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Riverine influence on the tropical Atlantic Ocean biogeochemistry

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Abstract

We assess the role of riverine inputs of N, Si, Fe, organic and inorganic C in the tropical Atlantic Ocean using a global ocean biogeochemistry model. We use two sensitivity tests to investigate the role of the western (South American Rivers) and eastern (African Rivers) riverine nutrient inputs on the tropical Atlantic Ocean biogeochemistry (between 20° S–20° N and 70° W–20°). Increased nutrient availability from river inputs in this area (compared to an extreme scenario with no river nutrients) leads to an increase in 14 % (0.7 Pg C a^{-1}) in open ocean primary production (PP), and 21 % (0.2 Pg C a^{-1}) in coastal ocean PP. We estimate very modest increases in open and coastal ocean export production and sea-air CO_2 fluxes. Results suggest that in the tropical Atlantic Ocean, the large riverine nutrient inputs on the western side have a larger impact on primary production and sea-air CO_2 exchanges. On the other hand, African river inputs, although smaller than South American inputs, have larger impact on the coastal and open tropical Atlantic Ocean export production. This is probably due to a combination of nutrient trapping in upwelling areas off the Congo River outflow, and differences in delivered nutrient ratios leading to alleviation in limitation conditions mainly for diatoms.

1 Introduction

The tropical Atlantic Ocean receives directly (i.e. the discharge is not filtered by regional seas or enclosed coastal areas) the discharge of the three largest rivers in the world: the Amazon River (0°, 50° W), the Congo River (6° S, 12° E), and the Orinoco River (10° N, 63° W). In this region, a weak Coriolis forcing leads to extended river plumes off the coast, creating nutrient-rich areas of optimal production in sites far removed from the coast (Corredor et al., 2003). The freshwater inputs of the three rivers represent ∼25 % of the global river freshwater discharge to the oceans (Dai and Trenberth, 2002), and together they represent 15–18 % of the total river input of organic carbon to the ocean (Coynel et al., 2005).

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The Western Tropical Atlantic receives massive freshwater and nutrient inputs from the Amazon and Orinoco rivers. The discharge of these rivers alone represents 20 % of the total annual riverine freshwater discharge to the oceans. A persistent front of high surface chlorophyll, visible in ocean satellite colour imagery, is associated with riverine inputs (Corredor et al., 2003; Hu et al., 2004). The Amazon River discharge generates a plume that covers up to 2106 km^2, characterized by low salinity and low inorganic carbon concentration. The plume may reach from 50 ° W to 25 ° W during the peak flow of the North Equatorial Countercurrent (NECC) (Cooley et al., 2007).

The Eastern tropical Atlantic receives the largest freshwater input to an eastern ocean boundary from the Congo River. The Eastern tropical Atlantic is characterized by oligotrophic oceanic waters, but a large river plume (Congo) with elevated nutrient concentration and the Benguela Current system with strong wind-driven coastal upwelling (Cadee, 1978; Dale et al., 2002;Schneider et al., 1997) impact the local productivity (Hardman-Mountford et al., 2003; Binet, 1983). Further north, the Gulf of Guinea receives freshwater input from a dense river network to the coastal ocean (e.g. Niger and Rio del Rey rivers (Adegbie et al., 2000)). It is also subject to coastal upwelling, mainly between July and September (Lefevre et al., 2008).

Here, we assess the impact of riverine input of carbon and nutrients on the Western and Eastern tropical Atlantic biogeochemistry. We exploit recent methods to estimate river nutrient (N, Si and Fe) and carbon (DIC, DOM, POM) inputs, and use a global ocean biogeochemistry model. We focus our results and discussion on the tropical Atlantic Ocean (70° W–20° E, 20° S–20° N).

2 Methods

We use the PISCES-T biogeochemistry model (Buitenhuis et al., 2006), in the version considering the riverine nutrient fluxes used by Cotrim da Cunha et al. (2007). PISCES-T includes the representation of diatoms and nanophytoplankton, mesozooplankton and microzooplankton, and co-limitation by light and by N:P, Si and Fe. PISCES-T is

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embedded in the OPA global circulation model (Levy et al., 1998; Madec and Imbard, 1996). The model was forced by the daily wind and water fluxes from NCEP/NCAR reanalysis (Kalnay et al., 1996) from 1948 to 2005 as in Buitenhuis et al. (2006) and Le Quéré et al. (2003). The solar radiation penetrates the top meters of the ocean. The downward irradiance is formulated with two extinction coefficients (Paulson and Simpson, 1977) whose values correspond to average open ocean conditions (Manizza et al., 2005). Annual riverine inputs of nutrients (organic and inorganic carbon (OC, IC), N, Si, Fe) to the ocean were computed according to the methods described in Cotrim da Cunha et al. (2007). We ran the model from 1948 to 1992 as in Carr et al. (2006) and McKinley et al. (2006). This is long enough for the surface ocean to approximate steady state, as shown by the stability of the results after 3–4 years of simulations. Then we did several simulations of 13 years from 1993 to 2005 with the PISCES-T model considering different riverine nutrient load estimates. We present average output for years 1998–2005.

We considered two scenarios, one without river nutrients, and one considering riverine inputs of DIC, DOC, POC, N, Si, and low Fe (Cotrim da Cunha et al., 2007). Additionally, we use two test scenarios to assess the impact of rivers on the tropical Atlantic biogeochemistry. Except for the change in nutrient river loads, the simulations were identical (Table 1).

– NO_RIVER: no river nutrient supply. This scenario represents an extreme situation where nutrient fluxes would stop completely due to river damming. We do not consider a reduction in freshwater input to the ocean.

– TODAY: This scenario considers riverine inputs of DIC, DOC, POC, DIN, and Si. Additionally, it has low riverine Fe input (considering 99 % dissolved Fe lost in the estuaries).

– AFRICA: Identical to TODAY but only African rivers flow to the tropical Atlantic Ocean. The South American river inputs were stopped. We do not consider a reduction in freshwater input to the ocean.

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- S_AMERICA: Identical to TODAY but only South American rivers flow to the tropical Atlantic Ocean. The African river inputs were stopped. We do not consider a reduction in freshwater input to the ocean.

We used the average of the absolute difference between modelled parameter (*an*) and available data (*cn*) values to estimate how the model simulates chlorophyll-*a* (Chl-*a*), NO_3, Si, primary production, export production and dissolved O_2 (Eq. (1), Table 2). This also allows us to assess how riverine nutrient fluxes affect these parameters. We calculate the mean absolute error (MAE) as follows:

$$\mathrm{MAE} = \frac{|a1 - c1| + |a2 - c2| + \ldots + |an - cn|}{n} \quad (1)$$

3 Results

In our model, the Amazon, Congo and Orinoco Rivers deliver ~70 % of the total river organic carbon to the tropical Atlantic Ocean. We have a good agreement between TODAY river OM inputs and data based on measurements. For the Amazon, Congo and Orinoco Rivers, we have in scenario TODAY 3.61 Tmol OC a^{-1}, 0.71 Tmol OC a^{-1}, and 0.53 Tmol OC a^{-1}, respectively, while Coynel et al. (2005) report river inputs of 3.65 Tmol OC a^{-1} for the Amazon and 1.20 Tmol OC a^{-1} for the Congo, and Lewis Jr. and Saunders III (1989)(Lewis Jr. and Saunders Iii, 1989) report 0.56 Tmol OC a^{-1} for the Orinoco River. Model vs. measured river DIC inputs to the ocean also agree for the Amazon (3.1 Tmol DIC a^{-1}, model, and 2.2 Tmol DIC a^{-1}, (Probst et al., 1994)) and Congo rivers (0.50 Tmol DIC a^{-1}, model, and 0.29 Tmol DIC a^{-1}, (Probst et al., 1994)). For the Orinoco, modeled river DIC inputs (0.22 Tmol DIC a^{-1}) are lower than literature value (0.94 Tmol DIC a^{-1}, (Lewis Jr. and Saunders III, 1989)).

The scenario TODAY is our best estimate of the current input of nutrients by rivers, and of its impact on the global marine biogeochemistry (Cotrim da Cunha et al., 2007). This simulation reproduces the main characteristics of ocean biogeochemistry. The

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tropical Atlantic surface chlorophyll-*a* (Chl-*a*) generally matches the World Ocean Atlas 2001 (Conkright et al., 2002b). Observed concentrations below 0.1 mg Chl-*a* m^{-3} found in the Atlantic subtropical gyres are reproduced by the model. However, it fails to reproduce the elevated concentrations (>1–2 mg Chl-*a* m^{-3} for the annual mean) observed in the areas of the Mauritanian upwelling and Guinea Dome on the eastern Atlantic.

The simulated gross annual primary production (PP, 95 % of which is particulate, 5 % as DOC) for the tropical Atlantic is 8.52 Pg C a^{-1} and 1.19 Pg C a^{-1} in the open and coastal ocean, respectively (Table 3). Our simulated export production (EP) is 0.84 Pg C a^{-1} and 0.12 Pg C a^{-1} in the open and coastal ocean, respectively. In PISCES-T, EP corresponds to the amount of particulate organic matter exported below the euphotic zone. In this version we consider it at 150 m. The simulated sea-to-air flux of CO_2 is 0.05 Pg C a^{-1} and 0.03 Pg C a^{-1} in the open and coastal ocean, respectively.

3.1 Impact of rivers in the tropical Atlantic

The impact of river nutrients can be assessed by subtracting the scenario NO_RIVER from scenario TODAY. This comparison allows us to bracket the impact of river inputs and to identify the features in the tropical Atlantic Ocean biogeochemistry that are caused by river nutrient fluxes (70° W–20° E, 20° S–20° N).

When riverine inputs are added, the model reproduces well the patterns of high primary production adjacent to the large rivers outflow (Fig. 2). Increased nutrient availability from riverine input in the Tropical Atlantic (TODAY - NO_RIVER) leads to an increase of 0.7 Pg C a^{-1} in open ocean primary production (+14 %), and 0.2 Pg C a^{-1} in coastal ocean primary production (+21 %). The increase in primary production is noticeable in coastal and open ocean areas adjacent to the Amazon and Orinoco outflow, and in open ocean eastwards the Congo outflow (Fig. 2), and the Gulf of Guinea. We estimate very modest increases in export production (EP) and sea-air CO_2 fluxes.

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3.2 Impact of South American rivers

In scenario S_AMERICA, our results suggest an increase in primary production along the Brazilian shelf and adjacent ocean areas, and no changes on the Eastern tropical Atlantic (compared to NO_RIVER). The modelled primary production in the open and coastal ocean is 8.39 $Pg\,C\,a^{-1}$ and 1.14 $Pg\,C\,a^{-1}$, respectively. The difference in PP between scenarios S_AMERICA and NO_RIVER correspond to 81 % and 72 % of the difference in PP between scenarios TODAY and NO_RIVER, for the open and coastal ocean, respectively.

In the North Brazilian Shelf (NBS) area, modelled average primary production (40 $mol\,C\,m^{-2}\,a^{-1}$) was within the range of the measured PP values for the offshore area of the NBS (4–75 $mol\,C\,m^{-2}\,a^{-1}$, average 25 $mol\,C\,m^{-2}\,a^{-1}$, (Smith Jr. and Demaster, 1996)).

Although the Western tropical Atlantic receives more river nutrients compared to the Eastern side (Table 1), our sensitivity tests suggest that South American rivers have a smaller impact than African rivers on coastal and open ocean export production (Table 3). Adding river nutrients and carbon slightly increases the sea-to-air CO_2 flux, as a result of river C outgassing and remineralisation (Table 3).

The increase in primary production is not proportional to the increase in export production on the Western tropical Atlantic Ocean. Additionally, the riverine inputs are insufficient to decrease or to revert the sea-to-air CO_2 flux. We have tested the change in the biological pump efficiency (EBP) between the scenarios NO_RIVER and TODAY. EBP is defined as a ratio between the concentration of residual nutrients in surface waters and the concentration of nutrients in deeper waters (Eq. (2), (Sarmiento and Gruber, 2006):

$$E_{BP} = \frac{C_{deep} - C_{surf}}{C_{deep}} \tag{2}$$

where C_{deep} is the modelled average nitrate concentration between 100 m and 200 m, and C_{surf} is the modelled average nitrate concentration between 0,m and 100 m. On the

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Western tropical Atlantic the EBP is relatively high in both scenarios, decreasing on the continental shelf area when river nutrients and carbon are added (TODAY, Fig. 3). Our hypothesis is that despite the large amount of riverine nutrient inputs in scenario TODAY, the coastal ocean on the Western tropical Atlantic remains N-limited. In scenarios TODAY and S_AMERICA, the amount of river N input is not large enough to support the coastal ocean export production (Table 4). Thus, one may conclude that in these scenarios, the primary production is recycled in the upper layers, and little material is exported to the deeper layers.

Our results also suggest that the South American rivers, especially the Amazon and Orinoco, influence further areas in the Caribbean Sea (not shown in this study), in agreement with field measured data from Corredor et al. (2003). In scenarios TODAY and S_AMERICA, both regional primary and export production in the Caribbean Sea increase by about +45 %, compared to scenario NO_RIVER.

3.3 Impact of African rivers

In scenarios TODAY and AFRICA, our results suggest an increase in primary production along the Gulf of Guinea and the outflow of the Congo River, with no changes occurring in the Western tropical Atlantic (compared to NO_RIVER, Fig. 2). The modeled primary production in the open and coastal ocean is 8.15 $Pg\,C\,a^{-1}$ and 1.06 $Pg\,C\,a^{-1}$, respectively. The difference in PP between scenarios AFRICA and NO_RIVER correspond to 48 % and 37 % of the difference in PP between scenarios TODAY and NO_RIVER, for the open and coastal ocean, respectively.

Modeled average PP in the Congo plume is 60–63 $mol\,C\,m^{-2}\,a^{-1}$. An area of high PP extends from the coast up to 0° longitude (Fig. 2). The modeled values agree with PP satellite-derived data from Behrenfeld et al. (2005).

Although the overall impact of rivers to the tropical Atlantic export production is small, African rivers have a relative higher impact on EP than South American Rivers (Table 3). The difference in EP between scenarios AFRICA and NO_RIVER correspond to 71 % and 87 % of the difference in EP between scenarios TODAY and NO_RIVER, for

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the open and coastal ocean, respectively. The results of Cotrim da Cunha et al. (2007) suggested that river inputs over coastal upwelling areas (eastern margin type) have a higher impact on PP and EP than western margin areas. This is probably due to a combination of nutrient trapping in upwelling areas due to slower circulation and an alleviation of mainly Fe limitation conditions (mainly diatoms) by riverine inputs (Table 4).

The small increase in export production is not reflected by a decrease in the sea-air CO_2 fluxes, as it remains almost unchanged between scenarios AFRICA and NO_RIVER (Table 3). This suggests that nutrient inputs from African rivers are insufficient to decrease the sea-to-air CO_2 flux from the tropical upwelling areas in the Eastern Atlantic Ocean.

On the Eastern tropical Atlantic the EBP has medium values on scenarios TODAY and NO_RIVER, and remains unchanged on the continental shelf area when river nutrients and carbon are added (Fig. 3). This is typical of low-latitude upwelling areas (Sarmiento and Gruber, 2006), where light and nutrient supplies are high, but the EBP is medium to low. One hypothesis to explain this is that despite the river nutrient inputs (scenarios TODAY and AFRICA) the ecosystem is still limited by nutrients. In scenario AFRICA, riverine inputs of N, Si, and to a lesser extent, Fe, are insufficient to maintain coastal EP, corroborating the hypothesis that most of the nutrients are brought by upwelling waters.

3.4 Regional impact of river carbon and nutrient inputs

When river carbon and nutrient inputs are added to model scenarios, there is an overall increase in the primary production, sea-air CO_2 fluxes, and to a lesser extent, export production in the tropical Atlantic Ocean. In this section we will discuss the regional effects of river carbon and nutrients inputs.

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3.4.1 Western tropical Atlantic – Amazon River plume

Körtzinger (2003) identified an area strongly undersaturated with respect to atmospheric CO_2 in the Amazon River plume area. This local CO_2 sink is due to a combination of physical (mixing effect of river and seawater in the plume) and biological (production in the plume) effects (Fig. 4). Here we compare scenarios TODAY, S_AMERICA and NO_RIVER to assess the role of river nutrients and carbon in the modelled sea-to-air fluxes at the Amazon plume area (latitude 1° N–9° N, longitude 60° W–30° W). In this study we assume a regional atmospheric pCO_2 value of 358 µatm, as measured in 2002 in this region by Körtzinger (2003). This value is below the average of pCO_2 (371 µatm) from Ragged Point, Barbados, for the period between 1998–2005.

In scenario NO_RIVER, our results suggest that, for the Amazon plume region, surface waters with salinity <35 psu are undersaturated with respect to atmospheric CO_2. The maximum undersaturation occurs around 50° W, where salinity is at its lowest, in agreement with the measurements made by Körtzinger (2003). In Cotrim da Cunha et al. (2007) PISCES-T simulations suggest that riverine Si and Fe in the North Brazil Shelf area do not influence the sea-air CO_2 flux (small CO_2 sink) when added individually, while riverine N increases the "sink" effect.

In the Amazon plume area, our model results suggest that in scenarios TODAY and S_AMERICA, river carbon inputs (DIC, DOC, POC) reverse the undersaturation of CO_2 in surface seawater caused by the low salinity surface waters (physical effect), despite the increase in primary production (Fig. 4). This is supported by an increase in modeled alkalinity and DIC concentrations in surface waters. A narrow area of low surface water pCO_2 appears further east (48° W) in the plume, where primary production decreases and salinity is around 34.2 psu. In our simulations, river organic C, despite acting as an additional nutrient source, is insufficient to decrease the mineralization of organic matter and river DIC outgassing.

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3.4.2 Eastern tropical Atlantic – Congo River outflow area

On the E-Atlantic, the equatorial and coastal upwelling zones release CO_2 to the atmosphere. In this study we assume a regional atmospheric pCO_2 value of 367.7 μatm, as measured in 2006 by Lefèvre et al. (2008) in this region. In the Congo River mouth area, despite the amount of fresh water and nutrients delivered by the river, there are no significant changes in the surface waters pCO_2 values (Fig. 4). Our results suggest that in the eastern Atlantic physical processes control the sea-air CO_2 fluxes, and river nutrients and carbon inputs play a minor role in this case. The small influence of modeled river nutrients on sea-air CO_2 fluxes in this area may be explained by a nutrient trapping effect caused by regional slower circulation, thus having a local fertilizing effect. The regional primary production is rapidly exported (relative higher increase in coastal ocean export production, scenario AFRICA) but does not exceed the amount of carbon brought to surface waters by upwelling.

3.5 Limitations of the model

We present a sensitivity test to estimate the impacts of river nutrients and carbon on the tropical Atlantic Ocean biogeochemistry. However, our approach has limitations. First, our model does not have a real representation of the coastal zone. Because of its coarse resolution, it is not able to resolve coastal circulation patterns, like upwelling or increased vertical mixing. A higher resolution of the coastal ocean would improve the representation of very productive zones. Second, we used annual mean fluxes of riverine nutrients and carbon to the ocean. In these simulations, only the variation of monthly fluxes of riverine freshwater to the ocean was considered. In areas adjacent to strong river input like the Amazon, Orinoco or Congo, flood and drought periods alter the amount of river nutrient and carbon fluxes. This may have a direct impact in the regional net ecosystem production and sea-air CO_2 fluxes. Third, we use an average concentration for river Fe and Si. Development of databases considering river basin geology may alter the distribution of riverine Fe and Si significantly. Fourth, our model has

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a limited representation of the ecosystem. Including a more complex representation of the ecosystem will allow us to assess the impacts of changes on nutrient availability on plankton types and on fisheries at the regional scale, especially important at the Eastern tropical Atlantic Ocean (Hardman-Mountford et al., 2003;Le Quéré et al., 2005). Fifth, our model does not differentiate terrestrial and marine organic carbon reactivity (degradation and mineralization rates, C:N ratio). If riverine OC is more labile than marine OC, the regional budget of sea-to-air CO_2 flux and its impact on productivity should be expected to be higher. All these factors can enhance or dampen locally the impact of river inputs in ways that are difficult to assess. In spite of these limitations, our analysis provides estimates of the upper and lower bounds of the potential impact of nutrient and carbon supply by rivers in the tropical Atlantic Ocean, considering the most up-to-date tools (Cotrim da Cunha et al., 2007) and data available (Körtzinger, 2003;Lefevre et al., 2008).

4 Conclusions

We conclude from this sensitivity modeling study that South American river nutrient inputs may have a larger impact on tropical Atlantic primary production than African rivers. In our sensitivity tests we estimate that South American river input to the tropical Atlantic was responsible for up to 81 % of the increase in open ocean primary production difference between scenarios NO_RIVER and TODAY. The African river input was responsible for up to 48 % of the same open ocean primary production increase.

On the other hand, African rivers may have a larger impact on tropical Atlantic export production because of a combination of regional nutrient trapping and alleviation of Fe limitation in coastal areas from riverine inputs. African riverine nutrient inputs were responsible for up to 71 % of the increase in open ocean EP difference between scenarios NO_RIVER and TODAY, while South American rivers were responsible for up 69 % of the increase in EP if the same export production increase. Cotrim da Cunha et al. (2007) found that regional riverine impact on biogeochemistry depend on runoff

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intensity, local nutrient budgets, and adjacent ocean circulation. The impact may be higher in eastern margin areas with high runoff, because of the nutrient trapping effect of upwelling. In a modelling study using the PISCES model, Giraud et al. (2008) suggested that excess nutrients in coastal areas locally increase the primary production if the conditions of nutrient limitation are favourable. In the case of the western tropical Atlantic, riverine nutrients would be able to maintain almost all the coastal export production, and on the eastern tropical Atlantic, riverine inputs of Fe alleviate the regional nutrient limitation, increasing diatoms production, and consequently the export production.

The increase in primary and export production has very little impact on the sea-to-air CO_2 fluxes. On the eastern tropical Atlantic, scenarios TODAY and AFRICA suggest that despite the increase in production, the physical processes (upwelling) dominate the sea-to-air CO_2 flux. On the western tropical Atlantic, our results suggest that the regional atmospheric CO_2 sink of the Amazon River plume can be reversed by the increased production, organic matter respiration and river DIC outgassing in scenarios TODAY and S_AMERICA.

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Table 1. River nutrient scenarios.

Scenario	River nutrient inputs to the tropical Atlantic Ocean (20° S–20° N, 70° W–20° E)					
name	OM (Tmol C a^{-1})	DIC (Tmol C a^{-1})	N (Tmol N a^{-1})	Si (Tmol Si a^{-1})	Fe (Gmol Fe a^{-1})	Details on riverine nutrient inputs
NO_RIVER	0	0	0	0	0	No riverine inputs
TODAY	6.75	4.83	1.09	1.89	0.12	DIN[a], Si[b], Fe (99 % loss)[c], DIC[d], DOM[d], POM[d]
S_AMERICA	5.09	3.91	0.77	1.37	0.08	DIN[a], Si[b], Fe (99 % loss)[c], DIC[d], DOM[d], POM[d], only South American rivers
AFRICA	1.66	0.92	0.32	0.52	0.04	DIN[a], Si[b], Fe (99 % loss)[c], DIC[d], DOM[d], POM[d], only African rivers

(a) World population = 6 10^9 inhabitants, (Smith et al., 2003; Doell and Lehner, 2002; UNPD, 2004),
(b) (Doell and Lehner, 2002; Treguer et al., 1995),
(c) 1 % net flux of riverine dissolved Fe to the ocean (Doell and Lehner, 2002; Chester, 1990; Martin and Meybeck, 1979),
(d) (Doell and Lehner, 2002; Ludwig et al., 1996a; Ludwig et al., 1996b).

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Table 2. Mean absolute error (MAE) between PISCES-T simulations NO_RIVER and TODAY (average 1998–2005) and available data for the tropical Atlantic Ocean (20° S–20° N, 70° W–20° E)

Scenario name	Mean absolute error					
	Chl-*a*[a] (mg Chl-*a* L^{-1})	NO3[b] (µM)	Si[b] (µM)	PP[c] gC m^{-2} a^{-1}	EP[d] gC m^{-2} a^{-1}	Dissolved O_2[e] (µM)
NO_RIVER	0.06	0.98	2.89	30.45	5.16	3.25
TODAY	0.07	1.09	2.97	51.45	6.63	4.53

(a) surface Chl-*a* (Conkright et al., 2002b),
(b) surface NO3 and Si (Conkright et al., 2002a),
(c) primary production (Behrenfeld et al., 2005),
(d) export production (Schlitzer, 2002),
(e) surface dissolved O_2 (Locarnini et al., 2002).

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Table 3. Primary (PP) and export production (EP), and sea-to-air CO_2 fluxes (CFLX) in Pg C a^{-1} for each scenario considering the whole and coastal tropical Atlantic Ocean (20° S–20° N, 70° W–20° E). The numbers in parenthesis correspond to the change in % relative to scenario NO_RIVER. Positive values for CFLX denote outgassing of CO_2 to the atmosphere.

Scenario	PP	COASTAL PP	EP	COASTAL EP	CFLX	COASTAL CFLX
NO_RIVER	7.80	0.98	0.78	0.09	+0.03	+0.02
TODAY	8.52 (+9.2)	1.19 (+21.9)	0.84 (+8.0)	0.12 (+22.0)	+0.05 (+46.4)	+0.03 (+66.2)
S_AMERICA	8.39 (+7.6)	1.14 (+15.8)	0.81 (+4.7)	0.10 (+3.2)	+0.06 (+82.5)	+0.03 (+70.3)
AFRICA	8.15 (+4.5)	1.06 (+8.1)	0.82 (+5.7)	0.11 (+19.1)	+0.03 (+3.9)	+0.02 (+1.0)

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Table 4. Modeled coastal ocean EP (N, Si and Fe), riverine inputs (N, Si, and Fe) and ratios [a] between riverine inputs and EP in the tropical Atlantic Ocean (20° S–20° N, 70° W–20° E).

	Export production				River nutrient inputs				River: coastal EP ratio		
Simulation	EP Tmol C a^{-1}	EP[b] Tmol N a^{-1}	EP[b] Gmol Fe a^{-1}	EP_Si[c] Tmol Si a^{-1}	River C[d] Tmol C a^{-1}	River N Tmol N a^{-1}	River Fe Gmol Fe a^{-1}	River Si Tmol Si a^{-1}	River:EP N	River:EP Fe	River:EP Si
NO_RIVER	7.86	1.03	0.04	1.22	0	0	0	0	–	–	–
TODAY	9.59	1.26	0.05	1.84	6.75	1.09	0.12	1.89	87	250	103
S_AMERICA	8.11	1.06	0.04	1.27	5.09	0.77	0.08	1.37	72	197	108
AFRICA	9.37	1.23	0.05	1.71	1.66	0.32	0.04	0.52	26	85	30

(a) The ratio gives an estimate of the how much of the coastal EP is supported by riverine nutrients.
(b) N and Fe coastal ocean EP values were estimated using the model molar ratios of C:N (7.6:1), and C:Fe (1:5 10^{-6}).
(c) Si coastal ocean EP is estimated by the model.
(d) River carbon inputs are the sum of dissolved (DOC) and particulate organic carbon (POC).

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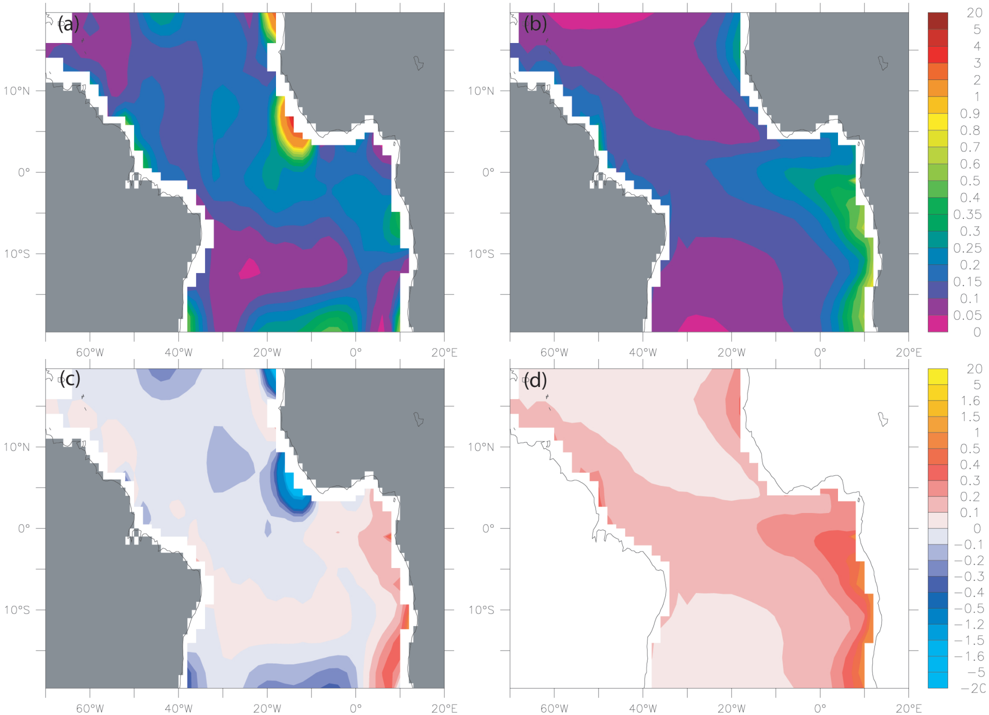

Fig. 1. Annual mean surface chlorophyll-*a* (Chl-*a*) in mg Chl-*a* m^{-3} from **(a)** World Ocean Atlas 2001 (Conkright et al., 2002b), and **(b)** Standard scenario TODAY (average 1998–2005). Difference in surface chlorophyll-*a* (mg Chl-*a* m^{-3}) between **(c)** scenario TODAY and World Ocean Atlas 2001, and **(d)** the two scenarios TODAY and NO_RIVER. Figures 1b, 1c and 1d are an average of model results from 1998–2005.

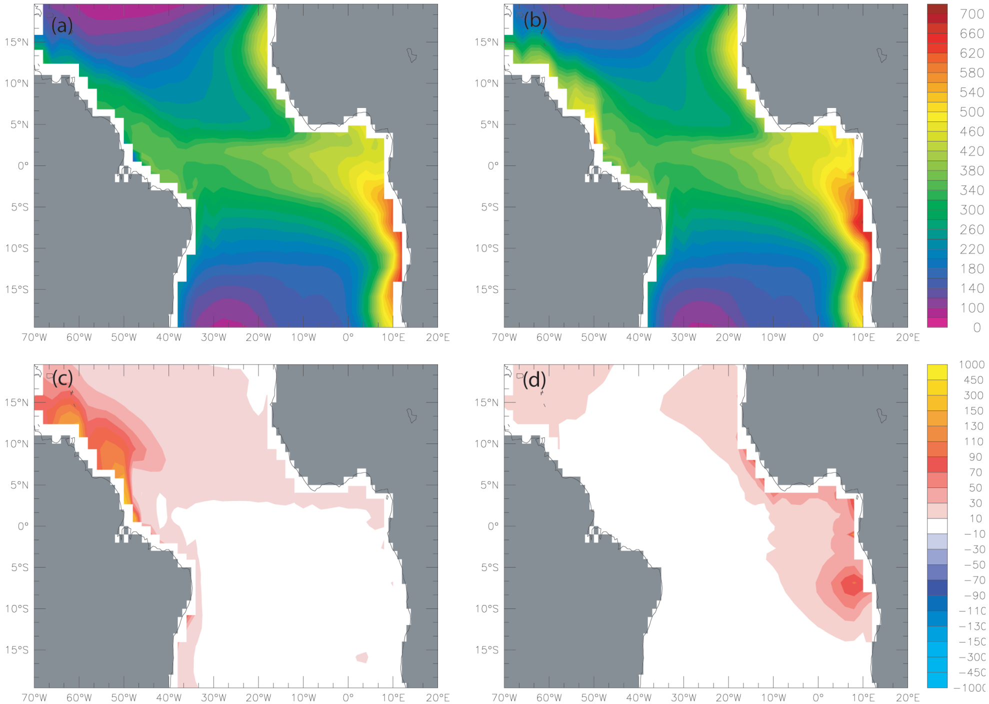

Fig. 2. **(a)** and **(b)** Average (1998–2005) mean fields of integrated PP from scenarios NO_RIVER and TODAY in mg C m^{-2} a^{-1}, respectively; **(c)** and **(d)** Difference in integrated PP in mg C m^{-2} a^{-1} between the scenario S_AMERICA (average 1998–2005) and NO_RIVER (average 1998–2005), and scenario AFRICA (average 1998–2005) and NO_RIVER (average 1998–2005), respectively.

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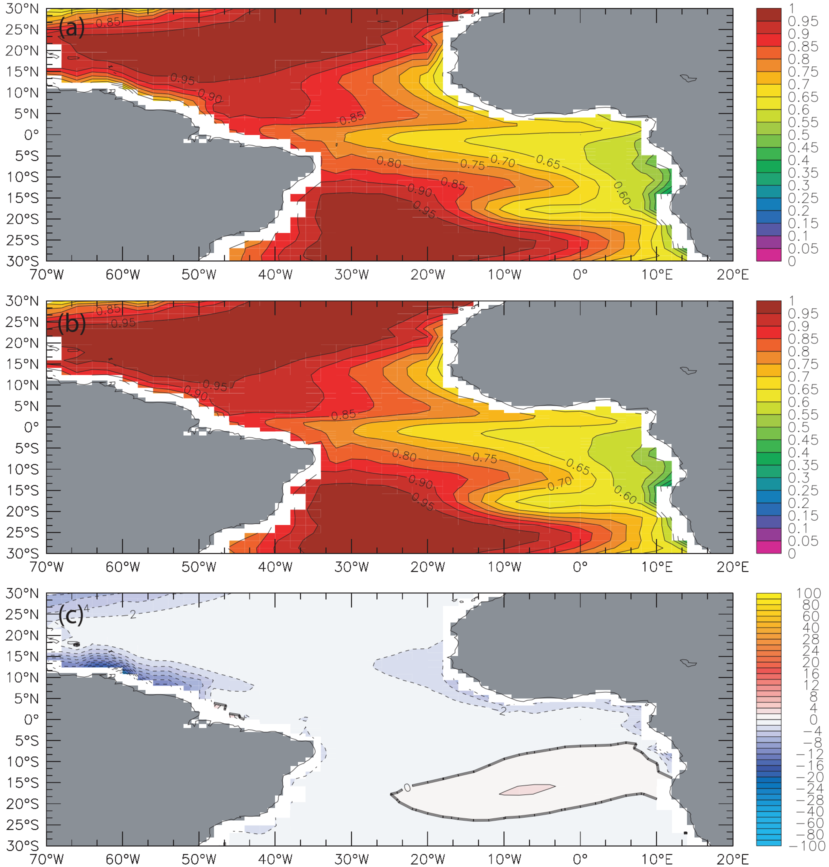

Fig. 3. **(a)** and **(b)** Average (1998–2005) mean fields of biological pump efficiency (E_{BP}, unitless) from scenarios TODAY and NO_RIVER, respectively; and **(c)** Difference in E_{BP} between the scenario TODAY (average 1998–2005) and NO_RIVER (average 1998–2005). This is a change in percent compared to scenario TODAY.

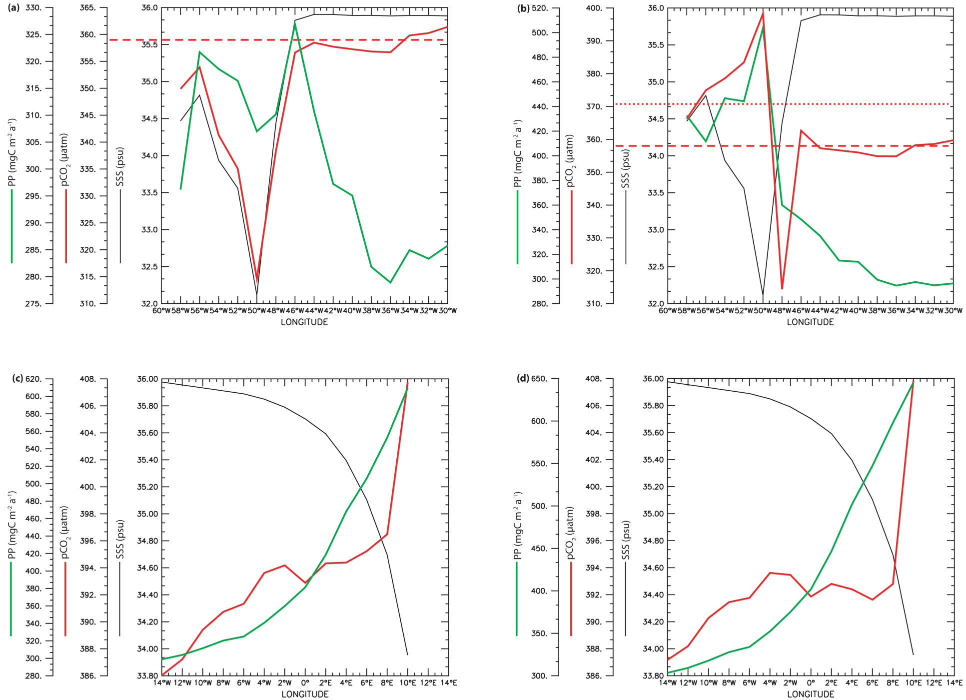

Fig. 4. **(a)** and **(b)** Average (1998–2005) mean integrated PP ($mgC\,m^{-2}\,a^{-1}$), surface water $p\mathrm{CO_2}$ (µatm) and surface water salinity (psu) from scenarios NO_RIVER and TODAY, respectively, for the Amazon River plume area (latitude average 1° N–9° N, 60° W–30° W). The dashed line represents the measured atmospheric $p\mathrm{CO_2}$ in situ (Körtzinger, 2003), and the dotted line represents the average 1998–2005 measured atmospheric $p\mathrm{CO_2}$ at Ragged Point, Barbados; **(c)** and **(d)** Average (1998–2005) mean integrated PP ($mgC\,m^{-2}\,a^{-1}$), surface water $p\mathrm{CO_2}$ (µatm) and surface water salinity (psu) from scenarios NO_RIVER and TODAY, respectively, for the Congo River outflow area (latitude average 4° S–6° S, 15° W–15° E).

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