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Quantitative analysis of the influence of dust sea surface forcing on the primary production of the subtropical Atlantic Ocean using a ten-year time series of satellite observations

Malik Chami,^{1,2} Marc Mallet,^{3,4} and Bernard Gentili¹

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[1] Dust aerosols that are not deposited over oceans are able to significantly reduce the solar energy available at the sea surface. Here, the impact of dust aerosols on the photosynthetically available radiation (*PAR*) at the sea surface and on the associated oceanic primary production (*PP*) is quantified over the subtropical Atlantic Ocean based on a ten-year time series of satellite observations. The ten-year average value of the attenuation of both *PAR* and *PP* due to dust aerosols is high ($\sim 15\%$). The comparisons with predictions suggested that the decrease of *PP* might be $\sim 35\%$ in the case of intense episodic events (i.e., dust aerosols optical depth > 0.6). Therefore, dust aerosol events could significantly alter the organic carbon budget of the underlying oceanic ecosystems. The analysis of the interannual variations of the relative reduction of primary production ($\Delta PP/PP$) due to dust aerosols showed that the evolution of $\Delta PP/PP$ does not exhibit any major trend of variation within the entire study area over the decade. However, a significant tendency (0.22% per year) is found near Africa in summer. Thus, dust aerosol events might induce a major decrease of the marine productivity the next centuries. The radiative forcing of dust aerosols on the sea surface needs to be accounted for in coupled atmosphere–ocean models for calculating correctly the primary production. A more extensive analysis of the aerosol radiative budget is also required to better understand the link between the atmospheric and oceanic processes driving the primary production over dust aerosol areas.

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1. Introduction

[2] Photoautotrophic production by oceanic phytoplankton is a key process for the oceanic carbon cycle. The primary production rate of any plant biomass depends on the size of the biomass itself, on the availability of nutrients down the water column and on the amount of energy impinging onto the biomass and able to drive the photosynthesis process. Because of their contribution to supply additional iron into the water mass, desert dust aerosols could stimulate phytoplankton photosynthesis when they are deposited over the oceans. As an example, the subtropical North Atlantic region

zone, which is an iron limited region [Moore *et al.*, 2006], is characterized by significant dust aerosol depositions [Jickells *et al.*, 2005]. From this point of view, dust aerosols could influence and locally increase the biological productivity of the ocean [Bonnet and Guieu, 2004; Cropp *et al.*, 2005]. However, the dust aerosols which remain in the atmospheric layer could also contribute to reduce the solar energy reaching the sea surface thus leading to a potential decrease of oceanic primary production. Such a decrease could be significant in regions for which the dust aerosol loading is high, such as regions found in the subtropical oceanic waters (e.g., offshore West Africa coast). A preliminary 1D modeling study, which was devoted to investigate the potential impact of dust aerosol radiative forcing on the sea surface and the subsequent biological oceanic productivity, was recently performed [Mallet *et al.*, 2009]. Based on a radiative transfer modeling approach, Mallet *et al.* [2009] showed that the attenuation of light due to a high dust aerosol loading (i.e., dust aerosol optical depth of 0.6) could theoretically lead to a decrease by about 15% to 25% of primary production (*PP*).

[3] On the basis of Mallet *et al.*'s [2009] study, the main objective of the present paper is to exploit time series of

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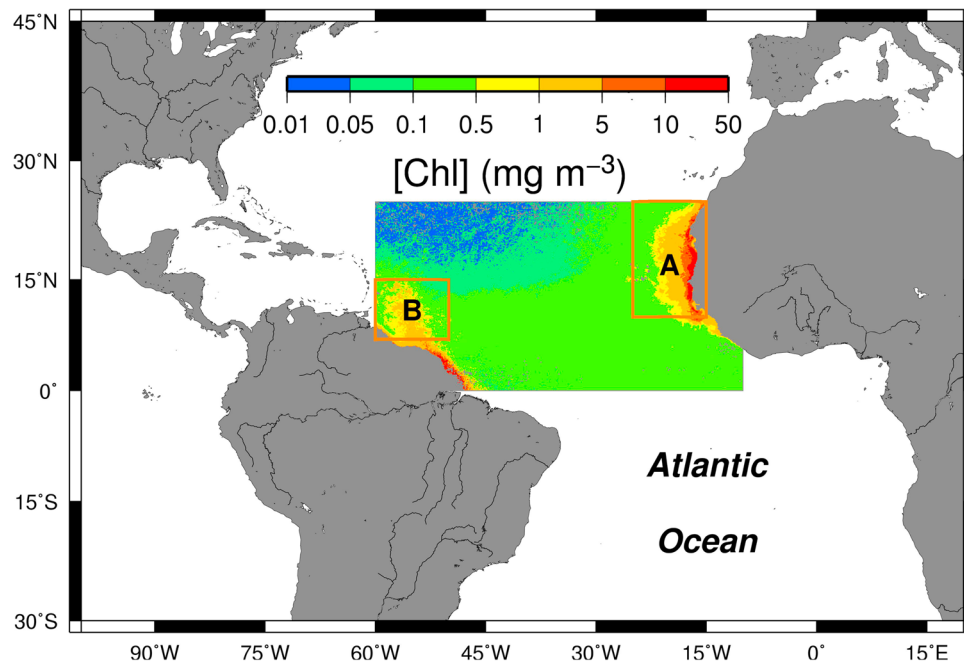


Figure 1. Map of the study area (subtropical Atlantic Ocean). The ten-year average [Chl] concentration (mg m^{-3}), as derived from SeaWiFS time series, is also represented for spring season. Zone A corresponds to the West Africa zone; zone B corresponds to the North East Brazilian zone.

ocean color satellite observations to quantify the real effect of dust aerosols on the attenuation of the photosynthetically available radiation (*PAR*) and on the primary production over regions where the occurrence of dust aerosols is high. Another objective is to analyze the temporal variations (seasonal, interannual and ten-year) of the impact of the dust sea surface forcing on the *PAR* and *PP* over a nearly ten-year period, namely 1998–2009. The originality of this study is to use directly satellite observations (i) to validate some theoretical results dealing with the evaluation of the role of dust aerosols in the reduction of the *PAR* [Mallet *et al.*, 2009] and (ii) to investigate any interannual trend in the reduction of the primary production due to dust sea surface forcing over the last decade. Such a study represents to our knowledge (in addition to the first one of Mallet *et al.* [2009]), the first attempt in looking at the potential impact of dust on biological productivity due to dust-radiation processes. Indeed, the majority of studies [Matsui *et al.*, 2008; Mercado *et al.*, 2009] have been focused on the continental ecosystem responses (and not on the marine ecosystem response) to the aerosol continental surface direct forcing. The methodology used in this work is based on the analysis of satellite ocean color images at a large regional scale. The study area is focused on the subtropical region of Atlantic Ocean, between West Africa coast and South America continent. Although mineral dust is emitted from North Africa over the course of the year [Haywood *et al.*, 2008; Marticorena *et al.*, 2011], satellite observations were analyzed for the spring and summer periods only since these seasons correspond to important dust aerosol generation over the Saharan region together with large phytoplankton activity.

[4] The paper is organized as follows. First, the satellite data processing and the methodology used for the analysis

are presented. Second, the influence of the dust aerosols on the *PAR* at the sea surface and on the primary production is studied. Then, the seasonal, interannual and ten-year variations of the reduction of primary production related to dust sea surface forcing are discussed.

2. Data and Method

2.1. Study Area

[5] The area selected for this study is the subtropical Atlantic Ocean (Figure 1). Such an area is relevant especially because coasts of Africa and South America are part of the most intense zones around the world in terms of both dust aerosol loading and biological productivity. In particular, the study area is highly influenced by the emission and transport of Saharan dust aerosols over the Atlantic Ocean [Prospero *et al.*, 2002]. When they are emitted in Africa, a significant part of the Saharan dust aerosols is typically deviated southeastward in the direction of the Inter-Tropical Convergence Zone (*ITCZ*). Another part of dust aerosols moves westward across the Atlantic Ocean in the direction of South America. Therefore, the latitude range of the study area is defined as $[0^{\circ}\text{N}–25^{\circ}\text{N}]$. In addition to this large regional scale area, the analysis of the effect of dust aerosols on the downwelling sea surface radiation was also focused on two specific subregions of interests, hereafter referred to as zone A and zone B (Figure 1), defined as follows. The zone A (offshore Africa) is delimited by $[10^{\circ}\text{N}–25^{\circ}\text{N}]$ and $[15^{\circ}\text{W}–25^{\circ}\text{W}]$ in latitude and longitude respectively; the zone B (offshore Brazil) is delimited by $[7^{\circ}\text{N}–15^{\circ}\text{N}]$ and $[50^{\circ}\text{W}–60^{\circ}\text{W}]$ in latitude and longitude respectively. The analysis of these two regions subsets is scientifically of great interest because they are characterized by a significant biological

productivity (the chlorophyll *a* concentration is greater than 1 mg m^{-3} in spring, see Figure 1), thus allowing to study the potential effect of dust aerosols on the regional primary production. From the aerosol point of view, the zone A is close to the source of dust aerosol emission [Generoso *et al.*, 2008]. Such a zone is likely characterized by a strong vertical transport of dust aerosols in altitude. Zone B is a relevant area to evaluate the impact of dust aerosols on primary production when dust aerosols are located very far from the zone where they are emitted in the atmosphere [Generoso *et al.*, 2008].

2.2. Data

[6] Ocean color level 3 data as provided by SeaWiFS satellite sensor were used over the period 1998–2009. SeaWiFS data were considered primarily for a weekly period (8 days) prior to being averaged for the spring and summer season. For each year, the spring season includes data acquired for the months of March–April–May (MAM); the summer season includes data acquired for the months of June–July–August (JJA). Values of the geophysical satellite products were averaged for each season over the period 1998–2009 to provide the ten-years variation of these parameters. Note that SeaWiFS sensor encountered some problems during 2008 and 2009 which induce a lack of availability of some data for spring and summer seasons. However, more than a half of the data (i.e., more than 6 weeks out of 12 weeks given a season) are systematically available in 2008 and 2009 for both seasons. The data processing of the time series is carried out based on the available data. The geophysical products of interest for this study are: the aerosol optical depth at 550 nm (τ_{a550}), the Angström exponent α , which is the coefficient describing the spectral dependence of aerosol optical depth (α was calculated between 443 and 865 nm), the photosynthetically available radiation (*PAR*) and the chlorophyll *a* concentration ([*Chl*]). Note that the Angström exponent α , which typically varies in the range [0–2], is informative on the size of the aerosols. Values of α lower than 1 mean the occurrence of large aerosols while values of α which are greater than 1 are informative on the presence of small aerosols. Therefore, the values of α as derived from satellite observations were used to identify the occurrence of dust aerosols within satellite images. It is important to highlight that satellite atmospheric correction performed over regions of high dust loading is difficult. The validation of satellite atmospheric correction algorithm using in situ measurements remains a challenging task. As an example, the comparison of satellite retrieval of aerosol optical depth with in situ measurements over areas for which the spatial distribution of aerosols could be highly heterogeneous, as in Saharan dust regions, is difficult. This is mainly because the satellite pixel size ($\sim 1 \text{ km}$) is much greater than the spatial area covered by in situ measurements (\sim few meters). Most of the comparisons between in situ data such as those measured by AERONET network and satellite retrievals of aerosol optical depth were conducted over land as recently shown in Bréon *et al.* [2011]. The comparison between the range of variation of the aerosol optical depths retrieved by SeaWiFS over our study area and that measured by AERONET Marine Aerosol Network stations was performed here based on the literature. Sakerin *et al.* [2007] and Macke *et al.* [2008] measured aerosol optical depth at 500 nm of about 0.3–0.7 near the West African coast. Such range of

values is consistent with that obtained by SeaWiFS in the present study.

[7] Pixels of the study area for which $\alpha < 1$ and $\tau_{a550} > 0.2$ were classed as being “dust aerosol pixels” (Figure 2). The condition $\tau_{a550} > 0.2$ is typically observed during dust storms. Based on these criteria, the probability of occurrence of dust aerosols is significant offshore Africa, as expected, with values reaching 90% in summer. The probability is reduced off Brazil relatively to Africa region but remains greater than 30%. The mean values of τ_{a550} calculated over the entire area when the “dust aerosol pixels” criterion is applied for the time period [1998–2009] are fairly similar for both seasons, namely 0.256 ± 0.020 (Table 1). Values of dust aerosol optical thicknesses are thus important for both seasons and they show little variability (i.e., low standard deviation) over the study area. It should be highlighted that the “dust aerosol pixel” criterion might seem rough to argue that dust aerosol pixels are really present. However, it should be reminded that the study area was selected especially because of the high probability of dust aerosol occurrence in the atmosphere due to the strong influence of Sahara desert. Furthermore, the fact that some aerosols might be wrongly identified as being dust aerosols using this criterion is not of critical matter here since the evaluation of the effect of aerosols (including non-dust aerosols) sea surface forcing on the phytoplankton productivity remains of great interest despite it is not the main focus of this study. The sea surface temperature (*SST*) satellite data, which are necessary for the calculation of the primary production, were provided by AVHRR satellite sensor. The “dust aerosol pixel” criterion was applied systematically to all satellite remote sensing level 3 data. Thus, all the results which are presented in this study are obtained based on the analysis of dust pixels only.

2.3. Method

[8] The oceanic primary production (*PP*) is calculated over the study area using both satellite derived products, namely *PAR*, [*Chl*] and *SST*, and a modeling approach. The model of Antoine and Morel [1996], which was specifically designed for satellite data, was used to calculate the oceanic primary production. The model is based on the following general equation [Morel and Berthon, 1989]:

$$PP = (1/39)PAR(0+)Chl_{tot} \psi^* \quad (1)$$

where *PP* is the net carbon fixation within the productive layer (in gC m^{-2}) over a given time interval, *PAR*(0+) is the photosynthetically available radiant energy at the sea level per unit of surface (W m^{-2}) over the same interval, Chl_{tot} is the column integrated chlorophyll content ($\text{m}^2 (\text{g Chl})^{-1}$), ψ^* is the cross section for photosynthesis per unit of chlorophyll ($\text{m}^2 (\text{g Chl})^{-1}$). The derivation of Chl_{tot} from the surface chlorophyll concentration [*Chl*] is explained in detail in the appendix B of Antoine and Morel [1996]. The parameter ψ^* in equation (1) is inferred from date and latitude using a look-up table. The selection of the value of ψ^* is dependent on both *SST* and the stratification conditions of the water column. AVHRR satellite data are used to get the *SST* values. The stratification conditions are determined using climatology of in situ data of mixed layer depth and chlorophyll *a* satellite data. Briefly, the chlorophyll *a* concentration is related to the euphotic depth which is then

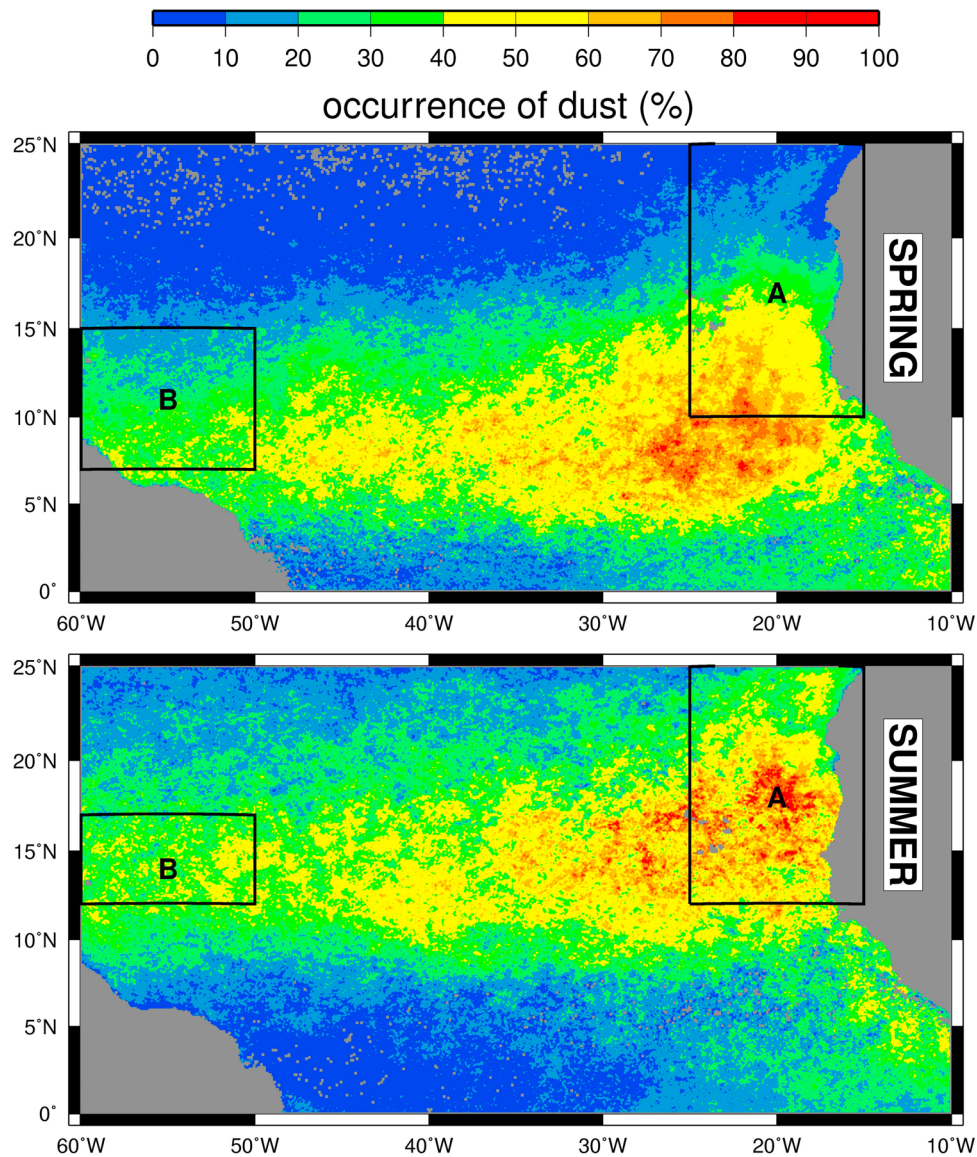


Figure 2. Ten-year average of the occurrence of dust aerosols (in %) for spring and summer season.

compared to the depth of the mixed layer. The results of the comparison indicate whether the water column is stratified or not. The reader is referred to *Antoine and Morel [1996]* for more details.

[9] To analyze the influence of dust aerosols on the oceanic primary production, it is necessary to compare

calculations of *PP* made for real-world conditions of atmospheric turbidity (i.e., $\tau_{a550} \neq 0$) with calculations performed for a clear sky condition. A residual value of τ_{a550} of 0.05, which is representative of clear atmosphere at the latitudes of the study, is used to simulate the clear sky conditions. To calculate the primary production for a clear sky condition

Table 1. Ten-Year Average Values and Standard Deviations of the Remotely Sensed Parameters Used in This Study Over the Entire Study Area, Over Africa Zone (Zone A) and Brazilian Zone (Zone B)^a

	τ_{a550}	[Chl]	PP	PAR/PAR _{cs}	PP/PP _{cs}	PP-PP _{cs}
Full zone spring	0.256 ± 0.021	0.52 ± 1.75	0.73 ± 0.59	0.856 ± 0.043	0.878 ± 0.027	-0.11 ± 0.10
Full zone summer	0.256 ± 0.020	0.46 ± 1.34	0.77 ± 0.58	0.825 ± 0.054	0.851 ± 0.034	-0.15 ± 0.12
Zone A spring	0.258 ± 0.017	2.11 ± 3.46	1.33 ± 0.85	0.885 ± 0.014	0.897 ± 0.008	-0.18 ± 0.12
Zone A summer	0.271 ± 0.019	1.14 ± 2.20	1.15 ± 0.73	0.846 ± 0.033	0.866 ± 0.020	-0.18 ± 0.11
Zone B spring	0.252 ± 0.012	0.70 ± 0.81	0.96 ± 0.44	0.878 ± 0.018	0.892 ± 0.010	-0.15 ± 0.08
Zone B summer	0.259 ± 0.013	0.55 ± 0.55	0.96 ± 0.32	0.847 ± 0.020	0.864 ± 0.012	-0.17 ± 0.07

^aThe values are given for spring and summer season. “Full zone” means the entire study area. See the Notation section for the definition of the acronyms (including the units).

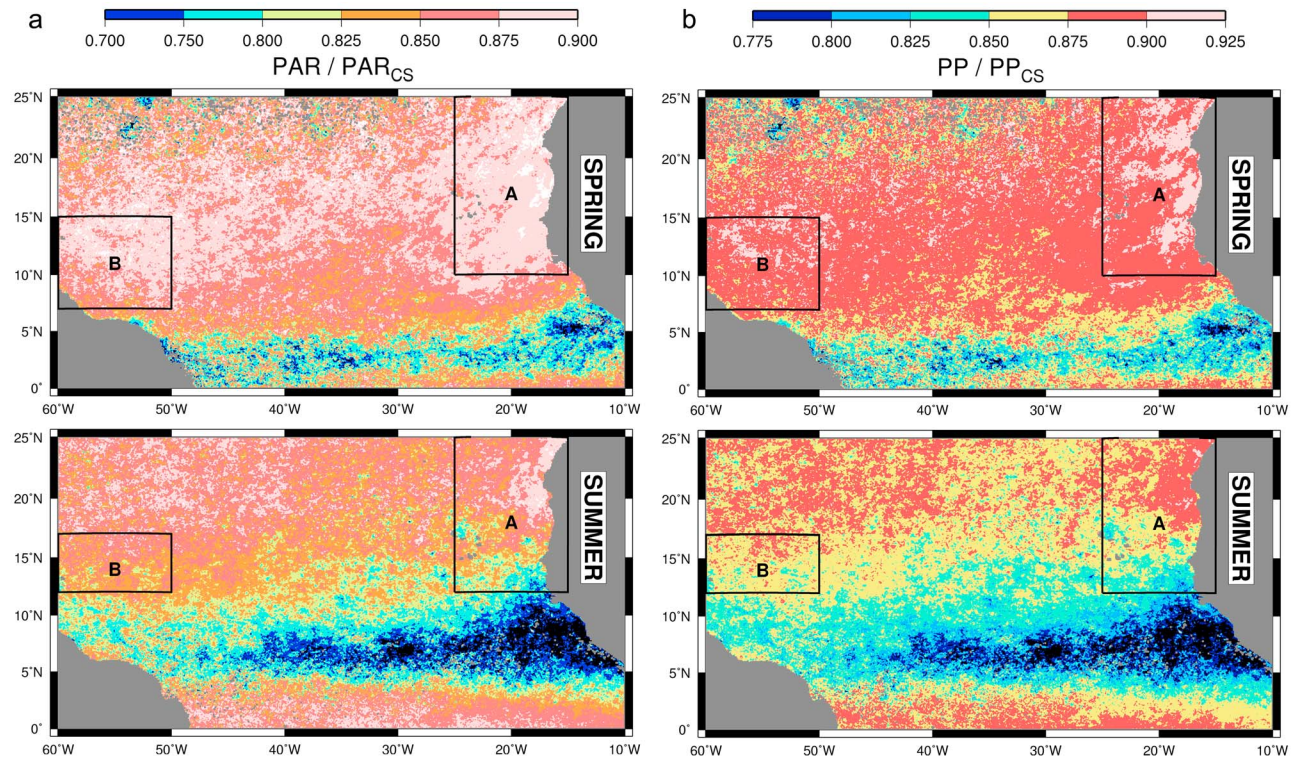


Figure 3. (a) Ten-year average of the ratio PAR/PP_{CS} between the PAR as derived from satellite observations and the PAR calculated for a clear sky condition ($\tau_{a550} = 0.05$). (b) Map of the ten-year average of the ratio PP/PP_{CS} between PP as derived from satellite observations and PP calculated for a clear sky condition ($\tau_{a550} = 0.05$). The results are shown for spring and summer season.

(hereafter noted as PP_{CS}), the values of the PAR for such specific conditions (hereafter noted as PAR_{CS}) are needed. These values were simulated using the GAME radiative transfer model [Dubuisson *et al.*, 2004], which has been successfully evaluated for simulating direct radiative forcing of different aerosol types, including mineral dust particles [Roger *et al.*, 2006; Mallet *et al.*, 2008; Saha *et al.*, 2008]. The GAME model solves the radiative transfer equation using the discrete ordinates [Stamnes *et al.*, 1988], which allows accurate treatment of scattering and absorption by aerosols, clouds, and molecules. The aerosol optical depth τ_{a550} was set up to 0.05 to compute PAR_{CS} .

3. Influence of Dust Aerosols on the Photosynthetically Available Radiation at Sea Level and on the Primary Production Over the Decade

3.1. Influence of Dust Aerosols on the PAR

[10] Figure 3a shows the ten-year variation of the ratio PAR/PP_{CS} in spring and summer season. Note that Figure 3 and all forthcoming figures were obtained based on the pixels that met the “dust aerosols” criterion only. The ratio PAR/PP_{CS} is informative of the reduction of the solar incoming radiation reaching the sea surface induced by dust aerosols. The averaged values of PAR/PP_{CS} calculated over all the pixels contained within the entire study area defined in Figure 1 are 0.856 ± 0.043 and 0.825 ± 0.054 in spring and summer respectively (Table 1). Thus, about 14% and

17% of the solar radiation at top of atmosphere is attenuated by aerosols before entering into the ocean in spring and summer respectively. Note that these values of PAR/PP_{CS} are consistent with the calculations of Mallet *et al.* [2009] who predicted a reduction of PAR of 15% for similar values of aerosol optical depths and dust single scattering albedo of 0.85 (at 550 nm). A reduction of PAR in the range 14–17% is meaningful since it could have some potential impact on the phytoplankton photosynthesis, as it will be discussed later. In Africa zone (zone A), the average decrease of PAR/PP_{CS} is higher in summer than in spring. This is because of the dust aerosol abundance which is significantly greater in summer (mean value of $\tau_{a550} = 0.271 \pm 0.019$) than that observed in spring (mean value of $\tau_{a550} = 0.258 \pm 0.017$). Average values of PAR/PP_{CS} in zone B are fairly similar to those observed in zone A for each season (Table 1). However, a much lower variability of PAR/PP_{CS} is observed in summer within zone B relatively to that observed within zone A (40% of difference of variability between both zones). It could be explained by the fact that the Angström exponent values are homogeneously distributed within the range [0.5–0.6] in zone B, while a greater heterogeneity is observed in zone A for which α varies within the range [0.6–0.9] (not shown). Note also that the comparison of the values of α between zone A and zone B points out that the size of dust aerosols is significantly different from Africa to South America. Largest particles (i.e., small values of α) are observed offshore Brazil. Generoso *et al.* [2008] showed, based on CALIPSO satellite lidar measurements, that dust aerosol plumes could

extend up to an altitude of 8 km in summer near their source region (Africa, zone A) and gradually descend below an altitude of 2 km throughout their travel over the Atlantic Ocean (South America, zone B). The descent of the plume could be attributed to both particle sedimentation and the general descent of air between Africa and South America [Colarco *et al.*, 2003]. As a result, it makes sense to observe a lower variability of PAR/PP_{cs} near South America, especially because of particle sedimentation process which could lead to make dust aerosols more homogeneously distributed in size than those observed near their source region (Africa).

3.2. Influence of Dust Aerosols on the Oceanic Primary Production

[11] The implications of the decrease of PAR due to dust aerosol occurrence for the oceanic primary production are important since PAR is one of the variables which are directly related to PP as shown in equation (1). Figure 3b shows the ten-year variation of the ratio PP/PP_{cs} in spring and in summer. Based on equation (1), the ratio PP/PP_{cs} is not dependent on $[Chl]$ since PP and PP_{cs} are calculated for two different PAR conditions (clear and natural turbid sky conditions) using the same value of $[Chl]$ for both sky conditions. The ratio PP/PP_{cs} directly depends on the ratio PAR/PP_{cs} . Thus, it is not surprising to observe that the main patterns of the spatial variations of PP/PP_{cs} are consistent with those of PAR/PP_{cs} (Figure 3a). However, PP/PP_{cs} is also dependent on the ratio ψ^*/ψ_{cs}^* , where ψ_{cs}^* is the cross section for photosynthesis corresponding to the clear sky radiation PAR_{cs} . As a result, values of PP/PP_{cs} differ from those of PAR/PP_{cs} by the weighting factor ψ^*/ψ_{cs}^* , which is informative on the influence of the photoinhibition process on the primary production as it will be discussed in section 3.3. Figure 3b and Table 1 show that the primary production is reduced by 12% and 15% when aerosols are present over the entire study area in spring and summer respectively. In spring, the values of PP/PP_{cs} mostly vary within 0.87 and 0.92 for the majority of the pixels of the entire study area while a greater heterogeneity is observed within the image in summer (values ranging from 0.77 to 0.90). The impact of dust aerosols on primary production is higher in the latter case because dust aerosols are more abundant at this season, especially for latitudes smaller than 15°N ($PP/PP_{cs} < 0.82$) where the reduction of PP could reach a maximum of 23% (south of zone A at latitude smaller than 7°N). The ITCZ (i.e., latitudes typically smaller than 7°N) is well known to play a role in the atmospheric circulation and in the dust aerosol transport toward the southern hemisphere [Generoso *et al.*, 2008]. The atmospheric dynamics within the ITCZ is characterized by high levels of Saharan dust aerosol concentration which in turn may explain the more important impact on the oceanic productivity observed here near the Equator. Mallet *et al.* [2009] proposed some parameterizations of the variation of PP/PP_{cs} as a function of the dust aerosol optical depth. Their predictions showed that PP/PP_{cs} values of 0.85 are obtained in highly turbid atmospheres, typically when the dust aerosol optical depth is greater than 0.6. Here, a similar value of PP/PP_{cs} ($PP/PP_{cs} = 0.85$) is observed for a much lower threshold value of the optical depth ($\tau_{a550} > 0.2$). The satellite observations over the last decade agree with the modeling

study of Mallet *et al.* [2009] inasmuch as the dust aerosol occurrence could induce a significant decrease of the oceanic productivity. However, the observations point out that the influence of the dust aerosol turbidity on PP is much higher (by a factor of 3) than the model predictions which yet covered various scenarios (i.e., various chlorophyll concentrations, various sea surface temperature, various dust aerosol single scattering albedo). This means that local strong episodic dust aerosol events which typically show optical depth larger than 0.6 and even greater than 0.8 [Generoso *et al.*, 2008] should induce a reduction of PP which could be much higher than 15%. Based on the shape of the parameterisation proposed by Mallet *et al.* [2009], one can expect values of PP/PP_{cs} of 0.65 for a value of τ_{a550} of 0.6, thus inducing a reduction of the primary production by 35% during episodic strong dust aerosol events.

[12] Figure 4 shows the ten-year variation of the difference between PP and PP_{cs} , noted as ΔPP (i.e., $\Delta PP = PP - PP_{cs}$, units $\text{gC m}^{-2} \text{day}^{-1}$). Negative values of ΔPP are informative of the decrease of organic carbon produced by phytoplankton due to the attenuation of the sea surface radiation by dust aerosols. Based on equation (1), variations of ΔPP are directly related to variations of both chlorophyll content and PAR . The average value of ΔPP over the entire study area and over zone A is about $-0.11 \pm 0.10 \text{ gC m}^{-2} \text{day}^{-1}$ and $-0.18 \pm 0.12 \text{ gC m}^{-2} \text{day}^{-1}$ respectively, for both seasons (see Table 1). The decrease of organic carbon due to the occurrence of dust aerosols in the atmosphere is maximum in spring near the West Africa coast (Figure 4a, zone A) where ΔPP could reach $-1 \text{ gC m}^{-2} \text{day}^{-1}$. Since the average value of PP in zone A in spring is $1.33 \pm 0.85 \text{ gC m}^{-2} \text{day}^{-1}$ (see Table 1), a value of ΔPP of $-1 \text{ gC m}^{-2} \text{day}^{-1}$ leads to a strong local relative decrease of PP , $\Delta PP/PP$, ($\sim 75\%$). In summer, the average value of PP in zone A is $1.15 \pm 0.73 \text{ gC m}^{-2} \text{day}^{-1}$. The highest values of primary production within this zone are observed northward relatively to spring time. Typically, PP values are maxima at latitudes greater than 20°N . This is because Ekman transport is the largest in this range of latitude in summer [Carr and Kearns, 2003]. As a result, negative values of ΔPP are maxima above 20°N and thus, the impact of the dust aerosols in terms of a decrease of organic carbon produced by phytoplankton is higher (Figure 4b). Because a large body of primary production measurements are available from the Atlantic Meridional Transect cruises [Tilstone *et al.*, 2009], it is worthwhile to compare the primary production as derived from SeaWiFS satellite data here with that obtained from in situ measurements to estimate the related loss of PP (ΔPP) due to the occurrence of dust aerosols. The comparison was performed for satellite pixels located along the North–south transect centered at longitude 35°W within the latitude range [10°N – 25°N] and for the month of May 2003, 2004 and 2005, which correspond to the same location and time period as the sampling stations analyzed in Tilstone *et al.* [2009]. Tilstone *et al.* [2009] reported average values of PP , noted as $PP_{measured}$, of $0.304 \pm 0.005 \text{ gC m}^{-2} \text{day}^{-1}$ with minimal and maximal values of PP of $0.14 \text{ gC m}^{-2} \text{day}^{-1}$ and $0.59 \text{ gC m}^{-2} \text{day}^{-1}$ respectively, along the transect from May 2003 to May 2005. The corresponding average value of PP obtained from satellite data is $0.418 \pm 0.102 \text{ gC m}^{-2} \text{day}^{-1}$, which remains within the range of PP measured in situ. Over the same area and time period, our study shows $\Delta PP = -0.07 \pm 0.03 \text{ gC m}^{-2} \text{day}^{-1}$,

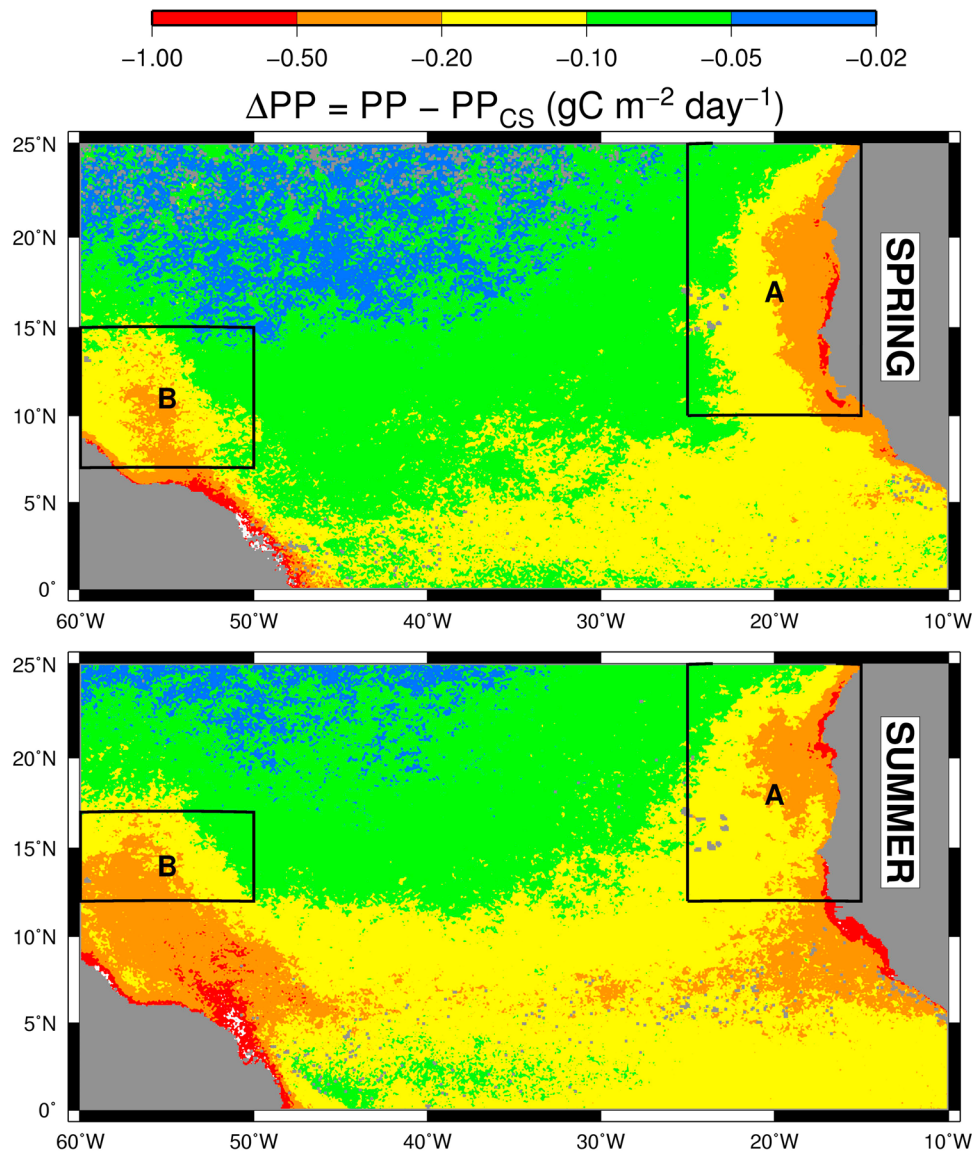


Figure 4. Ten-year average of the difference between PP and PP_{CS} ($\Delta PP = PP - PP_{CS}$, in $\text{gC m}^{-2} \text{day}^{-1}$) for spring and summer season.

which means that the occurrence of dust aerosols could induce a relative decrease $\Delta PP/PP_{measured}$ by 23% when the average PP measured in situ, namely $0.304 \pm 0.005 \text{ gC m}^{-2} \text{day}^{-1}$, is used as the reference value of PP .

3.3. Impact of the Dust Aerosols on the Limitation of Phytoplankton Photoinhibition Process

[13] The region that is investigated in this study, which is located in the tropics, encounters some of the highest levels of insolation in the global ocean. Therefore, phytoplankton may encounter damaging level of insolation causing photolysis or inhibition (so-called photoinhibition process) which could lead to reduce the efficiency of phytoplankton for photosynthesis and thus, decreasing the primary production. The presence of a dust aerosol layer in the atmosphere over the study area contributes to attenuate the PAR radiation as previously discussed in the paper. Since the amount of light

received by phytoplankton is reduced when the PAR is attenuated by dust aerosols, the amplitude of the photoinhibition process is not as strong as for clear sky conditions. Subsequently, the phytoplankton efficiency for photosynthesis is increased and the primary production could be enhanced in the case of a turbid atmosphere relatively to the clear sky conditions. The primary production model which is used in this study (equation (1)) includes a term, namely the cross section for photosynthesis ψ^* , which is informative on the influence of photoinhibition on the primary production. As mentioned in section 3.2, the decrease of primary production due to dust aerosols (PP/PP_{CS}), is not only related to the decrease of PAR (PAR/PAR_{CS}) but also to the ratio of the cross section for photosynthesis estimated between the turbid and clear sky conditions, ψ^*/ψ^*_{CS} . The ratio ψ^*/ψ^*_{CS} is systematically greater than 1 because the phytoplankton efficiency for photosynthesis increases when the incident

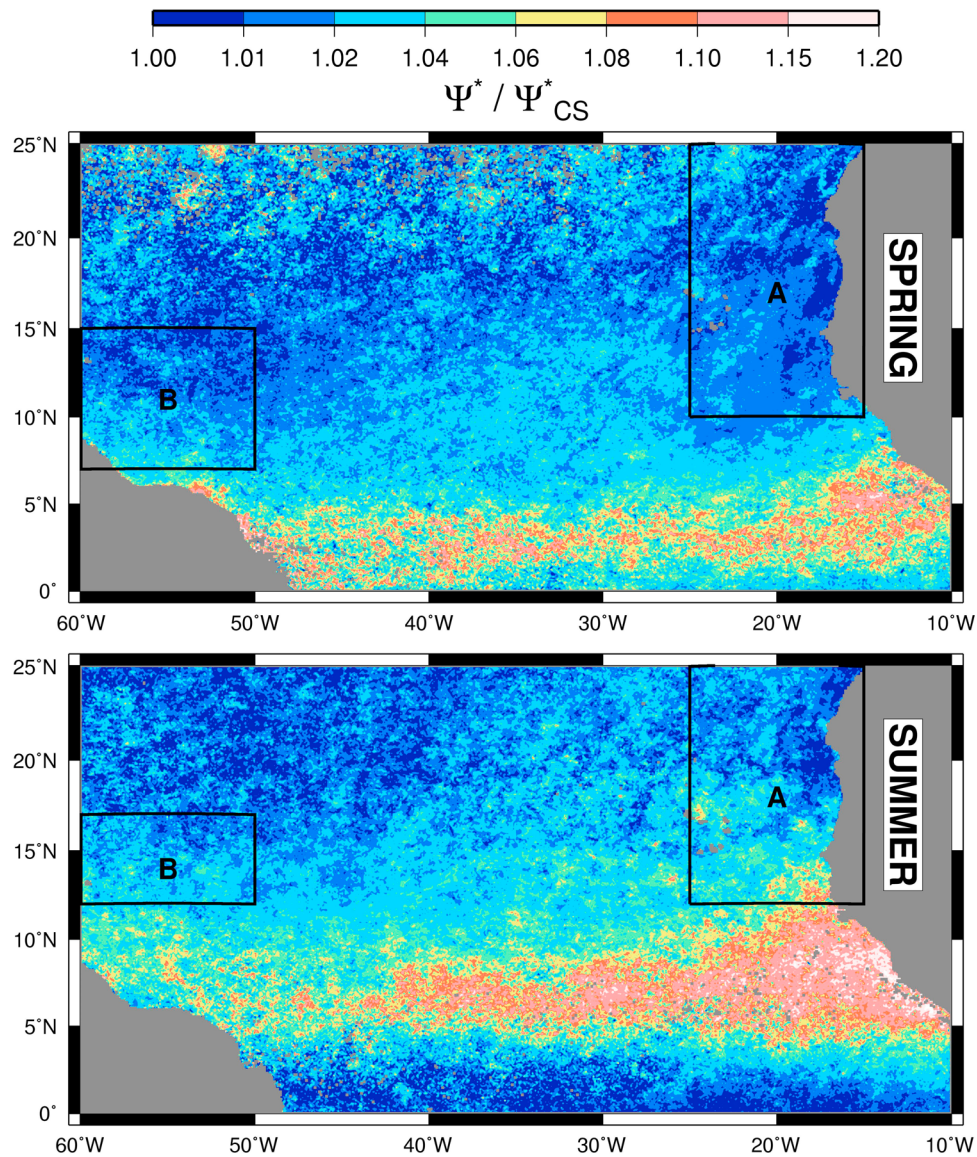


Figure 5. Ten-year average of the ratio ψ^*/ψ_{CS}^* where ψ^* is the cross section for photosynthesis for a given atmospheric condition and ψ_{CS}^* is the cross section for photosynthesis for a clear atmosphere (i.e., $\tau_{a550} = 0.05$).

radiation decreases (i.e., $PAR < PAR_{CS}$ leads to $\psi^* > \psi_{CS}$). Since ψ^*/ψ_{CS}^* is greater than 1, the decrease of primary production (PP/PP_{CS}) induced by a decrease of PAR is less strong than it would be in the case of absence of photo-inhibition process. Figure 5 shows the ten-year variations of the ratio ψ^*/ψ_{CS}^* in spring and summer over the entire study area. The spatial average values of ψ^*/ψ_{CS}^* calculated over all the area are 1.028 and 1.036 in spring and summer respectively. These values mean that the photoinhibition process induce an enhancement of the primary production by 2.8% and 3.6% in spring and summer which thus slightly counterbalances the decrease of primary production induced by the attenuation of PAR . As expected, the phytoplankton efficiency for photosynthesis is higher in summer because of the lower inhibition caused by a thicker layer of dust aerosols at this season. The maximum enhancement of primary production is observed around 5°N near Africa where it could

reach 17% ($\psi^*/\psi_{CS}^* = 1.17$) in summer and 12% in spring. In these locations, the influence of photoinhibition process on the increase of primary production to counterbalance the decrease of primary production linked to the attenuation of PAR is important.

4. Interannual Variations of Oceanic Primary Production in Dust Aerosols Dominated Areas

4.1. Temporal Variations of the Area Occupied by Dust Aerosols

[14] Prior to analyzing the temporal variations of oceanic primary production over the course of the ten-year time series of satellite data, it is of interest to assess the consistency of the dust aerosol events in their surface area at various locations (i.e., entire study area, zone A and zone B) from year to year. Figure 6 shows the interannual variations

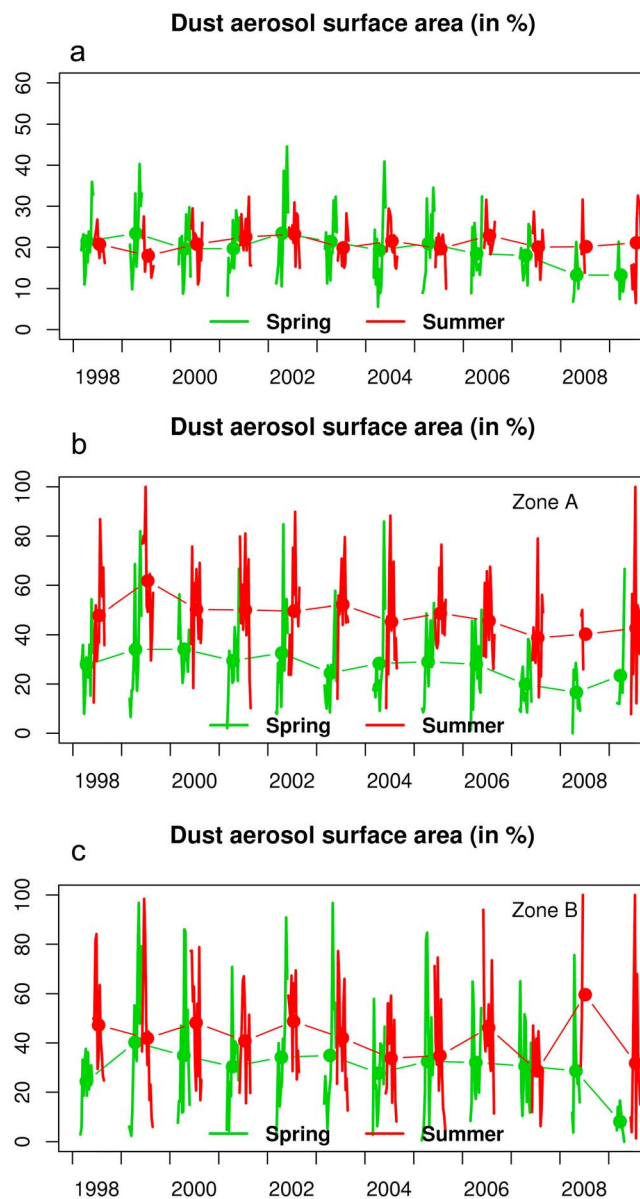


Figure 6. Interannual variations of the dust aerosol surface area, which is defined as the ratio (in %) between the number of pixels for which the dust aerosol criterion is verified and the total number of unflagged pixels of a satellite image (a) over the entire study area, (b) over zone A and (c) over zone B in spring and summer.

of the dust aerosol surface area, which is defined as the ratio (in %) between the number of pixels for which the dust aerosol criterion is verified and the total number of unflagged pixels of a satellite image, over the entire study area (Figure 6a), over zone A (Figure 6b) and over zone B (Figure 6c) in spring and summer. In Figure 6, the average values of the dust surface area calculated over a given a season are represented by dots; the weekly variation (8-day) of the dust surface area is shown by solid lines. The results indicate that the seasonal average extent of dust surface over the entire study area (Figure 6a, dots) oscillates around 20% for both seasons, which is a high value given the size of the

entire zone. The interannual variations of such average remain weak, which mean that the dust events are consistent for year to year. The 8-day variations of the dust surface (Figure 6a, solid lines) vary in a much wider range than the seasonal average. The highest variability in the extension of dust area is observed in spring 2001 where the dust aerosols occupy from 5% to 40% of the entire study area from the beginning to the end of the season. The surface occupied by dust aerosols is much higher when dealing with zone A and zone B (Figures 6b and 6c). The larger occurrence of dust pixels in these places is due to the fact that these zones are either close to the dust production area (this is the case of zone A) or on the way of the dust transport across the Atlantic ocean (this is the case of zone B).

[15] Over zone A (Figure 6b), the seasonal average values of the percentage of dust area are greater in summer (between 40% and 60%) than in spring (between 20% and 40%). Such a seasonal difference was expected since the dust aerosols are more efficiently produced in summer. The interannual variations of the seasonal average values of dust area remain fairly stable over the course of the decade, which highlight the consistency of dust event from year to year. The 8-day variations of the dust area show a strong variability given a season. The extension of dust area between the beginning and the end of a given season typically vary up within a factor of 2. It could vary up to a factor of 4 as it could be observed in spring and summer 2004 where the percentage varies from $\sim 20\%$ to $\sim 80\%$ over the course of the season. It is also interesting to note that the dust area could cover almost 100% of the entire zone A in summer depending on the year (as in 1999 and 2009). Over zone B, the seasonal average percentage of the surface occupied by dust aerosols varies within the same range as what was observed for zone A for both season. However, the seasonal differences are less pronounced than for zone A. Again, the 8-day variations show a strong variability given a season with percentages of dust area reaching almost 100% for a high number of years over the decade (1999, 2003, 2008, and 2009). Note that these results about the quantification of the surface occupied by dust aerosols over the selected study areas (entire zone, zone A and zone B) confirm that the consideration of 8-day satellite images rather than daily images, which do not allow to fully cover the selected study areas due to the satellite revisit period, could be sufficient and relevant to infer the direct impact of dust event (which are short in time (several days) but intense) on the oceanic primary production, as it will be discussed in the following sections.

4.2. Temporal Variations of Oceanic Primary Production Over the Entire Study Area

[16] Figure 7 shows the interannual variations of the seasonal average values of the relative decrease of primary production, namely $\Delta PP/PP$, over the entire area. The trend of variations of these seasonal average values (dashed lines) is also reported in Figure 7 together with the weekly variations of $\Delta PP/PP$ (i.e., 8-day average) observed during a given season (solid lines). The 8-day time scale is convenient to emphasize the effect of dust aerosols which are often emitted after intense short time episodic events. Given a season, an important 8-day variability in $\Delta PP/PP$ is observed every year (Figure 7). In spring, the highest range

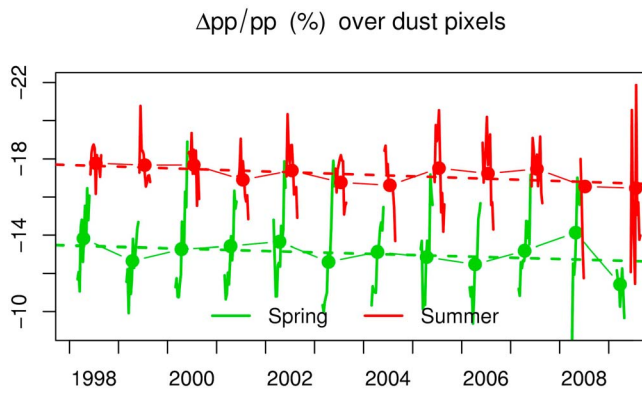


Figure 7. Interannual variations of the relative decrease of the primary production ($\Delta PP/PP$) during the period 1998–2009 for spring and summer period. The variations of the seasonal average (dots), of the weekly average (solid lines) are also reported in the figure. The tendency of the evolution of $\Delta PP/PP$ is shown (dashed lines).

of variation of $\Delta PP/PP$ is observed in 2005 and 2008 where $\Delta PP/PP$ varies from -10% to -17% . In summer, the variability in $\Delta PP/PP$ is maximum in 2009 where $\Delta PP/PP$ varies within the range $[-11\%, -22\%]$.

[17] The interannual variations of the seasonal average values of $\Delta PP/PP$ for the entire study area (Figure 7, dots) are now discussed. Figure 7 shows that the variations of these seasonal average values oscillate around the ten-year average value for each season. Typically, $\Delta PP/PP$ varies around -14% and -17% in spring and summer respectively over the course of the ten-year time series. As expected from the analysis of the ten-year average of PP/PP_{cs} in section 3.2, the relative decrease of the primary production is higher in summer relative to spring season mainly because of the higher turbidity of dust aerosols at this season. The slope and standard deviation of the tendency over the decade (dashed lines in Figure 7) are reported in Table 2. Whatever the season, the variation of $\Delta PP/PP$ does not show any pronounced general tendency over the decade when the whole study area is considered. A relative decrease of PP of 0.07% per year and 0.08% per year is obtained for spring and summer period respectively. Note that the slope obtained in summer only is statistically significant. Such weak values of the slopes point out that the relative decrease of PP remains fairly stable with time over the ten-year time series. At least, the ten-year time series which is used here is not sufficiently long to identify any global climate change

effects on the dust sea surface forcing and on the subsequent oceanic productivity over the entire area.

[18] We investigated the possible link between the interannual variations of the occurrence of dust aerosols, which could be a proxy of the strength of the dust event, with the interannual variations of some regional climate indices, such as the North Atlantic Oscillation (*NAO*) index and the North Tropical Atlantic (*NTA*) index as provided by NOAA agency (USA), which are informative on specific features of the atmospheric circulation and sea surface warming/cooling of the Atlantic Ocean. The *NAO* index describes the phenomenon of fluctuations in the difference of atmospheric pressure at sea level between the Icelandic low pressure and the Azores high pressure systems. Through east–west oscillation motions of the Icelandic low pressure and the Azores high pressure systems, this phenomenon controls the strength and direction of westerly winds and storm tracks across the North Atlantic. The *NTA* index describes the time series of sea surface temperature (*SST*) anomalies which were calculated relative to the 1951–2000 climatology over the North tropical Atlantic Ocean. Note that the *NTA* index is established for the same area as the one used in this study (Figure 1) while the *NAO* mostly concerns Western Europe but it can have an influence on North Africa weather. Figure 8 shows the comparison between the occurrence of dust aerosols and the *NAO* and *NTA* indices in spring and summer over the course of the decade. In spring, there is no general relationship between the parameters. It is observed that the occurrence of dust aerosols is closely related to *NAO* index between the year 2000 and 2002. In summer, an interesting correlation (coefficient of determination is $r^2 = 0.93$) is obtained between the occurrence of dust aerosols and *NAO* from 2001 to 2009 (excluding the year 2005). The relationship shows that the occurrence of dust aerosols decreases as *NAO* index varies from positive to negative values. When the *NAO* index is low (e.g., $NAO < 0$), westerly winds blowing across the Atlantic Ocean are suppressed and storms track southerly toward the Mediterranean Sea. This brings increased storm activity and rainfall to southern Europe and North Africa. Thus, for low values of *NAO* index, one could think that lifetime of Saharan African dust aerosols in the atmosphere near Africa are reduced since they may fall into the continent/ocean. Less dust aerosols could be transported across the Atlantic Ocean. Therefore, the decrease of the occurrence of dust aerosols as observed here is consistent with a decrease of *NAO* index toward negative values.

[19] The relationships between the interannual variations of $\Delta PP/PP$ as observed in Figure 7 (dots) and *NAO* and

Table 2. Slope S_{tendency} (in % Per Year) and Standard Deviation σ_{tendency} of the Tendency of the Relative Decrease of the Primary Production $\Delta PP/PP$ Over the Decade As Observed in Figure 7 (Entire Study Area) and Figure 10 (Zone A and Zone B)^a

Area	Season	Slope S_{tendency} (%/year)	σ_{tendency} (%/year)	Statistic Significance of the Slope
Entire area	Spring	0.070	0.059	The slope is NOT statistically significant
	Summer	0.084	0.033	The slope is statistically significant
Zone A	Spring	0.111	0.055	The slope is NOT statistically significant
	Summer	0.219	0.060	The slope is statistically significant
Zone B	Spring	0.078	0.086	The slope is NOT statistically significant
	Summer	-0.017	0.088	The slope is NOT statistically significant

^aThe slope is statistically significant if it never reaches the value zero within the confidence interval at 95% defined as $[S_{\text{tendency}} - 2\sigma_{\text{tendency}}, S_{\text{tendency}} + 2\sigma_{\text{tendency}}]$ (i.e., because a value of zero means that there is no tendency). A comment on the significance of the slope is reported in the table as well.

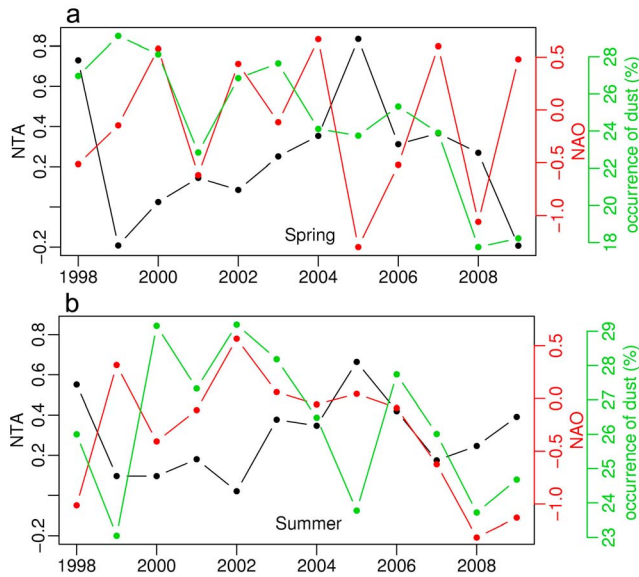


Figure 8. Comparison between the occurrence of dust aerosols and the *NAO* and *NTA* indices in (a) spring and (b) summer over the course of the decade. A strong correlation is found between the occurrence of dust aerosols and the *NAO* index in summer during the period [2001–2009] excluding the year 2005 (coefficient of determination $r^2 = 0.93$, see text).

NTA indices have also been investigated. Figure 9 shows the comparison between the interannual variations of $\Delta PP/PP$ with those of *NTA* and *NAO* indices for spring (Figure 9a) and summer (Figure 9b) period. In spring, it is difficult to establish any general link between $\Delta PP/PP$ and the two other parameters. One could just notice that the variation of $\Delta PP/PP$ is superimposed in phase opposition with *NAO* from 2007 until 2009. The analysis of the summer period shows more interesting features. The shape of variation of *NAO* index follows that of $\Delta PP/PP$ from 2001 to 2009 (Figure 9b). The general shape that is observed between *NAO* index and $\Delta PP/PP$ from 2001 and 2009 shows that an increase of *NAO* index from negative to positive values (from -1.0 to $+0.5$) is related to a higher decrease of *PP* due to dust aerosols (from -16% to -17.5%). Since low values of *NAO* index could be related to a shorter lifetime of dust aerosols in the atmosphere as previously mentioned, the role of the dust aerosols on the attenuation of *PAR* and on the reduction of oceanic productivity over the entire study area could be slightly less important (i.e., $\Delta PP/PP \sim -16\%$) than the case for which *NAO* index is higher (e.g., $NAO > 0$ and $\Delta PP/PP \sim -17.5\%$). However, it should be highlighted that the difference of $\Delta PP/PP$ between lower and higher values of *NAO* index is weak (1.5%) probably because a small fraction only of our study area is affected by the North Atlantic Oscillation and its subsequent changes in atmospheric dynamics over Western Europe.

[20] The relationship between $\Delta PP/PP$ and *NTA* index in summer shows that the shape of variation of $\Delta PP/PP$ is fairly consistent with that of *NTA* index from 2003 to 2009 (coefficient of determination $r^2 = 0.63$). In particular, the pronounced peak of $\Delta PP/PP$ observed in 2005 seems to be

closely related to the peak of *NTA* index for the same period. An increase of *NTA* index, which means an increase of *SST*, is related to an increase of $\Delta PP/PP$, which is informative on the effect of dust aerosols on *PP* as discussed earlier. This would suggest that the dust aerosol radiative forcing onto the sea surface in summer could be positive (i.e., occurrence of dust aerosols may partially explain the increase of *SST* through a “cloud cover” effect) with the consequence of reducing significantly the amount of oceanic primary production (e.g., by $\sim 18\%$ in 2005). Such a dust impact on *SST* contrasts with previous results showing a decrease of *SST* due to dust surface shortwave forcing [Foltz and McPhaden, 2008b; Martínez Avellaneda et al., 2010]. However, the interaction between dust aerosols and *SST* is not entirely understood [Foltz and McPhaden, 2008a]. This is mainly due to the interaction of dust aerosols with both shortwave (cooling at the surface) and longwave (heating at the surface) radiations as well as the important contribution of wind-induced latent heat loss and horizontal oceanic heat advection to changes in *SST* [Foltz and McPhaden, 2008a]. Note that the increase of *SST* in 2005 is observed in spring as well but it is not linked to an increase of $\Delta PP/PP$ as it is observed for summer period. Dust aerosol sea surface forcing is perhaps not as strong at this period of the year to explain the increase of *SST* which may be, in spring, mostly driven by other factors (e.g., oceanic circulation).

4.3. Temporal Variations of Oceanic Primary Production Over Zone A and Zone B

[21] Figure 10 shows the interannual variations of $\Delta PP/PP$ over zone A (Figure 10a) and over zone B (Figure 10b) for spring and summer season (dots). As for Figure 7, the general trend (dashed lines) and the weekly variations (8-day average, solid lines) of $\Delta PP/PP$ are reported in Figure 10. Both zones (A and B) show strong 8-day variability in $\Delta PP/PP$

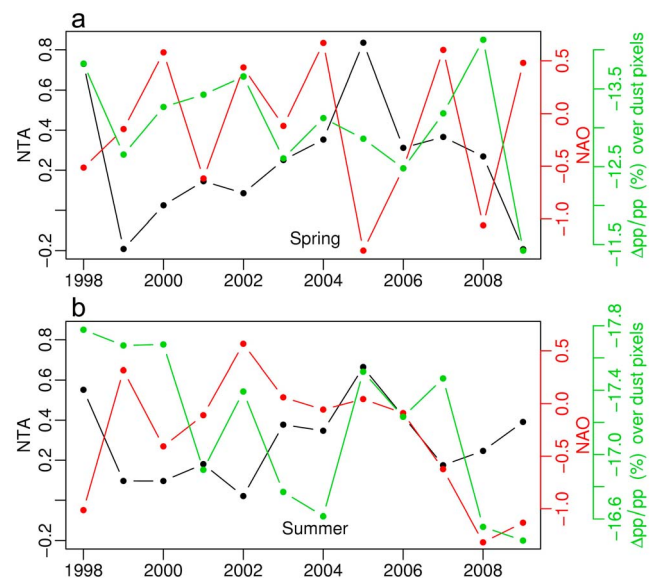


Figure 9. Comparisons between the relative decrease of the primary production $\Delta PP/PP$ with the North Atlantic Oscillation (*NAO*) and North Tropical Atlantic (*NTA*) climate indices as a function of the year: in (a) spring and (b) summer.

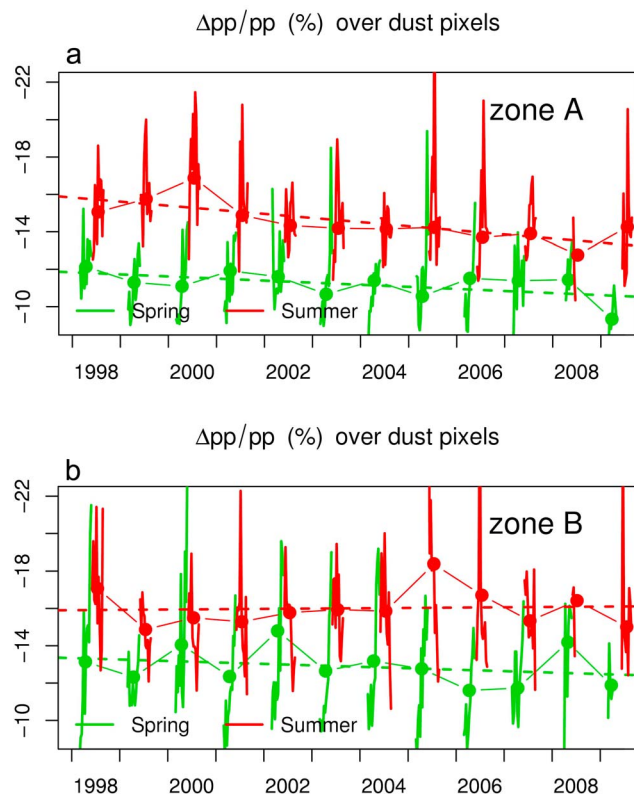


Figure 10. Same as Figure 7 but for (a) zone A and (b) zone B.

PP (solid lines) given a season. Note that this variability is repeated periodically every year. The impact of dust aerosols on PP (when 8-day average period are considered) could induce a decrease in primary production up to 20% in spring (e.g., zone A, in 2005) and 22% in summer (e.g., zone A and B, in 2005, 2006 and 2009). Therefore, the short lifetime of dust aerosol atmospheric events which occur near their source of emission like West Africa coast or after their transportation across the ocean could significantly alter the organic carbon budget of the underlying oceanic ecosystems. Table 2 reports the slope and standard deviation of the tendency (dashed lines in Figure 10). In zone A, the three-month average seasonal variations of $\Delta PP/PP$ over the course of the ten-year period shows a statistically significant tendency of decrease of 0.22% per year in summer, while the tendency of decrease of PP in spring, which is twice smaller than for summer time (0.11% per year), is not statistically significant. Fairly flat interannual variations of PP , which are not statistically significant, are observed over zone B for both seasons. Note that the shape of $\Delta PP/PP$ is chaotic in spring over such area. These observations illustrate that it is difficult to draw any conclusions about a potential effect of climate changes over these regions. However, despite the fact that the value of the slope obtained in summer over zone A seems small (0.22% per year), the high occurrence of dust aerosol events in such a zone might have some major consequences on the marine productivity at a long-term climatologic scale (e.g., several decades or centuries) given the size of the area. Based on this study, a decrease of PP of 22% could be expected over the next 100 years. Since the

surface area of the Saharan desert might increase as a consequence of climate change inducing a higher production of dust aerosols, the regional oceanic carbon cycle over zone A might be strongly affected through a decrease of the carbon produced by marine organisms due to the sea-surface direct radiative forcing of aerosols. Note that it is not relevant here to attempt to link the interannual variations of $\Delta PP/PP$ over these two specific regions with some climate indices (as it was carried out in section 4.2) because these indices are defined for geographical areas having a larger regional scale.

5. Conclusion

[22] The impact of the dust sea surface forcing on the oceanic productivity was studied based on a ten-year time series of satellite observations (ocean color and sea surface temperature) and a modeling approach. Most of the previous studies analyzed the effect of the deposit of dust aerosols into the water column and the associated nutrients inputs, such as iron, on the biological productivity. Here, it is the first time, to our knowledge, that the effect of an atmospheric forcing, such as the dust aerosol forcing, on the oceanic organic carbon budget is quantified using satellite observations. The study area covers the subtropical Atlantic Ocean [0°N–25°N] from Africa to South America. The analysis of the satellite data was also focused on two specific zones of interest, offshore West Africa and North East of Brazil, and for two seasons, namely spring and summer period. First, the impact of the occurrence of dust aerosols in the atmosphere on the reduction of the shortwave radiations entering into the ocean (PAR) was studied. The results showed that the ten-year average of the attenuation of the PAR due to the occurrence of dust aerosols is high, typically between 14% and 17%, over the study area. A higher attenuation was observed offshore Africa coast in summer as a result of the greater dust aerosol loading near the sources of emission. The estimates of the attenuation of PAR were consistent with the modeling study of Mallet *et al.* [2009] who predicted a similar decrease of PAR ($\sim 15\%$) when dust aerosol optical depth value is similar as that observed here by satellite ($\tau_{a550} \sim 0.25$). The implications of the decrease of the incoming radiation at the sea surface due to dust aerosols for the oceanic primary production are important. It was observed that PP decreases by 12% and 15% in average over the decade in spring and summer respectively. A significant spatial variability in this decrease is noticed especially over the Africa zone (zone A) where PP could be reduced by 23%. The comparisons with the predictions performed by a previous study suggested that the decrease of PP due to dust aerosols might be much greater ($\sim 35\%$) in the case of intense episodic dust aerosol events for which the aerosol optical depth could be higher than 0.6. Despite the fact that the first order effect of the occurrence of dust aerosols is to reduce the PAR radiation and thus the primary production, a second order effect of their presence is related to the decrease of phytoplankton photoinhibition amplitude and thus, to a potential increase of primary production. The results showed that the diminution of the inhibition resulting from the smaller amount of radiation reaching the surface caused by the occurrence dust aerosols induces an increase of primary production of 2.8% and 3.6% in average over the entire study area in spring and summer respectively. The

increase of primary production could reach 17% at low latitudes in summer. Therefore, the phytoplankton efficiency for photosynthesis could significantly counterbalance the effect of the attenuation of *PAR* at low latitudes by enhancing the primary production. In terms of carbon budget, it was established that the organic carbon, which is produced through photosynthesis process, is reduced by $\Delta PP = -0.11 \text{ gC m}^{-2} \text{ day}^{-1}$ in average over the whole area. Again, a strong spatial variability was observed. The average reduction of organic carbon is $-0.18 \text{ gC m}^{-2} \text{ day}^{-1}$ over zone A where it could reach a maximum value of $-1.0 \text{ gC m}^{-2} \text{ day}^{-1}$ in spring.

[23] The interannual variations of the seasonal average of the relative reduction of primary production due to dust aerosols, $\Delta PP/PP$, were also studied. Despite a strong variability of the weekly variations of $\Delta PP/PP$, the evolution of $\Delta PP/PP$ does not exhibit any major trend of variation with regard to the entire area over the course of the decade. A ten-year time series is likely to be too short to evaluate potential effects of global climate changes. However, a statistically significant tendency of decrease of $\Delta PP/PP$ of 0.22% per year was observed over zone A in summer. Such a slope could have some important implications for the marine productivity of ecosystems in this area at a climatological time scale (e.g., several centuries) since an increase of Saharan dust emission could be expected as a result of regional long-term climate change effects. An attempt was made to compare the interannual variations of the strength of dust aerosols events such as the occurrence of dust aerosols and that of $\Delta PP/PP$ with the interannual variations of regional climate indices, namely the North Atlantic Ocean (*NAO*) and the North Tropical Atlantic (*NTA*) indices, which may have some influences on the study area. An interesting correlation was obtained between *NAO* and the occurrence of dust aerosols in summer from 2001 to 2009 (excluding the year 2005). A decrease of the occurrence of dust aerosols is observed when the *NAO* index decreases toward negative values, which is consistent with the fact that less dust aerosols could be present in the atmosphere when *NAO* values are negatives. The results showed that a weak difference of $\Delta PP/PP$ was observed in summer between lower and higher values of *NAO* index ($\Delta PP/PP$ varies within 1.5%). A consistency between $\Delta PP/PP$ and *NTA* index was observed in summer between 2003 and 2009. This consistency between $\Delta PP/PP$ and *NTA* might suggest that dust aerosol radiative forcing onto the sea surface could be positive in these conditions. It would mean that dust aerosols might partially explain an increase of the sea surface temperature (i.e., *NTA* index increases) through a “cloud cover” effect and a higher reduction of the oceanic primary production (i.e., negative values of $\Delta PP/PP$ are higher) through a decrease of *PAR*. It was highlighted that such a dust impact on *SST* contrasts with the literature showing a decrease of *SST* [Foltz and McPhaden, 2008b; Martínez Avellaneda et al., 2010] due to the surface dust shortwave forcing. Thus, the dust impact should be verified in the future, for example through a more extensive analysis of the aerosol radiative budget over the study area. A much longer time series of satellite measurements (e.g., thirty-year time series) is also required to better understand the potential effects of climate change on the impact of the aerosols on the primary production. This study highlights the need to include the radiative forcing of

aerosols on the sea surface in coupled atmosphere–ocean models for calculating correctly the primary production. As an example, a forecast ocean model should include atmospheric optical parameter, such as the aerosol optical depth, to account for the significant effect of dust aerosols on the biological activity. Future work should consist in investigating deeply which of the depressive effect of dust aerosols on primary production (through the attenuation of the incoming radiation) or the stimulating effect of dust aerosols on phytoplankton growth (through the addition of iron in the water column) drives primarily the production of organic carbon over regions affected by strong dust aerosol plumes.

Notation

α	Angström exponent
AVHRR	Advanced Very High Resolution Radiometer
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation
[Chl]	Chlorophyll <i>a</i> concentration (mg m^{-3})
ITCZ	Inter Tropical Convergence Zone
NAO	North Atlantic Oscillation index
NTA	North Tropical Atlantic index
PAR(0+)	Photosynthetically Available Radiation at the sea level (W m^{-2})
PAR _{cs}	PAR calculated for clear sky conditions ($\tau_{a550} = 0.05$)
PP	Primary production ($\text{gC m}^{-2} \text{ day}^{-1}$)
PP _{cs}	Primary production calculated for clear sky conditions ($\tau_{a550} = 0.05$)
SeaWiFS	Sea-viewing Wide field of View Sensor
SST	Sea surface temperature ($^{\circ}\text{C}$)
τ_{a550}	Aerosol optical depth at 550 nm
ψ^*	Cross section for photosynthesis per unit of chlorophyll ($\text{m}^2 (\text{g Chl})^{-1}$) for a given atmospheric condition
ψ^*_{cs}	Cross section for photosynthesis per unit of chlorophyll ($\text{m}^2 (\text{g Chl})^{-1}$) for a clear sky condition ($\tau_{a550} = 0.05$)

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