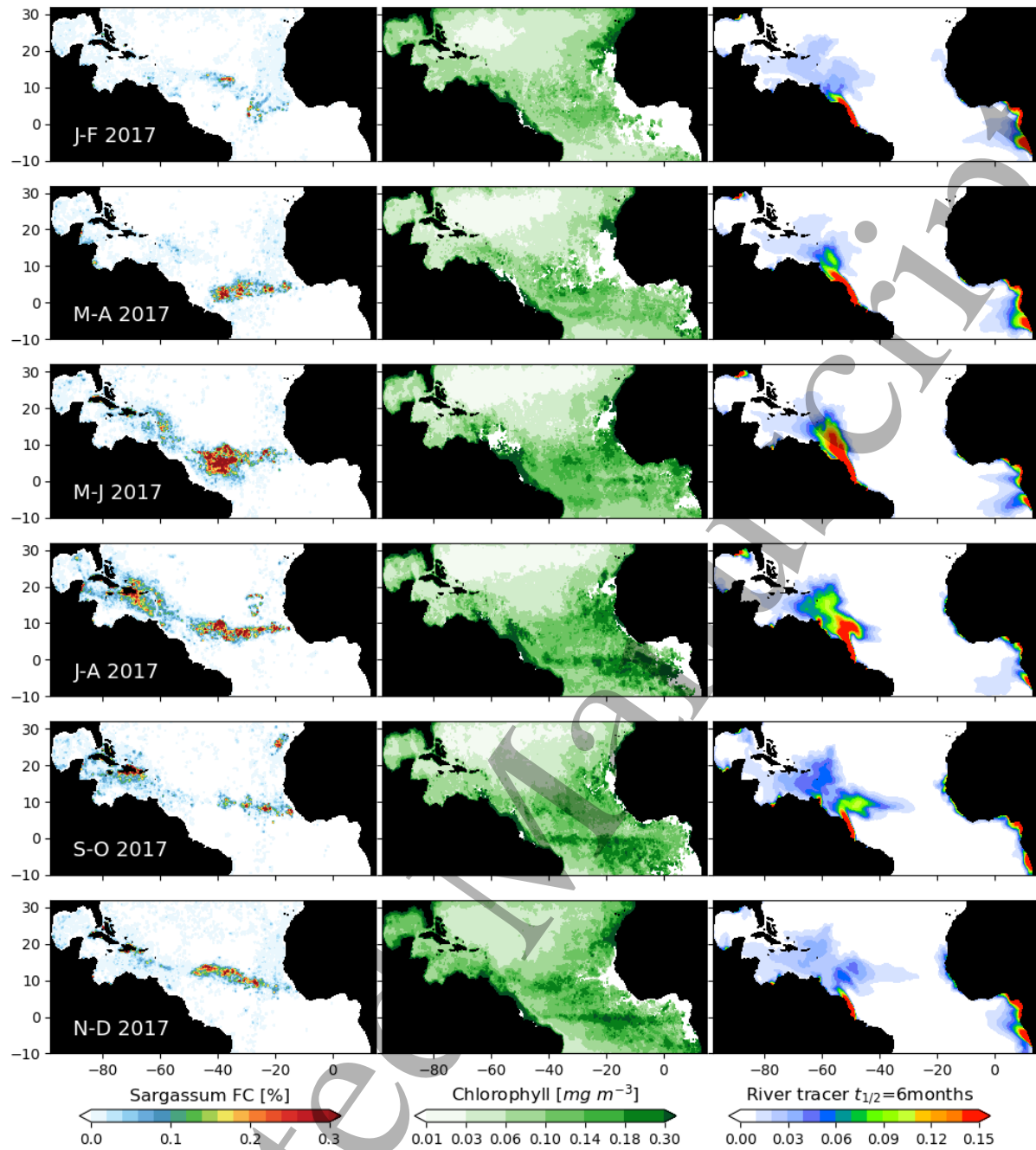


413 **Figure 2.** a) Mean chlorophyll concentrations (in  $\text{mg m}^{-3}$ ) from GlobColour monthly MODIS  
414 GSM product at  $\frac{1}{4}^\circ$  horizontal resolution for the period 2003-2018. b) Difference of chlorophyll  
415 concentration between the period 2011-2018 and the period 2003-2010. Black contours indicate  
416 the 0.3 and 0.6  $\text{mg m}^{-3}$  chlorophyll concentration iso-contours. The boxes indicate the extent of  
417 the regions used to computed the chlorophyll time series in Figure S5.

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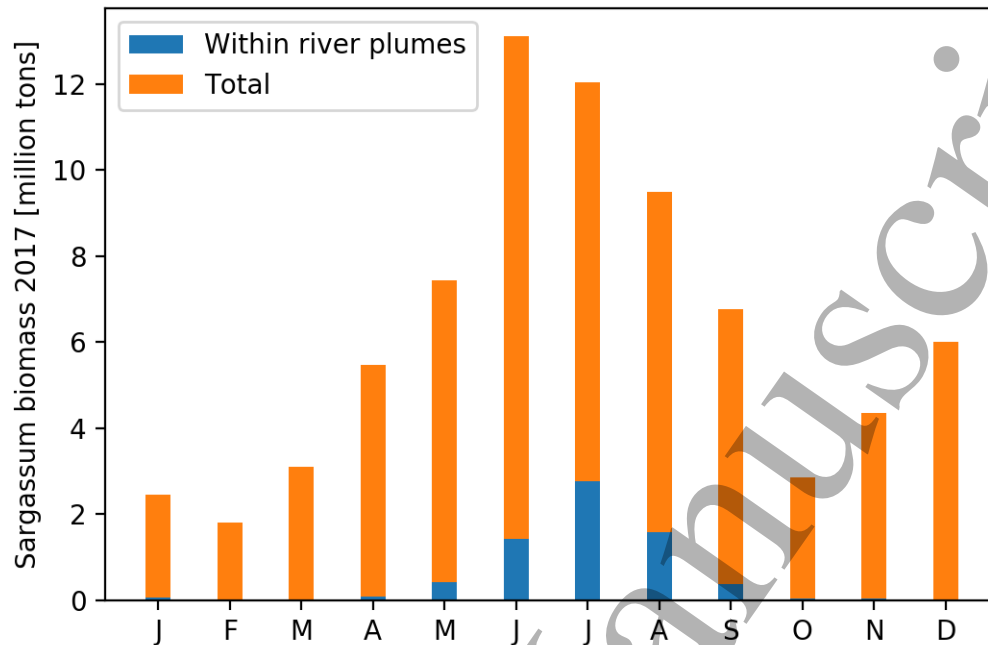
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422 **Figure 3.** (a) Fractional Coverage (%) of *Sargassum*, (b) chlorophyll from monthly GlobColour  
 423 GSM merged product ( $\text{mg m}^{-3}$ ), (c) river tracer surface distribution (no unit, initialized at 1 at  
 424 the river mouth) with half-life time scale of 6 month from a  $\frac{1}{4}$  degree NEMO regional  
 425 simulation. Data are all for year 2017 and have been averaged over two-month periods.

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428 **Figure 4.** Monthly mean *Sargassum* biomass for year 2017 estimated from MODIS in the  
429 Caribbean and Central Atlantic (5°S-25°N, 89°W-15°E). The blue bar marks the fraction of the  
430 biomass which is colocalized with the model river plume (defined as areas with surface  
431 concentration of riverine waters  $> 0.05$ , i.e. more than 5% of kg of water with riverine origin  
432 per kg of ocean water; the spatial distribution of the river tracer is shown in Fig. 3c).