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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**

1
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 m³ s⁻¹,
58
59 61 Congo, 42 000 m³ s⁻¹ and Orinoco, 35 000 m³ s⁻¹), 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 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 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 NO_3^- increase really
114 is. On the other hand, the more frequent recording of high NO_3^- fluxes is of concern and suggests
115 a potential evolution of the dissolved NO_3^- export that needs to be investigated. However, it
116 should be noted that the marked changes in terms of 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

1
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
6
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**

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

33
34 213
35 214 As a conclusion, while increasing inputs of nitrogen and phosphorus in the watershed from
36 214 As a conclusion, while increasing inputs of nitrogen and phosphorus in the watershed from
37 215 human activity, predominantly from land-based activities, are thought to have the potential to
38 215 human activity, predominantly from land-based activities, are thought to have the potential to
39 216 significantly increase the nutrient fluxes toward the ocean and have been proposed as
40 216 significantly increase the nutrient fluxes toward the ocean and have been proposed as
41 217 contributors of the *Sargassum* proliferation, this analysis suggests that riverine fertilization is
42 217 contributors of the *Sargassum* proliferation, this analysis suggests that riverine fertilization is
43 218 unlikely a key controlling factor of both seasonal and interannual variability of the *Sargassum*
44 218 unlikely a key controlling factor of both seasonal and interannual variability of the *Sargassum*
45 219 biomass. In agreement with recent findings by Johns et al, (2020), it fails to explain the
46 219 biomass. In agreement with recent findings by Johns et al, (2020), it fails to explain the
47 220 *Sargassum* distribution shift that occurred after 2010. Instead, Johns et al. (2020) proposed that
48 220 *Sargassum* distribution shift that occurred after 2010. Instead, Johns et al. (2020) proposed that
49 221 an extreme negative phase of the North Atlantic Oscillation triggered the 2011 event and that
50 221 an extreme negative phase of the North Atlantic Oscillation triggered the 2011 event and that
51 222 vertical mixing dynamics below the ITCZ sustains *Sargassum* growth in the Central Tropical
52 222 vertical mixing dynamics below the ITCZ sustains *Sargassum* growth in the Central Tropical
53 223 Atlantic. This is in line with the enhanced chlorophyll concentrations observed below the ITCZ
54 223 Atlantic. This is in line with the enhanced chlorophyll concentrations observed below the ITCZ
55 224 (Figure 4). However, the forcing processes sustaining the productivity there remain to be
56 224 (Figure 4). However, the forcing processes sustaining the productivity there remain to be
57 225 clarified. This study also reminds us that advection is instrumental in controlling the seasonal
58 225 clarified. This study also reminds us that advection is instrumental in controlling the seasonal
59 226 distribution of *Sargassum*, as already revealed by several studies (Brooks et al. 2018, Wang et
60 226 distribution of *Sargassum*, as already revealed by several studies (Brooks et al. 2018, Wang et
227 al. 2019, Berline et al. 2020). Although much progress has been made recently on how
228 *Sargassum* advection responds to currents and winds (Berline et al. 2020, Putman et al. 2020,

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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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21 241 providing hydrogeochemistry Amazon river data.
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30 243 **Authors contributions**

31 244 All authors contributed to the interpretation of the results and writing of the manuscript. J.J. and
32 245 J.S.M. designed the study. J.J. implemented the numerical simulations, and conducted the
33 246 comparison with observations. G.M.M and F.M. participated to the long-term hydrological
34 247 measurements. J.S.M, W.S. and J.M.M. performed the hydrological analysis. L.B. and W.P.
35 248 produced the basin scale *Sargassum* observations. M.H.R. contributed to the ocean color
36 249 analysis.
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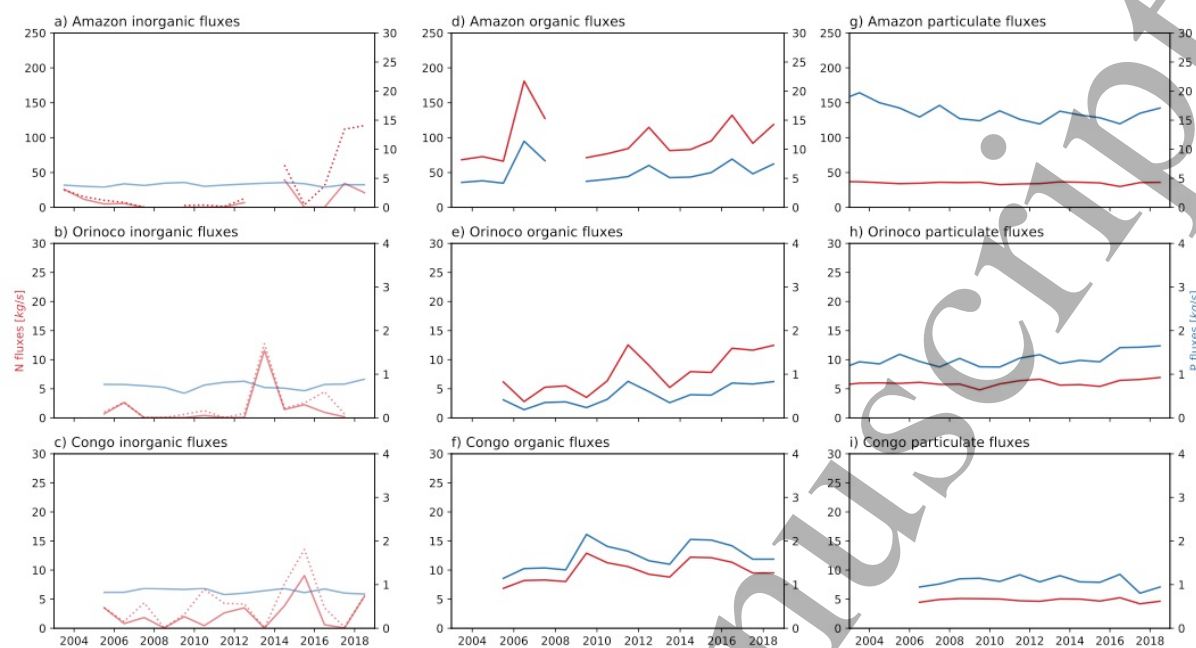
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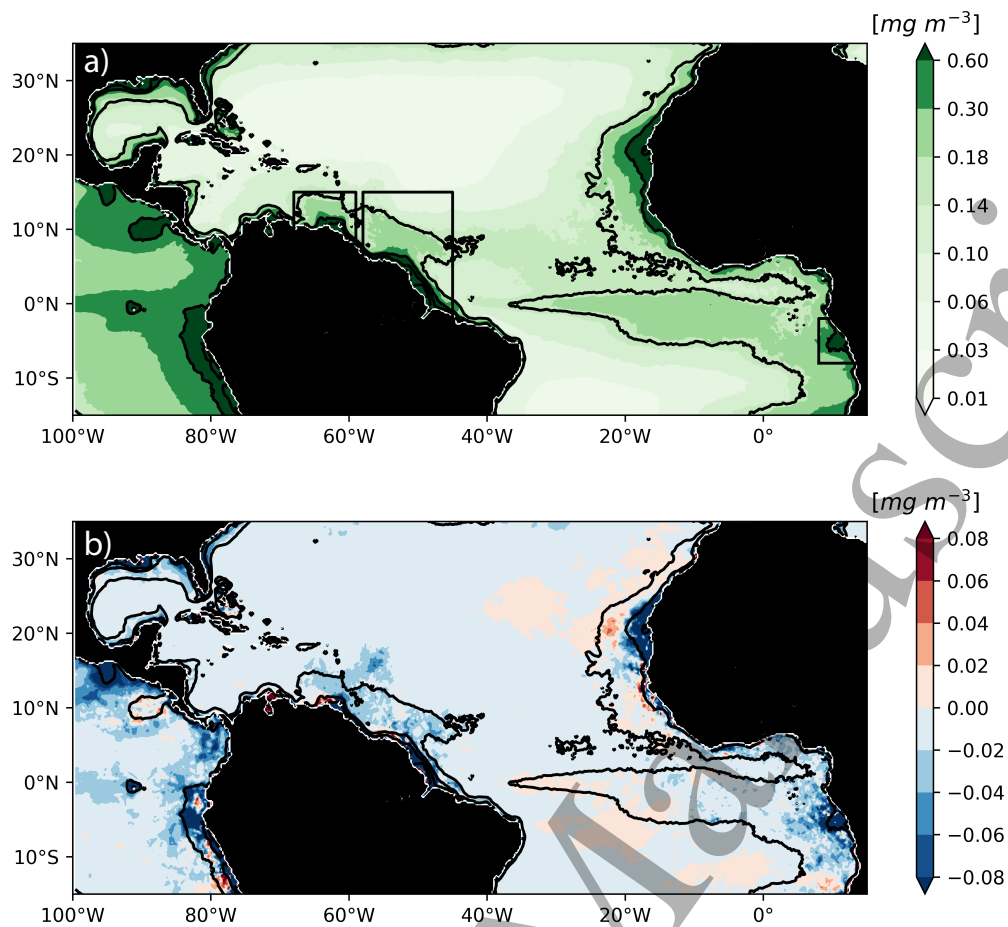
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403 **Figure 1.** Interannual variations of dissolved inorganic N (red) and P (blue) fluxes (left
 404 column), dissolved organic N and P fluxes (central column) and particulate N and P fluxes
 405 (right column). Data are from 2003 to 2018 and include 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 NO₃⁻
 410 concentrations (dashed line) but also removing the 10% extreme values for each year
 411 (continuous line).

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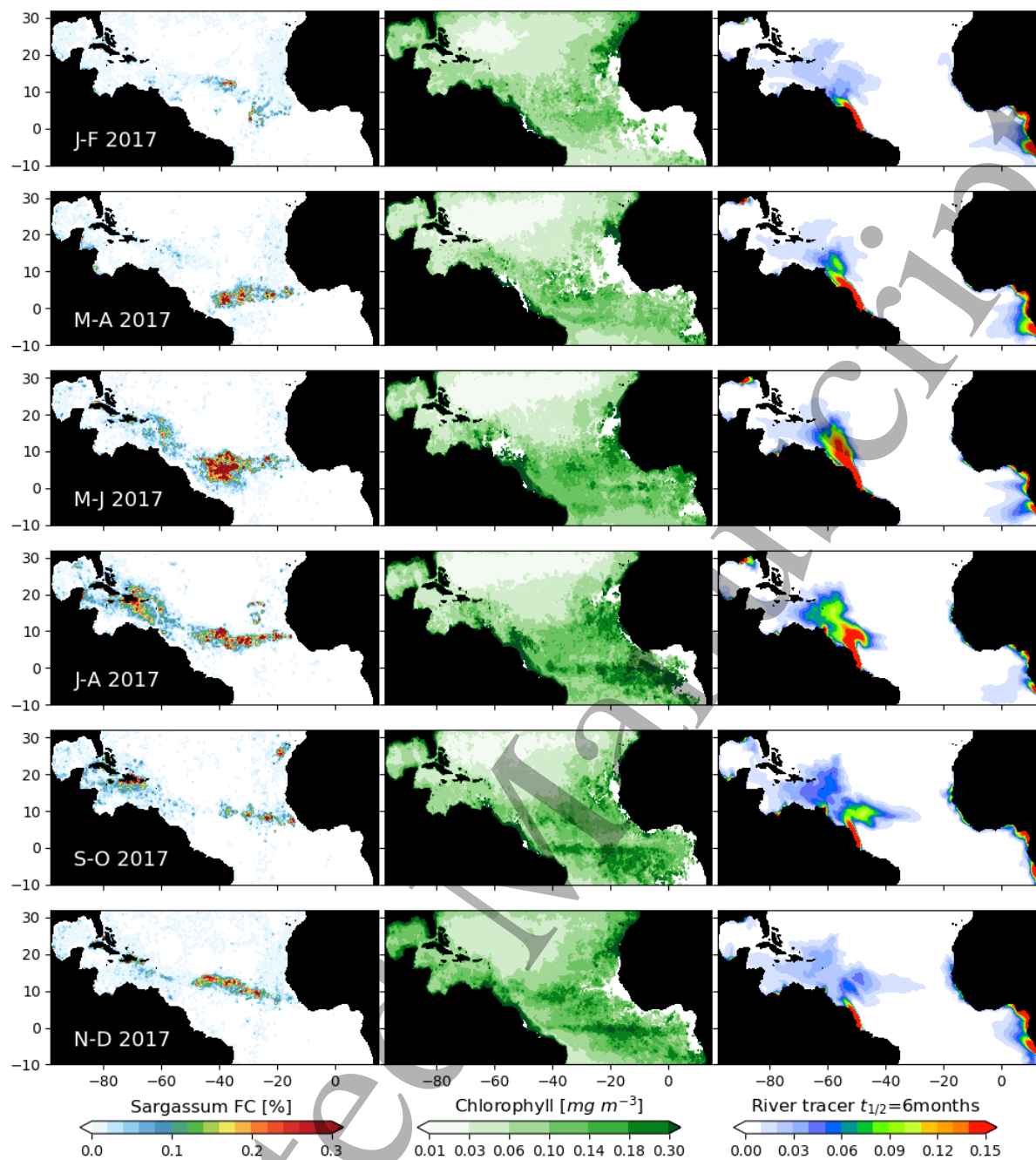


413 **Figure 2.** a) Mean chlorophyll concentrations (in mg m^{-3}) from GlobColour monthly MODIS
414 GSM product at $\frac{1}{4}^\circ$ horizontal resolution for the period 2003-2018. b) Difference of chlorophyll
415 concentration between the period 2011-2018 and the period 2003-2010. Black contours indicate
416 the 0.3 and 0.6 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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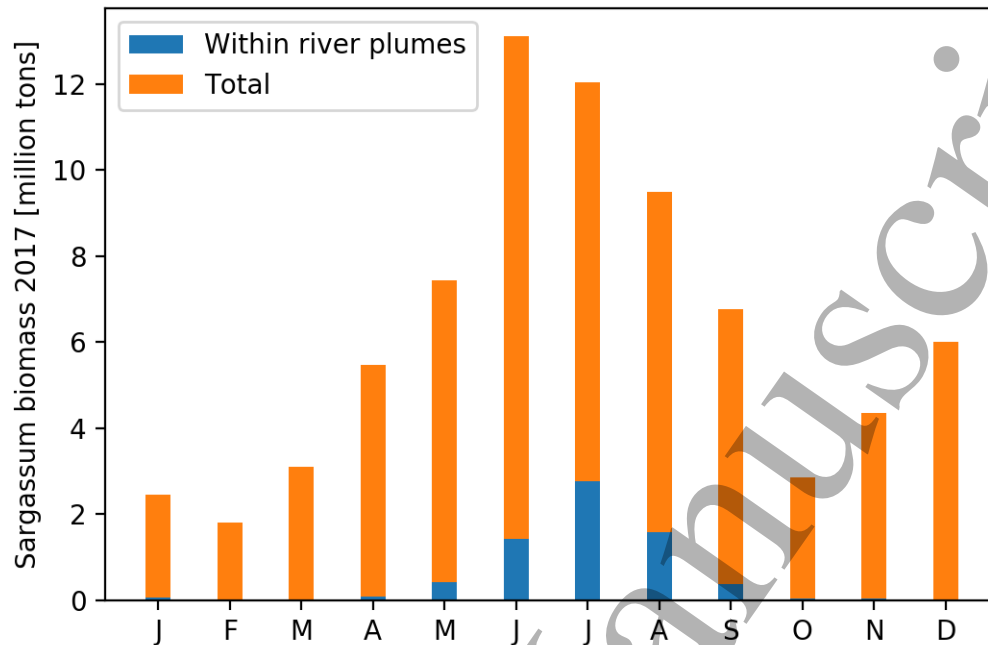
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422 **Figure 3.** (a) Fractional Coverage (%) of *Sargassum*, (b) chlorophyll from monthly GlobColour
 423 GSM merged product (mg m^{-3}), (c) river tracer surface distribution (no unit, initialized at 1 at
 424 the river mouth) with half-life time 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).

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