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Seasonal and inter-annual (2002-2010) variability of the suspended particulate matter as retrieved from satellite ocean color sensor over the French Guiana coastal waters.

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ABSTRACT

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A regional algorithm has been developed for estimating total suspended matter (TSM) concentration over the MODIS time period in the French Guiana coastal waters. The temporal analysis of the 8-year time series (2002-2010) shows very different patterns of temporal variability translating the influence of the various hydrodynamic forcings occurring in this coastal system. Hydrodynamical rings formation associated with the retroflecting North Brazil current system induce strong irregular variations in the TSM loads offshore the Guiana coast. Further, strong significant 8-year interannual changes have been detected along the nearshore waters of French Guiana. The alternance in the distribution of the areas showing increasing and decreasing trends might underline the migration of mud banks particularly dynamic in this coastal region.

ADDITIONAL INDEX WORDS: *remote sensing, temporal variability, suspended particulate matter*

INTRODUCTION

Due to the high variability of the physical and biogeochemical processes occurring in coastal areas, traditional approaches based on oceanographic cruises and *in situ* time series, although essential, are very time-consuming, expensive and sometimes uncertain to yield meaningful results on the studied phenomena. In this context, remote sensing of biological and physical parameters can provide relevant information. Satellite data are not as accurate as *in situ* measurements and are limited to the surface layer. However, the latter limitations are largely compensated by the spatial and temporal coverage offered by the satellite observations. Remote sensing of ocean colour is a very powerful tool for the management of resources and activities of continental shelf waters.

The estimation of total suspended matter concentration (TSM) from satellite imagery can provide relevant insight for the assessment and monitoring of marine ecosystems. Algorithms initially developed for estimating TSM in the open ocean were based on the co-variation of the phytoplankton Chlorophyll a and suspended matter concentration. This assumption is not valid in the coastal ocean where the sources of particulate matter are diverse, and independent from the phytoplankton dynamics (IOCCG, 2000).

TSM spatio-temporal variability in the French Guiana coastal waters is analyzed from the Moderate Resolution Imaging Spectroradiometer (MODIS) from 2002 to 2010. These coastal waters are unique in a sense that their characteristics are essentially driven by natural forcing. They are largely under influence of the Amazon river, but are also affected by local forcings such as rivers inputs and mud banks migration processes (Froidefond *et al*., 2002; Froidefond *et al*., 2004; Anthony *et al*., 2008*)*. A specific regional algorithm is applied to assess the TSM loads in these very turbid waters where very few studies based on ocean color remote sensing have been performed (Froidefond et al., 2002; Loisel et al., 2009). The derived TSM is compared with *in situ* measurements performed during different field experiments in 2006, 2009 and 2010. In order to describe the TSM patterns of temporal variability over the French Guiana coast, the MODIS monthly time series are then decomposed into a seasonal, an irregular and a trend-cycle term using the Census X-11 procedure (Pezzulli *et al.*, 2005; Vantrepotte and Mélin, 2009; Vantrepotte *et al.,* 2010; Mélin *et al*., 2010). In addition, the presence of significant interannual changes in the water masses turbidity over the MODIS 8-yr period is evaluated using non-parametric statistical analyses. These spatio-temporal patterns are then discussed and related to the influence of the regional environmental forcings.

METHOD

In situ measurements

Field measurements of optical, radiometric, and biogeochemical parameters were performed in the nearshore and offshore waters of the French Guiana in September 2006, 2009 and 2010 (N = 47). In the frame of this study, we focus only on the total suspended matter concentration, TSM ($g.m^{-3}$), and the remote sensing reflectance, R_{rs} (is sr^{-1}). A detailed description of the protocol used for these measurements is given in Loisel *et al.* (2009). The *in situ* TSM values range from 3 to 325 $g.m^{-3}$ with a mean value and a coefficient of variation of 34 $g.m^{-3}$ and 173%, respectively. This data set has been split in two different parts, one for the algorithm development, the other for the validation exercise.

Ocean Color Data

Monthly data of MODIS-derived remote sensing reflectance, R_{rs}, at the 1x1 km^2 spatial resolution, were acquired from the NASA Goddard Distributed Archive Center for the 2002-2010 time period (reprocessing 2009.1). For the studied area, the standard cloud mask algorithm usually fails, as turbid water pixels are generally classified as clouds, leading to a loss of data. This is explained by the assumption made by the standard cloud mask that the marine reflectance is close to zero in the near-infrared (NIR). While this assumption is valid over the open ocean, it validity does not stand for coastal waters where a high NIR reflectance prevails due to suspended matter and non-maritime aerosols. To improve the detection between clouds and turbid waters pixels we applied a recent algorithm that is based on the lower spectral variability of clouds compared to water (Nordkvist *et al*., 2009).

The assessment of the suspended total suspended matter, TSM, (in $g.m^{-3}$) from R_{rs} is performed using the formulation developed by Nechad *et al*. (2010) who have proposed a generic single band algorithm as follows:

$$TSM = \frac{A.\rho_w}{1-\rho_w / C} + B \qquad (1)$$

where ρ_w corresponds to the water reflectance (with $\rho_w = R_{rs} . \pi$) and A, B and C the coefficients of the nonlinear regression. Here we use ρ_w (678) which corresponds to the MODIS band in the red part of visible spectrum. The R_{rs} variability at this wavelength (Figure 1) is mostly driven by the concentration of particulate matter.

Statistical Analyses

The analysis of time series of TSM concentration has to consider the spatial variability in the temporal coverage of the ocean color data. A pre-treatment has been applied to TSM data in order to eliminate gaps in the series. It leads essentially to the consideration of shortened time series (of variable period, p, see the detailed method in Vantrepotte and Mélin, 2009; Vantrepotte *et al.*, 2011; Mélin *et al.*, 2011). A time series X(t) (here the monthly series of TSM) can be decomposed as X(t) = S(t)+T(t)+I(t), where S, T and I represent the seasonal, the trend-cycle, and the irregular (or residual) component, respectively. In practice, this decomposition has been performed by using the Census X-11 method which is based on an iterative bandpass filter algorithm that explicitly allows the consideration of inter-annual variations in the seasonal cycle shape (Pezzuli *et al.*, 2005, Vantrepotte and Mélin, 2009). The relative part of variance of the initial series associated with the component S(t), I(t) and T(t) has then been estimated on a grid-point basis in order to identify the main spatial patterns of temporal variability. In addition, the presence of significant monotonic change in the data over the period investigated has been assessed using the seasonal Kendall test applied on X(t). The amplitude of the observed changes (in $\%.yr^{-1}$) has been quantified using the Sen's slope estimator (Gilbert, 1987).

RESULTS AND DISCUSSION

SPM regional algorithm

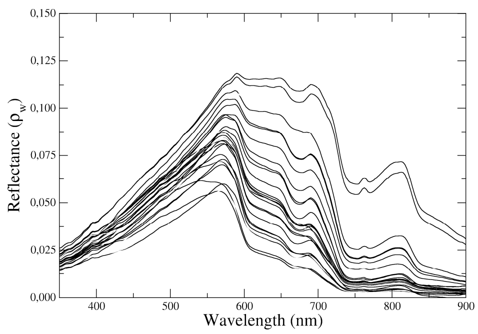

Figure 1: Illustration of the varability in the *in situ* reflectance spectra (TRIOS, 350-700 nm) observed in the coastal waters of French Guiana in 2010.

The remote sensing reflectance spectra exhibit a great variability in shape and amplitude (Figure 1). This variability is driven by the relative contribution, in addition to pure water, of the colored dissolved organic matter and total suspended matter, as well as by the nature of the suspended particulate matter (Lubac and Loisel, 2007).

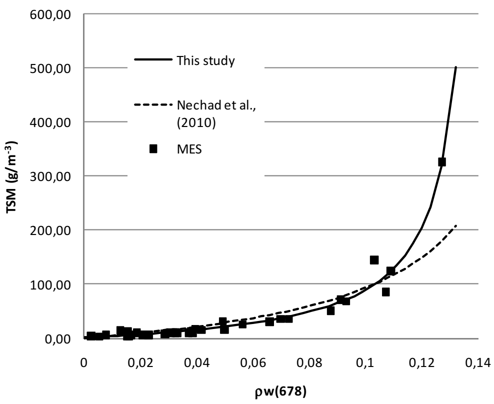

Figure 2: Relationships between i*n situ* water reflectance at 678 nm (ρ_w(678)) and TSM concentration ($g.m^{-3}$) derived from the 2009 dataset. The full line represents the algorithm developed in this study while the dotted line shows the one by Nechad *et al*., (2010).

The relationships between ρ_w(678) and TSM concentration is shown in Figure 2 for the 2009 *in situ* data set. The different coefficients appearing in Eq. 1 were obtained from a nonlinear curve fit: A = 260; B = 1.092 and C = 0.142 (R^2 = 0.97, p<0.001). As seen in the Figure 2, these coefficients slightly differ from those documented in Nechad et al. (2010) which have been defined from an *in situ* data set collected in the North Sea.

The accuracy of the satellite TSM estimates has been checked using various indicators. Considering the distributions $(x_i)_{i=1,N}$ and $(y_i)_{i=1,N}$ of field and satellite values, respectively, the mean absolute relative difference between the two is expressed as:

$$|\psi| = 100.\frac{1}{N}\sum_{i=1}^{N}\frac{|y_i - x_i|}{x_i} \qquad (2)$$

Further, the root mean square difference (RMSD) is computed as:

$$RMSD = \sqrt{\frac{\sum_{i=1}^{N}(y_i - x_i)^2}{N}} \qquad (3)$$

The latter indicators show that the performance of the regional algorithm developed in this study is better than that of Nechad et al., (2010) for this area (RMSD = 9 vs 26 g.m^{-3} and $|\psi|$ = 23 vs 50 %, respectively, N= 37). This formulation has been found to retrieve the TSM concentration for the 2010 cruise with a good accuracy (TSM estimated/TSM measured = 1.11, variation coefficient= 30%, N=10).

TSM dynamics

Figures 3 a and b show the MODIS 8-yr average TSM and variation coefficient (standard deviation/average x 100) derived from the time series computed from the regional algorithm developed in this study. The strong coastal to offshore gradient in the TSM loads logically reflects the strong impact of the terrestrial inputs of particulate material from river discharges, bottom and/or coastal erosion on the Guiana coastal ecosystem. TSM vary from concentrations below 1 g.m^{-3} in the offshore waters to up to 150 g.m^{-3} in some individual nearshore pixels and time periods.

Suspended matter shows different patterns of temporal variability over the coastal waters of Guiana as illustrated by the Figures 4a and 4b which represent the relative contribution of the X-11 seasonal and irregular components (in %) to the total variance of the MODIS TSM 8-yr time series. The strong variability existing in the waters under the influence of the Amazon river (Figure 3b) can be associated with the high seasonality in the TSM loads (>50%, Figure 4a) that underlines the strong annual fluctuation in the charge of particulate material delivered by this river to the coastal ocean (Martinez *et al.*, 2009). Maximum TSM concentrations are found between May and July while the lowest are observed during winter, in good agreement with the seasonal variability of the Amazon discharge (Figure 5).

In the most nearshore waters, a relative low temporal variability (Figure 3b) and seasonality is usually found (Figure 4a) emphasizing the permanent presence of a strong particulate material background in these very shallow areas. Conversely, large temporal variation (Figure 3b) and seasonal fluctuation (Figure 4a, Figure 5) are found in a coastal band slightly distant from the ultra nearshore domain. The latter feature might be related to annual variation in the extension to the shore of the most turbid waters according to the succession of the wet-dry seasons.

A particularly low seasonality (<25%) is observed in a large area offshore the French Guiana coast (Figure 4a), where TSM temporal variability appears to be essentially irregular (Figures 4b and 5). Indeed, while the irregular (or residual) component represents on average 25% of TSM the temporal variability for the whole studied area, its contribution largely increases up to about 60% between 5-6°N and 52-54°W. The origin of such an important residual variability in this area all along the 8 years period (Figure 5) could be related to the offshore presence of the North Brazil Current rings. The latter may affect the spatial distribution of TSM in this region by modifying the local currents and particulate matter transport. Based on satellite observations performed between September 1997 and September 2000 Fratantoni and Glickson (2002) have identified 18 hydrodynamic rings (about 6 per year) translating toward the Caribbean Sea. Moreover, the latter authors did not detect any seasonality in the ring formation processes, in good agreement with previous altimetry observations (Goni and Johns, 2001).

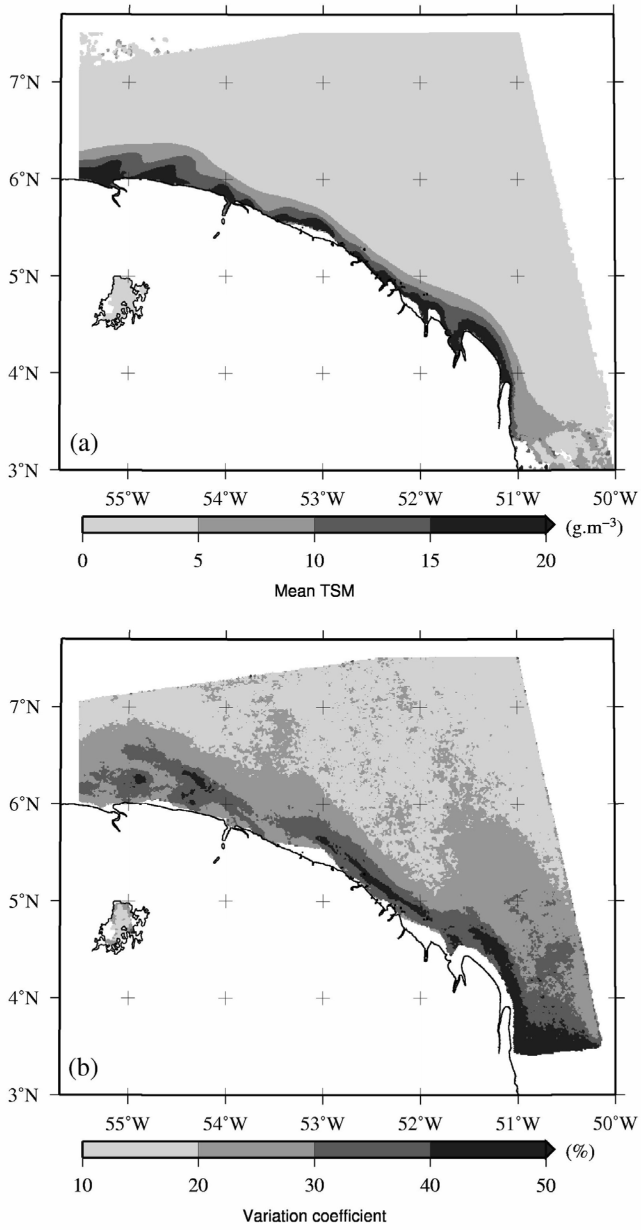

Figure 3: MODIS 8-years (a) average (g.m^{-3}) and (b) variation coefficient (%) of the TSM loads estimated from the single band algorithm developed from the *in situ* data set.

No significant interannual change in TSM has been found in the water masses offshore Guiana over the period 2002-2010. Conversely, the monotonic trend analysis reveals the presence of strong significant changes (up to 6%. year^{-1} in absolute value) in the water masses turbidity within patchy areas of the nearshore domain (Figure 6).

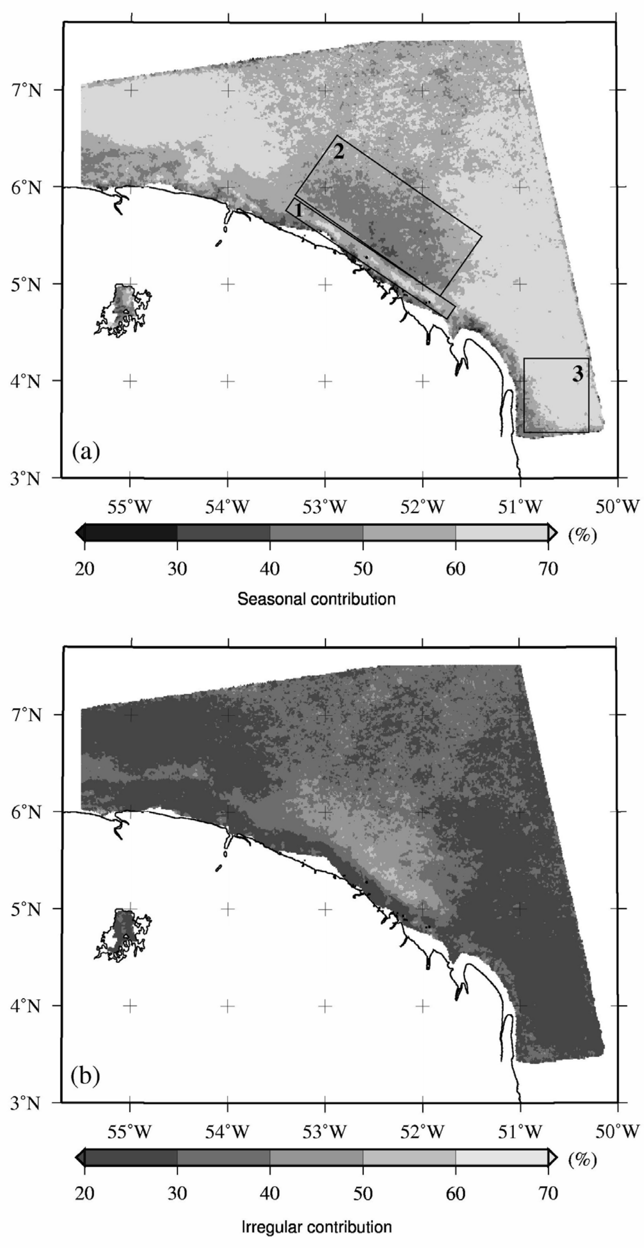

Figure 4: Relative contribution of (a) the seasonal component S(t) (in %) and (b) the irregular component I(t) to the variance of the TSM detected from the X-11 decomposition procedure applied to the MODIS 8-year monthly time series.

These trends are not associated with comparable changes in river discharges, which are usually slightly or not significant over the MODIS period (according to the DIREN Guyane data). However, it should be stressed that interannual variation in the particulate matter flux from the rivers to the coastal ocean might not be depicted from the river discharges data only. For instance, Martinez *et al.* (2009) have pointed out the presence of significant interannual changes in the particulate matter inputs from the Amazon river without any relevant modification of the freshwater flow.

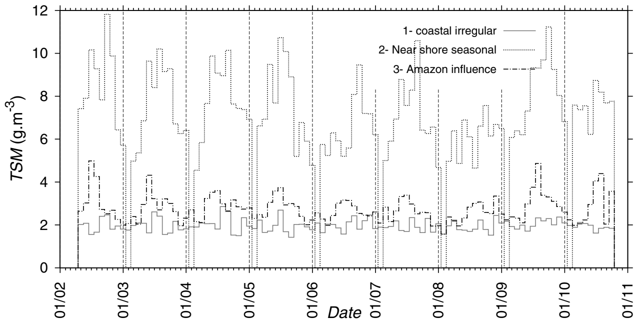

Figure 5: MODIS 8-year monthly time series of TSM loads averaged within (1) the highly seasonal nearshore region, (2) the Amazon plume and (3) the highly irregular offshore area which boundaries are represented in the Figure 4a.

Importantly, a pronounced geographical alternance along the coastline is clearly observed between areas where TSM tends to increase and those where a significant TSM decrease has been detected. This result might underline that these 8-yr interannual changes in TSM correspond preferentially to the migration of the nearshore mud banks which has been shown to be highly dynamics in studied area (Gardel and Gratio, 2005; Anthony *et al.*, 2008). Further, several authors have pointed out the importance of the particulate material originating from these banks through re-suspension processes on the turbidity dynamics in the Guiana coastal waters (Froidefond *et al.*, 2002; Froidefond *et al.*, 2004).

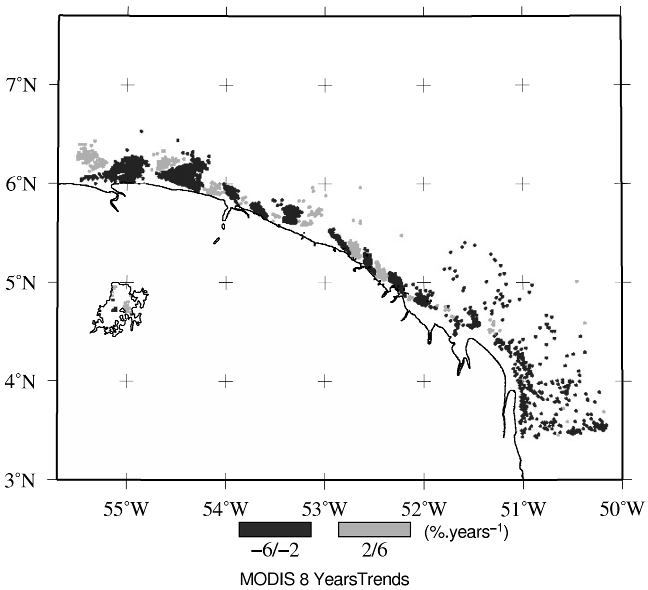

Figure 6: Significant monotonic trends ($p<0.05$) in TSM loads over the 8 years of MODIS data (in % yr^{-1}). Only the most pronounced trends have been represented (>2%.yr^{-1} in absolute value).

CONCLUSION

The data set collected during *in situ* campaigns has been used to develop a regional algorithm allowing to retrieve the TSM concentration in the coastal waters of French Guiana with a satisfying accuracy. The analysis of the MODIS 8-year time series has provided relevant information on the TSM dynamics in the studied region. First, hydrodynamical rings associated with the retroflecting North Brazil current system induce strong irregular variations in the TSM loads offshore the Guiana coast. Further, strong significant 8-year interannual changes have been detected along the nearshore waters of French Guiana. The clear alternance in the distribution of the areas showing an increasing or a decreasing TSM 8-yr trend might underline the migration of mud banks particularly dynamic in this coastal region (Gardel and Gratiot, 2005).

Further observation is required to explore in detail the relationships between the TSM variability and the various forcing mechanisms (i.e. the French Guiana and Amazon rivers discharge, the local wind stress, the retroflecting North Brazil Current, and the Amazon-derived mud bank migration). More in depth analyses will be performed on data with higher temporal (8-days) and spatial resolution (i.e. SPOT, 20 m) and using additional information on the regional hydrodynamics temporal variability (altimetry, SST, wind stress...). The analysis of the X-11 outputs within the high trend nearshore regions will also help to characterize the actual nature of the observed trends (gradual change, temporal shift....) and to relate these patterns to the mud bank dynamics.

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