

LETTER • OPEN ACCESS

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

To cite this article: Julien Jouanno *et al* 2021 *Environ. Res. Lett.* **16** 034042

View the [article online](#) for updates and enhancements.

ENVIRONMENTAL RESEARCH  
LETTERS

## LETTER

## OPEN ACCESS

## RECEIVED

14 September 2020

## REVISED

15 January 2021

## ACCEPTED FOR PUBLICATION

28 January 2021

## PUBLISHED

1 March 2021

Original content from this work may be used under the terms of the [Creative Commons Attribution 4.0 licence](#).

Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

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

Julien Jouanno<sup>1</sup> , Jean-Sébastien Moquet<sup>2</sup> , Léo Berline<sup>3</sup> , Marie-Hélène Radenac<sup>1</sup>, William Santini<sup>4</sup> , Thomas Changeux<sup>3</sup> , Thierry Thibaut<sup>3</sup> , Witold Podlejski<sup>3</sup>, Frédéric Ménard<sup>3</sup> , Jean-Michel Martinez<sup>4</sup> , Olivier Aumont<sup>5</sup> , Julio Sheinbaum<sup>6</sup> , Naziano Filizola<sup>7</sup> and Guy Dieudonne Moukandi N'Kaya<sup>8</sup>

<sup>1</sup> LEGOS, Université de Toulouse, IRD, CNRS, CNES, UPS, Toulouse, France

<sup>2</sup> CNRS/INSU, ISTO, UMR, 7327 Orléans, France

<sup>3</sup> Aix-Marseille University, Université de Toulon, CNRS/INSU, IRD, MIO UM 110, Mediterranean Institute of Oceanography (MIO), Campus of Luminy, 13288 Marseille, France

<sup>4</sup> GET, UMR5563, CNRS/IRD/Université de Toulouse-3, Toulouse, France

<sup>5</sup> Laboratoire d'Océanographie et de Climatologie: Expérimentation et Approches Numériques, IRD-IPSL, 4 Place Jussieu, 75005 Paris, France

<sup>6</sup> CICESE, Ensenada, Mexico

<sup>7</sup> Amazonas State Federal University—UFAM, Geoscience Department, Manaus, Brazil

<sup>8</sup> LMEI/CUSI/ENSP/Marien N'gouabi University, BP 69 Brazzaville, Congo

E-mail: [julien.jouanno@ird.fr](mailto:julien.jouanno@ird.fr)

**Keywords:** *Sargassum*, hydrology, Amazon

Supplementary material for this article is available [online](#)

**Abstract**

The Tropical Atlantic is facing a massive proliferation of *Sargassum* since 2011, with severe environmental and socioeconomic impacts. As a contribution to this proliferation, an increase in nutrient inputs from the tropical rivers, in response to climate and land use changes or increasing urbanization, has been often suggested and widely reported in the scientific and public literature. Here we discuss whether changes in river nutrient inputs could contribute to *Sargassum* proliferation in the recent years or drive its seasonal cycle. Using long-term *in situ* and satellite measurements of discharge, dissolved and particulate nutrients of the three world largest rivers (Amazon, Orinoco, Congo), we do not find clear evidences that nutrient fluxes may have massively increased over the last 15 years. Moreover, focusing on year 2017, we estimate that along the year only 10% of the *Sargassum* biomass occurred in regions under river plume influence. While deforestation and pollution are a reality of great concern, our results corroborate recent findings that hydrological changes are not the first order drivers of *Sargassum* proliferation. Besides, satellite observations suggest that the major Atlantic river plumes suffered a decrease of phytoplankton biomass in the last two decades. Reconciling these observations requires a better understanding of the nutrient sources that sustain *Sargassum* and phytoplankton growth in the region.

**1. Context**

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

Satellite imagery pointed to the presence of large amounts of *Sargassum* in areas under seasonal influence of the Amazon plume (Gower *et al* 2013, Sissini *et al* 2017, Oviatt *et al* 2019, Wang *et al* 2019) raising the hypothesis that river nutrient fluxes might play a role in this proliferation (Langin 2018, Oviatt *et al* 2019, Wang *et al* 2019). A possible influence of the Congo has also been invoked in several studies (Djakouré *et al* 2017, Oviatt *et al* 2019). A recent study by Johns *et al* (2020), however, did not find strong evidence to support this hypothesis as there

appears to be a spatiotemporal mismatch between *Sargassum* occurrence and these riverine sources of nutrients. Given the importance of this question and the present discrepancies in the scientific literature we find it important to examine to which extent the riverine source of nutrients may contribute to the proliferation of pelagic *Sargassum*. Indeed, several elements give support to a possible influence of the riverine sources of nutrients. First, rivers export nitrogen (N) and phosphorus (P), which are key limiting nutrients required for *Sargassum* growth (Lapointe 1986, 1995). Specifically, the Amazon also contains important concentrations of dissolved organic substrates that could be an important source of nutrient for *Sargassum* growth as reviewed in Oviatt *et al* (2019). Second, the Tropical Atlantic receives the fresh and nutrient 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>, 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 riverine flow (Milliman and Farnsworth 2011). Their low-saline and productive plumes extend thousands of kilometers far offshore (Muller-Karger *et al* 1988, Signorini *et al* 1999). Third, the watersheds undergo strong climatic and anthropogenic pressures that are thought to have the potential to modify oceanic biogeochemical systems. For instance, Seitzinger *et al* (2010) estimated that the total river input of N to the coastal seas has approximately doubled since the 70 s, with South America representing ~20% of the global increase. The Amazon basin already shows some signs of a transition to a disturbance-dominated regime in response to agricultural expansion and climate variability (Davidson *et al* 2012). The region experiences a strong anthropogenic pressure associated with a rapid urbanization (Richards and Vanwey 2015), intense hydropower dam construction (Latrubesse *et al* 2017), and increase of mining and oil extraction contamination (e.g. Moquet *et al* 2014). The overall consequences of these changes in terms of nutrient budget remain uncertain since they can act as a source or a sink of nutrients.

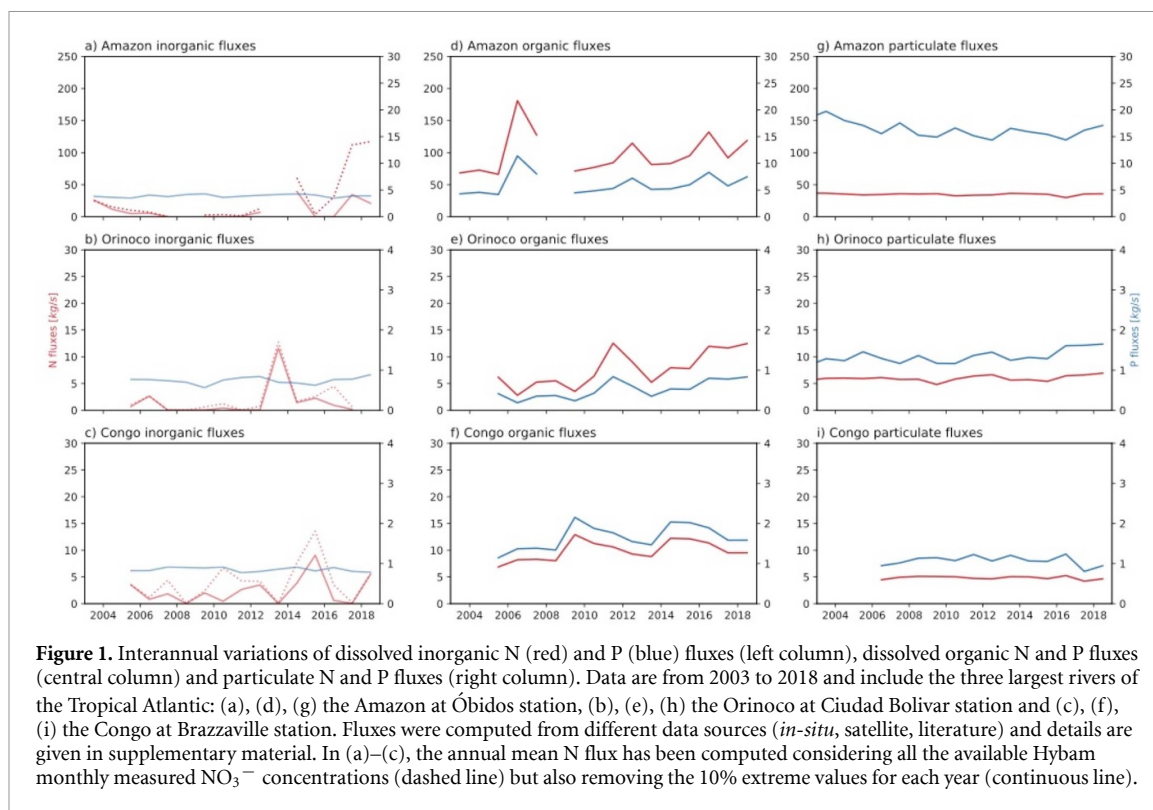
In this context, the long-term evolution of the continental nutrient export to the Tropical Atlantic is investigated on the basis of *in situ* observations of the major dissolved and particulate nutrients exported by the three main rivers of the basin (Amazon, Orinoco and Congo). Satellite estimates of chlorophyll provide an independent set of observations to monitor the long-term changes of biological activity in the large river plumes. Finally, the large-scale seasonal distribution of *Sargassum* for year 2017 is confronted to numerical experiments of river plume dispersal. We focused on this year because basin scale *Sargassum* fractional coverage observations from MODIS were available (Berline *et al* 2020), with concurrent observations carried out during two cruises in the Tropical

Atlantic (Ody *et al* 2019). Year 2017 was the third most important year of the decade in terms of quantity of *Sargassum* (as inferred from time series in Wang *et al* 2019), with a seasonal pattern that closely mirrors the averaged seasonal pattern from Wang *et al* (2019).

## 2. River nutrient fluxes

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

For the three rivers, the largest input of N is provided by the dissolved organic matter. Dissolved organic nitrate delivered by the Amazon is thought to become bioavailable in the offshore fraction of the plume through bacterial and photochemical transformations (Medeiros *et al* 2015). For the Amazon, this flux appears to regularly increase from 2004, apart from maxima in years 2007 and 2008. Observations for the Orinoco suggest a doubling of this flux over the last 15 years (figure 1). The particulate fluxes of N, estimated from remote sensing, is also expected to contribute to nutrient supply through desorption of the shelf (Demaster and Aller 2000). It is stable for the three rivers. The dissolved inorganic N flux, computed from NO<sub>3</sub><sup>-</sup> *in situ* measurements, show larger values during the last decade for the three rivers (figures 1(a)–(c)). Before 2013, values above the detection limit (0.01 mg l<sup>-1</sup>) were of similar magnitude than independent Amazon (Richey *et al* 2009, Ward *et al* 2015, Doherty *et al* 2017), Orinoco (Lewis and Saunders 1989) and Congo (Descy *et al* 2017) water analyses. They did not show a marked evolution over this period. From the years 2013–2014, the average concentration of NO<sub>3</sub><sup>-</sup> has increased for the three rivers. On the one hand, the scatter of the measured concentrations is so high that it is difficult to determine how significant the NO<sub>3</sub><sup>-</sup> increase really is. On the other hand, the more frequent recording of high NO<sub>3</sub><sup>-</sup> fluxes is of concern and suggests a potential evolution of the dissolved NO<sub>3</sub><sup>-</sup> export that needs to be investigated. However, it should be noted that the marked changes in terms of NO<sub>3</sub><sup>-</sup> for the different



**Figure 1.** Interannual variations of dissolved inorganic N (red) and P (blue) fluxes (left column), dissolved organic N and P fluxes (central column) and particulate N and P fluxes (right column). Data are from 2003 to 2018 and include the three largest rivers of the Tropical Atlantic: (a), (d), (g) the Amazon at Óbidos station, (b), (e), (h) the Orinoco at Ciudad Bolívar station and (c), (f), (i) the Congo at Brazzaville station. Fluxes were computed from different data sources (*in-situ*, satellite, literature) and details are given in supplementary material. In (a)–(c), the annual mean N flux has been computed considering all the available Hybam monthly measured  $\text{NO}_3^-$  concentrations (dashed line) but also removing the 10% extreme values for each year (continuous line).

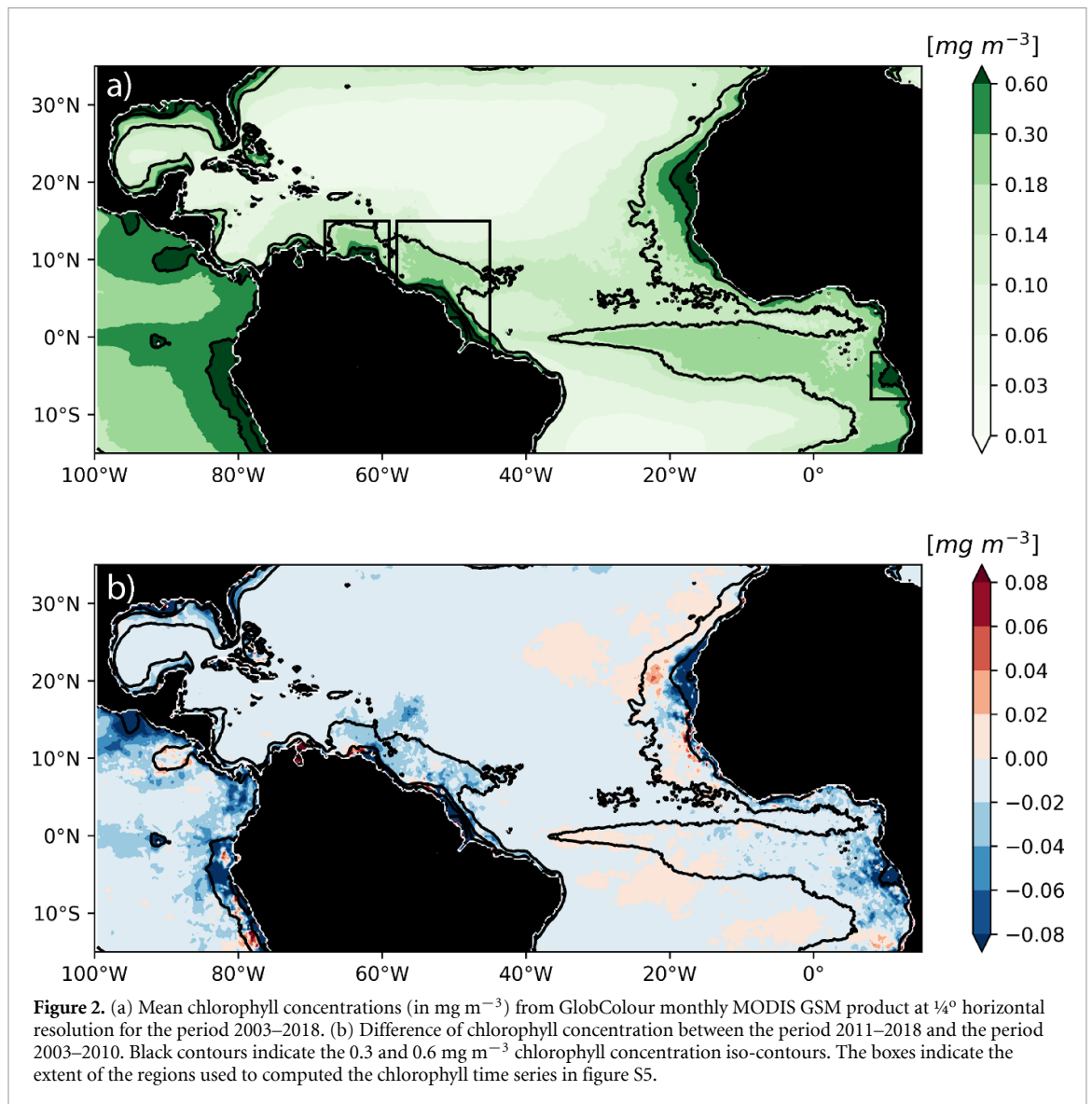
ivers occurred 2–3 years after the first massive proliferation of 2011.

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

So, observations show different long-term trends of inorganic, organic and particulate fluxes of N and P. No direct and clear relationship with *Sargassum* growth can be drawn, neither in terms of long-term evolution, nor in terms of interannual variability (e.g. no major peak of nutrient fluxes was observed during the record *Sargassum* years 2015 and 2018, and there is no clear relation with the basin scale *Sargassum* biomass time series from Wang *et al* 2019). Large uncertainties remain in the nutrient fluxes estimation and the fate of these nutrients in the open ocean, but these results already question whether the order of magnitude of the observed trends and variability are large enough to contribute to the inter-annual variability of the oceanic biological response.

### 3. Link with changes in plume productivity and *Sargassum* distribution

The diversity of the nutrient trends and the lack of knowledge on the lability of the dissolved and particulate riverine material render uncertain the assessment of the long-term evolution of the riverine fertilization of the ocean. As an independent marker of possible changes in the nutrient export by the large Tropical Atlantic rivers, the long-term evolution of surface chlorophyll estimated from satellite ocean color is now analyzed. Chlorophyll is the main pigment in phytoplankton and here we use chlorophyll as a proxy of phytoplankton biomass. As it has been evidenced for the Mississippi in the northern Gulf of Mexico (Lohrenz *et al* 1997, Rabalais *et al* 2002, Wysocki *et al* 2006), we expect that fluctuations in riverine nutrients alter the dynamics of phytoplankton growth and thus phytoplankton biomass in the large tropical river plumes. The difference between the ‘*Sargassum* period’ (2011–2018) and the years before (2003–2010) reveals an overall decrease of the chlorophyll concentration in the Tropical Atlantic (figure 2(b)). This decline is sharper in the Amazon, Orinoco, and Congo plume regions. Since Chlorophyll retrieval from space is subject to large discrepancies between the different available products, we compared five monthly chlorophyll products from three different groups (GlobColour, NOAA, and CCI). For the three rivers considered, four out of the five different products show a consistent decrease of chlorophyll concentration in the plume areas



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

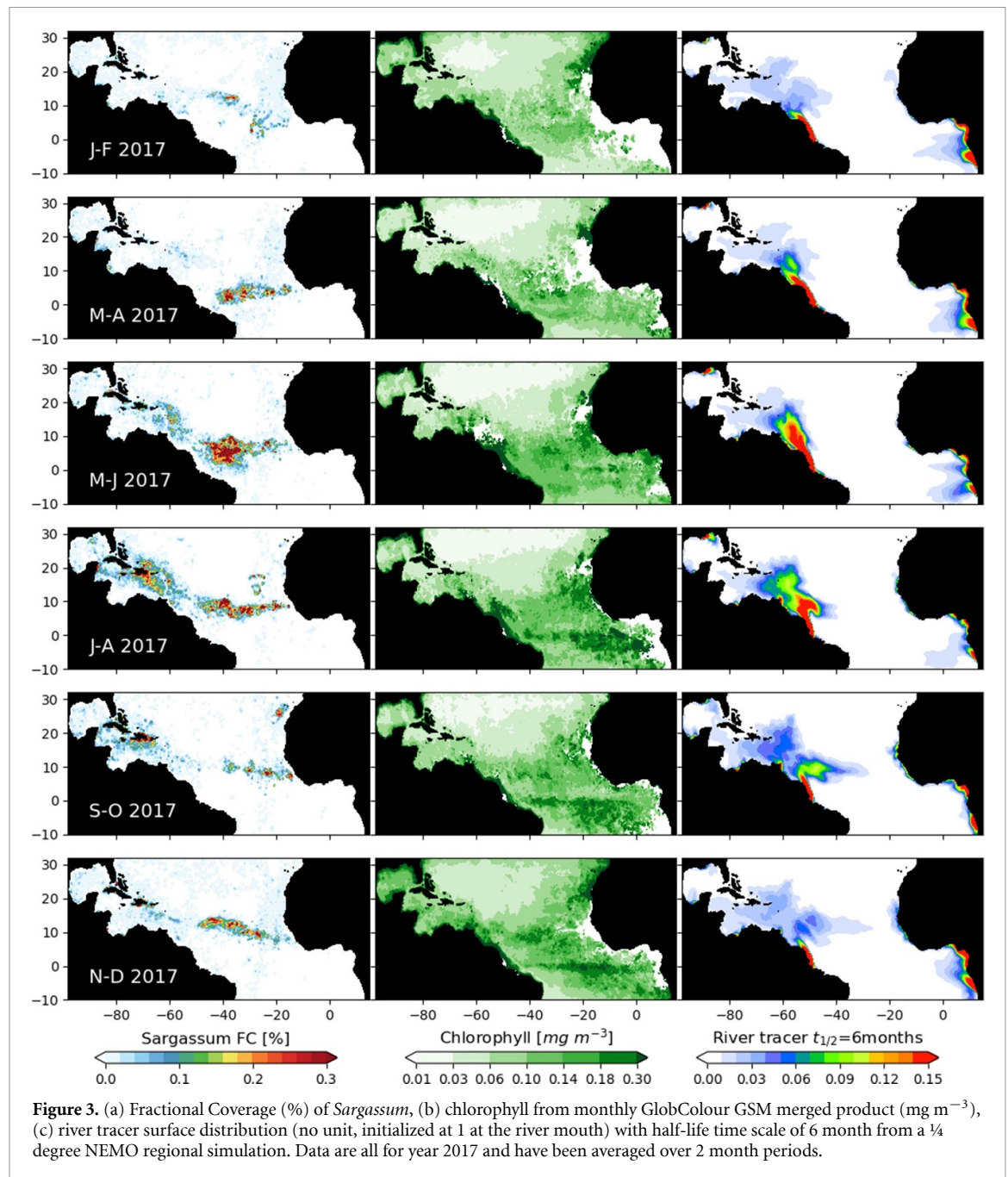
(figure S5 (available online at [stacks.iop.org/ERL/16/034042/mmedia](https://stacks.iop.org/ERL/16/034042/mmedia))).

The basin scale decrease of chlorophyll evidenced in figure 2(b) is in line with the study by Gregg and Rousseau (2019) that suggested that global net ocean primary production has experienced a small but significant decline in the 18 year satellite records from 1998 to 2015, in response to shallowing surface mixed layer depth, decreasing nitrate supply and changes in the phytoplankton communities. Chlorophyll concentrations in river plumes exhibit a larger decrease. The underlying cause of these changes in the chlorophyll content of the plumes is difficult to ascertain from observations only. It is worth mentioning that (a) colored detrital material contributes to total light attenuation in the blue region of the spectrum where chlorophyll-a also absorbs strongly (Fournier *et al* 2015) which could lead to large errors in ocean color retrievals, (b) the response of the productive plumes may not only depend on the riverine nutrient flux

but on other variables such as temperature, stratification, turbidity, or dust deposition. But this decrease, whether it is caused by a decrease of plume productivity or weaker discharge of dissolved colored material (which is not observed in SO-HYBAM observations of organic and particulate nutrient fluxes, figure 1) is difficult to reconcile with the hypothesis of an overall increase in fertilization by tropical rivers in recent years. A better understanding of the river plume biogeochemistry is required, together with analysis of possible competing growth dynamics between phytoplankton and *Sargassum*.

The seasonal distribution of *Sargassum* for year 2017 is shown in figure 3 together with the chlorophyll concentrations. The *Sargassum* bloom during the first 6 months of the year occurs preferentially in the Intertropical Convergence Zone (ITCZ; located between the equator and 10° N), where chlorophyll is relatively high compared to the surrounding subtropical oligotrophic area. To our knowledge,

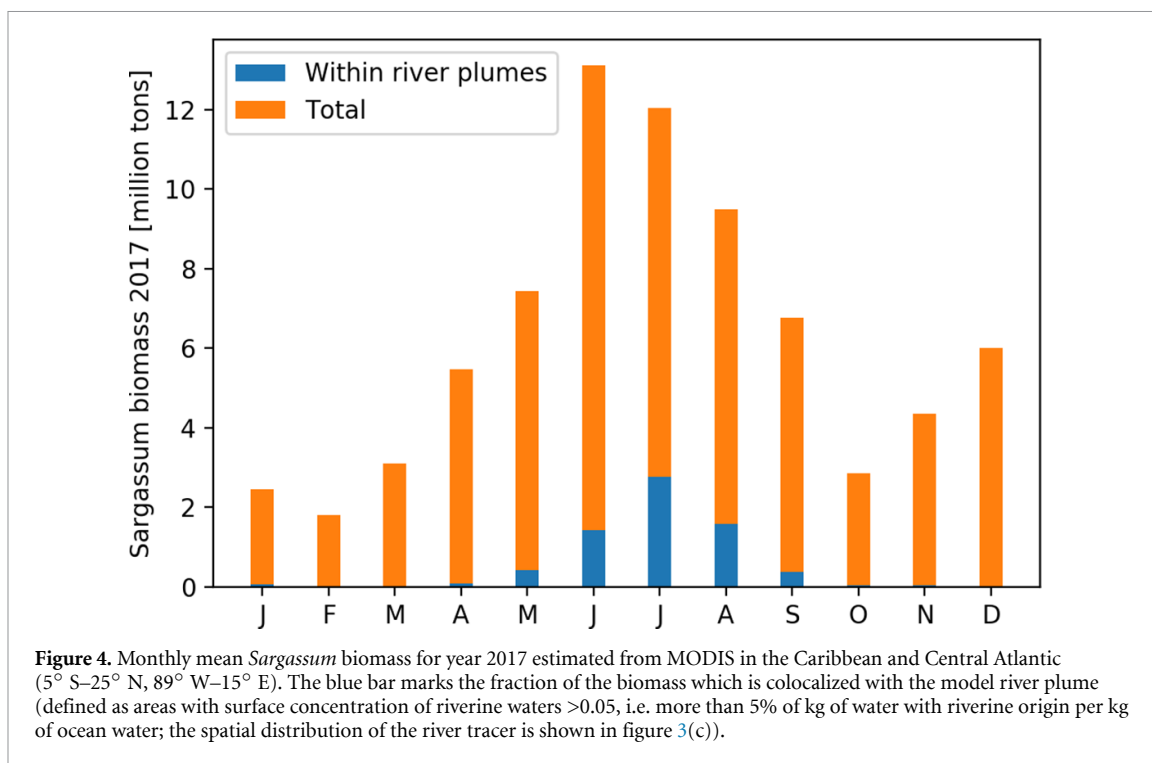




the causes of the high chlorophyll level have not been identified, but could be the result of diatoms-diazotroph assemblages (Subramaniam *et al* 2008, Schlosser *et al* 2014), atmospheric deposition of dust (Yu *et al* 2015), or biomass burning emissions (Barkley *et al* 2019). Yet, the presence of relatively high chlorophyll concentration indicates nutrient availability that may participate to sustain *Sargassum* growth.

Interestingly, we remark that during September–October, when the North Brazil Current retroflects and transports the Amazon riverine freshwater to the east, the abundance of *Sargassum* in the plume area between  $60^\circ$  W and  $40^\circ$  W, is drastically reduced relative to the two previous months. The North Brazil Current is mainly fed by waters originating from the

equatorial area and the southern Tropical Atlantic (Johns *et al* 1998) where no massive proliferation of *Sargassum* was observed in the previous months. Our interpretation is that the weak abundance of *Sargassum* in the plume at this time is mainly controlled by advection of low *Sargassum* water in the region. The low salinity of the plume could also limit the proliferation of *Sargassum* there. Indeed, culture experiments of *Sargassum natans* and *Sargassum fluitans* described in Hanisak and Samuel (1987) revealed some dependence of their growth rate to salinity. A reduction in salinity from 36 to 30 caused a reduction in the growth rates by almost half, and no growth was observed for salinity below 18. This effect may likely limit the fertilizing effect of the nutrient rich river plumes.



The river plume dispersion numerical experiment (figure 3) also reveals that the central Atlantic is not under the influence of the Amazon plume during the first half of the year. The largest coincidence between the plume and *Sargassum* distribution occurs in June–July–August (figure 4), when the Amazon plume extends toward the Lesser Antilles. This is in line with the analysis by Gouveia *et al* (2019) that showed that the Amazon plume fingerprints on oceanic primary productivity spatio-temporal variability are restricted to the western Tropical Atlantic. The first 6 months of the year appear to be crucial for the occurrence of *Sargassum* along the south American and Caribbean coasts a few months later (Wang and Hu 2017, Putman *et al* 2018, Wang *et al* 2019, Berline *et al* 2020). Even if Amazon river fertilization could contribute to the seasonal growth in the portion of western Tropical Atlantic under seasonal influence of the Amazon plume (an area between 60° W and 40° W and between 0° N and 20° N), this analysis further suggests that it does not drive the large-scale seasonal bloom. At the annual scale, we found that only 9% of the *Sargassum* biomass occurred in the river plume area in 2017, with occurrence below 5% from September to May and peak at 23% in July when the plume is well extended toward the Lesser Antilles. It is even more unlikely that the Congo and Orinoco rivers could contribute to the large-scale bloom due to the limited imprint of the plumes on the chlorophyll distribution and remoteness of the river plumes from the main *Sargassum* bloom areas.

As a conclusion, while increasing inputs of N and P in the watershed from human activity, predominantly from land-based activities, are thought to have

the potential to significantly increase the nutrient fluxes toward the ocean and have been proposed as contributors of the *Sargassum* proliferation, this analysis suggests that riverine fertilization is unlikely a key controlling factor of both seasonal and interannual variability of the *Sargassum* biomass. In agreement with recent findings by Johns *et al* (2020), it fails to explain the *Sargassum* distribution shift that occurred after 2010. Instead, Johns *et al* (2020) proposed that an extreme negative phase of the North Atlantic Oscillation triggered the 2011 event and that vertical mixing dynamics below the ITCZ sustains *Sargassum* growth in the Central Tropical Atlantic. This is in line with the enhanced chlorophyll concentrations observed below the ITCZ (figure 4). However, the forcing processes sustaining the productivity there remain to be clarified. This study also reminds us that advection is instrumental in controlling the seasonal distribution of *Sargassum*, as already revealed by several studies (Brooks *et al* 2018, Wang *et 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, Miron *et al* 2020), this issue has yet to be fully evaluated and understood. That key aspects of growth and movement are missing from our ability to understand and forecast spatiotemporal variability in the distribution of pelagic *Sargassum*.

#### 4. Methods

Methods and associated references are available in the supplementary material.

## Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: <https://hybam.obs-mip.fr>.

## Acknowledgments

This study was supported by IRD, the French Ministère de la Transition Écologique, the ANR project FORESEA (<https://sargassum-foresea.cnrs.fr>), and project TOSCA-SAREDA\_DA. Supercomputing facilities were provided by GENCI project GEN7298. We thank the HyBam research group, especially A Laraque, for open access to the hydrological, sedimentary and geochemical data, CNES for funding project TOSCA-SAREDA\_DA, and the NASA, GlobColour and CCI for providing chlorophyll data. We acknowledge J Bouchez for providing hydrogeochemistry Amazon River data.

## Authors contributions

All authors contributed to the interpretation of the results and writing of the manuscript. J J and J S M designed the study. J J implemented the numerical simulations, and conducted the comparison with observations. G M M and F M participated to the long-term hydrological measurements. J S M, W S and J M M performed the hydrological analysis. L B and W P produced the basin scale *Sargassum* observations. M H R contributed to the ocean color analysis.

## ORCID iDs

Julien Jouanno  <https://orcid.org/0000-0001-7750-060X>

Jean-Sébastien Moquet  <https://orcid.org/0000-0003-1925-9306>

Léo Berline  <https://orcid.org/0000-0002-5831-7399>

William Santini  <https://orcid.org/0000-0003-0098-9755>

Thomas Changeux  <https://orcid.org/0000-0002-0418-3321>

Thierry Thibaut  <https://orcid.org/0000-0001-8530-9266>

Frédéric Ménard  <https://orcid.org/0000-0003-1162-660X>

Jean-Michel Martinez  <https://orcid.org/0000-0003-3281-8512>

Olivier Aumont  <https://orcid.org/0000-0003-3954-506X>

Julio Sheinbaum  <https://orcid.org/0000-0001-7031-5225>

Naziano Filizola  <https://orcid.org/0000-0001-7285-7220>

Guy Dieudonne Moukandi N'Kaya  <https://orcid.org/0000-0002-9115-1896>

## References

- Barkley A E *et al* 2019 African biomass burning is a substantial source of phosphorus deposition to the Amazon, Tropical Atlantic Ocean, and Southern Ocean *Proc. Natl Acad. Sci.* **116** 16216–21
- Berline L, Ody A, Jouanno J, Chevalier C, André J-M, Thibaut T and Ménard F 2020 Hindcasting the 2017 dispersal of *Sargassum* algae in the Tropical North Atlantic *Mar. Pollut. Bull.* **158** 11431
- Berner R A and Rao J L 1994 Phosphorus in sediments of the Amazon River and estuary: implications for the global flux of phosphorus to the sea *Geochim. Cosmochim. Acta* **58** 2333–9
- Brooks M T, Coles V J, Hood R R and Gower J F 2018 Factors controlling the seasonal distribution of pelagic *Sargassum* *Mar. Ecol. Prog. Ser.* **599** 1–18
- Davidson E A *et al* 2012 The Amazon basin in transition *Nature* **481** 321
- Demaster D J and Aller R C 2000 Biogeochemical processes on the Amazon shelf: changes in dissolved and particulate fluxes during river/ocean mixing *The Biogeochemistry of the Amazon Basin* ed M E McClain, R Victoria and J E Richey (Oxford: Oxford University Press) pp 328–57
- Descy J-P, Darchambeau F, Lambert T, Stoyneva-Gaertner M P, Bouillon S and Borges A V 2017 Phytoplankton dynamics in the Congo River *Freshwater Biol.* **62** 87–101
- Djakouré S, Araujo M, Hounsou-Gbo A, Noriega C and Bourlès B 2017 On the potential causes of the recent Pelagic *Sargassum* blooms events in the tropical North Atlantic Ocean *Biogeosci. Discuss.* submitted (<https://doi.org/10.5194/bg-2017-346>)
- Doherty M *et al* 2017 Bacterial biogeography across the Amazon River-ocean continuum *Front. Microbiol.* **8** 882
- Fournier S, Chapron B, Salisbury J, Vandemark D and Reul N 2015 Comparison of spaceborne measurements of sea surface salinity and colored detrital matter in the Amazon plume *J. Geophys. Res.: Oceans* **120** 3177–92
- Gouveia N A, Gherardi D F M, Wagner F H, Paes E T, Coles V J and Aragão L E O C 2019 The salinity structure of the Amazon River plume drives spatiotemporal variation of oceanic primary productivity *J. Geophys. Res.: Biogeosci.* **124** 147–65
- Gower J, Young E and King S 2013 Satellite images suggest a new *Sargassum* source region in 2011 *Remote Sens. Lett.* **4** 764–73
- Johns E M *et al* 2020 The establishment of a pelagic *Sargassum* population in the tropical Atlantic: biological consequences of a basin-scale long distance dispersal event *Prog. Oceanogr.* **182** 102269
- Johns W E, Lee T N, Beardsley R C, Candela J, Limeburner R and Castro B 1998 Annual cycle and variability of the North Brazil Current *J. Phys. Oceanogr.* **28** 103–28
- Joo Y J, Li D D and Lerman A 2013 Global nitrogen cycle: pre-anthropocene mass and isotope fluxes and the effects of human perturbations *Aquat. Geochem.* **19** 477–500
- Langin K 2018 Seaweed masses assault Caribbean islands *Science* **360** 1157–8
- Lapointe B E 1986 Phosphorus-limited photosynthesis and growth of *Sargassum natans* and *Sargassum fluitans* (Phaeophyceae) in the western North Atlantic *Deep Sea Res. A* **33** 391–9
- Lapointe B E 1995 A comparison of nutrient-limited productivity in *Sargassum natans* from neritic vs. oceanic waters of the western North Atlantic Ocean *Limnol. Oceanogr.* **40** 625–33
- Latrubesse E M *et al* 2017 Damming the rivers of the Amazon basin *Nature* **546** 363–9
- Lewis W M and Saunders J F 1989 Concentration and transport of dissolved and suspended substances in the Orinoco River *Biogeochemistry* **7** 203–40
- Lohrenz S E, Fahnenstiel G L, Redalje D G, Lang G A, Chen X and Dagg M J 1997 Variations in primary production of northern Gulf of Mexico continental shelf waters linked to



- nutrient inputs from the Mississippi River *Mar. Ecol. Prog. Ser.* **155** 45–54
- Medeiros P M, Seidel M, Ward N D, Carpenter E J, Gomes H R, Niggemann J, Krusche A V, Richey J E, Yager P L and Dittmar T 2015 Fate of the Amazon River dissolved organic matter in the tropical Atlantic Ocean *Glob. Biogeochem. Cycles* **29** 677–90
- Milliman J D and Farnsworth K L 2011 *River Discharge to the Coastal Ocean—A Global Synthesis* (Cambridge: Cambridge University Press)
- Miron P, Olascoaga M J, Beron-Vera F J, Putman N F, Trínanes J, Lumpkin R and Goni G J 2020 Clustering of Marine-Debris- and Sargassum -Like Drifters Explained by Inertial Particle Dynamics *Geophys. Res. Lett.* **47** e2020GL089874
- Moquet J S, Maurice L, Crave A, Viers J, Aravelo N, Lagane C, Lavado Casimiro W and Guyot J L 2014 Cl and Na fluxes in an Andean foreland basin of the Peruvian Amazon: an anthropogenic impact evidence *Aquat. Geochem.* **20** 613–37
- Muller-Karger F E, McClain C R and Richardson P L 1988 The dispersal of the Amazon's water *Nature* **333** 56
- Ody A et al 2019 From *In Situ* to satellite observations of pelagic Sargassum distribution and aggregation in the Tropical North Atlantic Ocean *PLoS One* **14** e0222584
- Oviatt C A, HuiZenga K, Rogers C S and Miller W J 2019 What nutrient sources support anomalous growth and the recent Sargassum mass stranding on Caribbean beaches? A review *Mar. Pollut. Bull.* **145** 517–25
- Putman N F, Goni G J, Gramer L J, Hu C, Johns E M, Trínanes J and Wang M 2018 Simulating transport pathways of pelagic Sargassum from the Equatorial Atlantic into the Caribbean Sea *Prog. Oceanogr.* **165** 205–14
- Putman N F, Lumpkin R, Olascoaga M J, Trínanes J and Goni G J 2020 Improving transport predictions of pelagic Sargassum *J. Exp. Mar. Biol. Ecol.* **529** 151398
- Rabalais N N, Turner R E, Dortch Q, Justic D, Bierman V J and Wiseman W J 2002 Nutrient-enhanced productivity in the northern Gulf of Mexico: past, present and future *Nutrients and Eutrophication in Estuaries and Coastal Waters* (Berlin: Springer) pp 39–63
- Richards P and Vanwey L 2015 Where deforestation leads to urbanization: how resource extraction is leading to urban growth in the Brazilian Amazon *Ann. Am. Assoc. Geogr.* **105** 806–23
- Richey J E, Victoria R L, Hedges J I, Dunne T, Martinelli L A, Mertes L and Adams J 2009 Pre-LBA carbon in the Amazon River Experiment (CAMREX) data ORNL DAAC
- Ruttenberg K C 2004 The global phosphorus cycle *Treatise on Geochemistry* ed W H Schlesinger vol 8 (Amsterdam: Elsevier) pp 585–643
- Schlosser C, Klar J K, Wake B D, Snow J T, Honey D J, Woodward E M S, Lohan M C, Achterberg E P and Moore C M 2014 Seasonal ITCZ migration dynamically controls the location of the (sub)tropical Atlantic biogeochemical divide *Proc. Natl Acad. Sci.* **111** 1438–42
- Seitzinger S P et al 2010 Global river nutrient export: a scenario analysis of past and future trends *Glob. Biogeochem. Cycles* **24** GBOA08
- Signorini S R, Murtugudde R G, McClain C R, Christian J R, Picaut J and Busalacchi A J 1999 Biological and physical signatures in the tropical and subtropical Atlantic *J. Geophys. Res.: Oceans* **104** 18367–82
- Sissini M N et al 2017 The floating Sargassum (Phaeophyceae) of the South Atlantic Ocean—likely scenarios *Phycologia* **56** 321–8
- Smetacek V and Zingone A 2013 Green and golden seaweed tides on the rise *Nature* **504** 84–88
- Subramaniam A et al 2008 Amazon River enhances diazotrophy and carbon sequestration in the tropical North Atlantic Ocean *Proc. Natl Acad. Sci.* **105** 10460–5
- Wang M and Hu C 2016 Mapping and quantifying Sargassum distribution and coverage in the Central Western Atlantic using MODIS observations *Remote Sens. Environ.* **183** 350–67
- Wang M and Hu C 2017 Predicting Sargassum blooms in the Caribbean Sea from MODIS observations *Geophys. Res. Lett.* **44** 3265–73
- Wang M, Hu C, Barnes B B, Mitchum G, Lapointe B and Montoya J P 2019 The great Atlantic Sargassum belt *Science* **365** 83–87
- Ward N D, Krusche A V, Sawakuchi H O, Brito D C, Cunha A C, Moura J M S, da Silva R, Yager P L, Keil R G and Richey J E 2015 The compositional evolution of dissolved and particulate organic matter along the lower Amazon River—Óbidos to the ocean *Mar. Chem.* **177** 244–56
- Wysocki L A, Bianchi T S, Powell R T and Reuss N 2006 Spatial variability in the coupling of organic carbon, nutrients, and phytoplankton pigments in surface waters and sediments of the Mississippi River plume *Estuar. Coast. Shelf Sci.* **69** 47–63
- Yu H et al 2015 The fertilizing role of African dust in the Amazon rainforest: a first multiyear assessment based on data from Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations *Geophys. Res. Lett.* **42** 1984–91