

Measurement of oceanic chlorophyll by LIDAR, MODIS, fluorometry and above-water radiometry

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ABSTRACT

Comparisons between *in situ* measurements of surface chlorophyll concentration (CHL) and ocean color remote sensing estimates were conducted during an oceanographic cruise in the Brazilian Southeastern continental shelf and slope in November 2004. *In situ* estimates were based on fluorometry, above-water radiometry and lidar fluorosensor. Three empirical algorithms were used to estimate chlorophyll *a* concentration from radiometric measurements: Ocean Chlorophyll 3 bands (OC3M), Ocean Chlorophyll 4 bands (OC4v4), and Ocean Chlorophyll 2 bands (OC2v4). The satellite estimates of chlorophyll *a* were derived from data collected by the Moderate-resolution Imaging Spectroradiometer (MODIS) with a nominal 1.1 km resolution at nadir. Three algorithms were used to estimate chlorophyll concentrations from MODIS data: one empirical - OC3M, and two semi-analytical - Garver, Siegel, Maritorena version 01 (GSM01), and Carder. In this paper, LIDAR, MODIS and *in situ* above-water radiometry and fluorometry are briefly described and the estimated values of chlorophyll retrieved by these techniques are compared. Chlorophyll concentrations were fairly well estimated by all the methods. In general, the empirical algorithms applied to the satellite and *in situ* radiometric data showed a tendency for overestimating CHL. The semi-analytical GSM01 algorithm applied to MODIS data performed better than the Carder and the empirical OC3M algorithms.

Keywords: Chlorophyll, LIDAR, MODIS, above-water radiometry, fluorometry

1. INTRODUCTION

Ocean color remote sensing has changed our perspective of ocean observation. Global maps of surface chlorophyll concentration (CHL), and therefore, of phytoplankton primary productivity can be routinely produced^{1,2}. However, these products are based on the application of sometime complex bio-optical algorithms³, including atmospheric correction models⁴, on the water leaving radiances measured by the remote sensors. Therefore, satellite images must be calibrated and validated with the use of *in situ* instruments from research ships, moored buoys and drifters, for example³.

Satellite images have been systematically used for monitoring the oceanic environment on the Brazilian Southeastern continental margin. Aiming to advance scientifically and technically the current remote sensing data analysis procedures a two years research project - FITOSAT is being jointly conducted by INPE, PETROBRAS R&D Center and other universities. One of the phases of this project involved an oceanographic cruise with the simultaneous acquisition of *in situ* and remote sensing data in the Campos Basin region. The simultaneous data acquisition enabled the meteorological contextualization of the *in situ* data collection and allowed the evaluation of the remote sensing products.

In this context, *in situ* estimates of CHL were obtained with fluorometry, above-water radiometry and lidar fluorosensor. The satellite estimates of CHL were derived from MODIS data. In this article, these different methods are briefly described and their results are statistically compared.

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2. METHODOLOGY

2.1 *In situ* Chlorophyll

Chlorophyll measurements were measured in 18 stations during a cruise held in November 2004. The study area includes the continental shelf and slope of the Brazilian Southeastern region, from Cape Sao Tome to Cabo Frio (22°S), at Campos Basin, Rio de Janeiro (Figure 1). Phytoplankton abundance was estimated from 2L of surface samples filtered through Millipore cellulose membranes (0.45 μm). The filters were kept in liquid nitrogen and the chlorophyll *a* concentrations determined after extraction in acetone 90%, for 18 hours at 4° in a Turner TD-700 fluorometer⁵.

2.2 *In situ* Radiometry

Above water radiometric measurements were obtained with a hyperspectral SPECTRON SE590 radiometer in 31 stations (Figure 1). Each radiance spectrum was sampled between 400-800 nm, with a 5 nm resolution. The protocol adopted for the measurements was the one proposed by Fougnie et al.⁶, with a polarizer filter. The radiometric data were numerically integrated to simulate the spectral bands of SeaWiFS and MODIS orbital sensors, by the trapezoidal rule. The remote sensing reflectance, $R_{RS}(\lambda)$, was calculated by the following equation:

$$R_{RS} = \frac{L_w(\lambda)}{E_d(\lambda)} \quad (1)$$

where $L_w(\lambda)$ is the water leaving spectral radiance and $E_d(\lambda)$ is the downwelling spectral irradiance incident on the sea surface. $E_d(\lambda)$ was estimated by the radiance $L(\lambda)$ reflected by a Spectralon plate⁷, as follows:

$$E_d(\lambda) = L(\lambda)f_c\pi \quad (2)$$

where f_c is a correction factor estimated in the laboratory by the ratio of $L_{ref}(\lambda)$ of a standard reference (approximately 100%) by the Spectralon plate's $L(\lambda)$ used in the field.

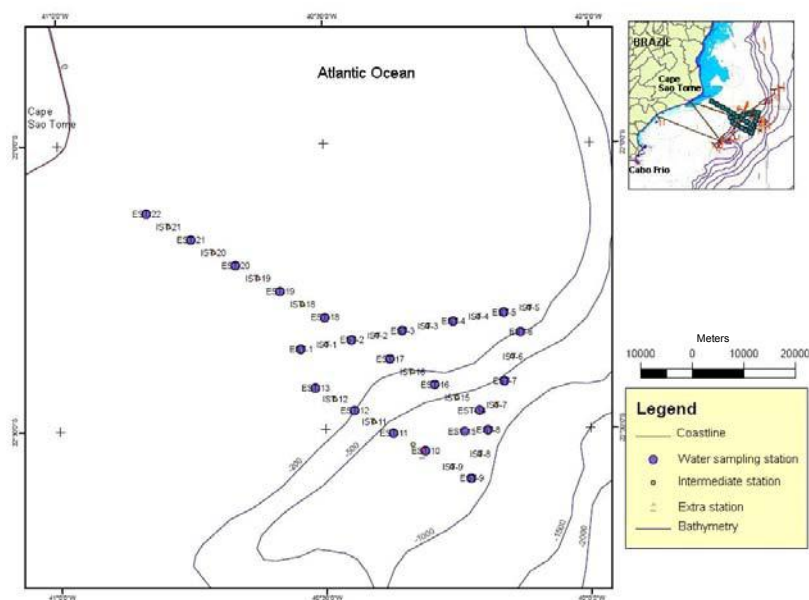


Fig. 1. Study area and field stations occupied during November 2004 at the Brazilian Southeastern continental margin. Isobaths in meters. Water sampling, above-water radiometry and LIDAR stations labeled with an “E”. Stations without water sampling labeled with an “T”.

The SeaWiFS empirical algorithms Ocean Chlorophyll 4-bands - OC4v4 and Ocean Chlorophyll 2-bands - OC2v4, and the MODIS algorithm Ocean Chlorophyll 4-bands - OC3M were applied to the radiometric data to estimate CHL.

The OC2v4 algorithm estimates CHL based on a band ratio of $R_{RS}(490)/R_{RS}(555)$ using a modified cubic polynomial function³:

$$CHL = 10,0^{(0,319-2,336R_{2S}+0,879R_{2S}^2-0,135R_{2S}^3)-0,071} \quad (3)$$

where $R_{2S} = \log_{10}(R_{555}^{490})$.

The algorithm OC4v4 also relates a band ratio with CHL using a polynomial function, but is based on the maximum band ratio determined as the highest ratio (R_{max}) between the values of $R_{RS}(443)/R_{RS}(555)$, $R_{RS}(490)/R_{RS}(555)$, and $R_{RS}(510)/R_{RS}(555)$ through the following function of forth order³:

$$CHL = 10,0^{(0,366-3,067R_{4S}+1,930R_{4S}^2-0,649R_{4S}^3-1,532R_{4S}^4)} \quad (4)$$

where $R_{4S} = \log_{10}(R_{max})$.

The algorithm OC3M also uses a polynomial function of forth order from R_{max} between $R_{RS}(443)/R_{RS}(550)$ and $R_{RS}(490)/R_{RS}(550)$, through the following equation³:

$$CHL = 10,0^{(0,283-2,753R_{3M}+1,457R_{3M}^2-0,659R_{3M}^3-1,403R_{3M}^4)} \quad (5)$$

where $R_{3M} = \log_{10}(R_{max})$.

2.3 LIDAR

The PUC-Rio Fluorosensor LIDAR system uses the excitation at 532 nm of the doubled frequency radiation (second harmonic) of Nd:YAG laser as light source. A rotating rectangular metal mirror directs the probing beam to the water surface by means of a hole. This mirror deflects the water backscattered signal to a 200 mm-diameter Newton-type reflecting telescope, which is filtered in order to eliminate elastic backscattering. This return signal passes through the entrance slit of the polychromator, which is assembled as an auto collimation lens focusing system. To detect the spectrum of the return signal, we use a CCD array camera with Peltier cooling, 1024 elements.

Two types of radiation are collected: one is the water-Raman backscattering (occurs at 655 nm) and the other is the fluorescence radiation generated when the source interacts with the fluorescent elements present in the water. This wavelength excites the fluorescence of chlorophyll, in a band centered at 685 nm, and of DOM, in a region from 540 to 620 nm. Over 13.000 spectra were obtained during the campaign, with the LIDAR installed at the gangway of the Astro-Garoupa vessel. In order to validate each spectrum, an analysis of the power spectrum of its Fourier transformation was made, and then a validation criterion of these spectra was established. Of the total number of spectra collected during the vessel's course between the November 21st and 25th, 9.511 of them are being objects of analysis.

The intensities of the chlorophyll bands (I_{cl}) were calculated according to the method developed by Barbosa⁸ to the equipment. The values of CSM were attained by means of an adjustment using calibration parameters obtained via laboratorial analysis of samples collected on a prior cruise at the same region where an event of algae flowering occurred. The calibration used is given by:

$$CHL_{LIDAR} = 4,9 * (I_{cl}) - 0,175 \quad (6)$$

2.4 Remote sensing

Ocean color remote sensing images acquired by MODIS sensor during the same period of the oceanographic cruise were processed as CHL fields with the application of one empirical and two semi-analytical algorithms. The MODIS sensor has 36 spectral bands, with 8 dedicated to ocean color applications. These bands have a spatial nominal resolution of 1.1 km and a temporal resolution of 1-2 days.

Level 1 MODIS images were acquired locally by INPE's receiving station and processed using SeaDAS software distributed by NASA. Initially, the data were radiometrically calibrated to generate the water normalized upwelling

radiances. The images considered of interest were selected in accordance to the study area. Atmospheric correction algorithms⁴ were applied to each image before the calculation of CHL values.

As mentioned before, the OC3M empirical algorithm³, and two semi-analytical algorithms, Garver, Siegel, Maritorea version 01 – GSM01⁹, and Carder¹⁰ were applied to estimate CHL with MODIS data. Maritorea et al. (2002)⁹ presented a protocol to improve the semi-analytical model initially proposed by Garver and Siegel (1997)¹¹, for global applications. The complete formulation of the model can be expressed as the following:

$$L_{WN}(\lambda) = \frac{tF_0(\lambda)}{n_w^2} \sum_{i=1}^2 g_i \left\{ \frac{b_{bw}(\lambda) + b_{bp}(\lambda_0)(\lambda/\lambda_0)^{-\eta}}{b_{bw}(\lambda) + b_{bp}(\lambda_0)(\lambda/\lambda_0)^{-\eta} + a_w(\lambda) + Chl_{ph}^*(\lambda) + a_{cdm}(\lambda_0) \exp[-S(\lambda - \lambda_0)]} \right\} \quad (7)$$

where L_{WN} is the normalized water leaving radiance, t is the air-sea transmission factor; $F_0(\lambda)$ is the extra-terrestrial solar irradiance; n_w is the refraction index of water; $g_1 = 0.0949 \text{ sr}^{-1}$ and $g_2 = 0.0794 \text{ sr}^{-1}$; $bb_w(\lambda)$ is the backscattering of water; $a_w(\lambda)$ is the absorption by water; $bb_p(\lambda)$ is the backscattering by particles; Chl_{ph}^* is the chlorophyll-*a* specific absorption coefficient; S is the spectral decay for the dissolved matter and detritus absorption (*cdm*); η is the exponent of the power law for the particulate backscattering coefficient; λ_0 is the wavelength 443 nm wavelength.

The Carder algorithm¹⁰ utilizes a more complex approach. The components associated with the absorption of the pigments are divided from those associated with the degradation products (for example, *gelbstoff* and detritus, $a_g^*(\lambda)$). The absorption coefficient of phytoplankton chlorophyll, $a_{ph}^*(\lambda)$, is adjusted in relation to the chlorophyll concentration and the availability of light and nutrients. The distinction between the effects of the principal constituents is obtained by the spectral differences between $a_{ph}^*(\lambda)$ and $a_g^*(\lambda)$. Comparing sea surface temperature with nitrate depletion temperature (NDT)¹², the presence of big cells rich in chlorophyll and small cells poor in chlorophyll can be deduced from the satellite data¹⁰. The chlorophyll rich cells with low values of $a_{ph}^*(\lambda)$, i.e., with packed pigments, occurs generally in ambient with low level of light and rich in nutrients. On the other hand, chlorophyll poor cells but with high values of $a_{ph}^*(\lambda)$, i.e., without packaging, are present in ambient replete of photons, but poor in nutrients. During the development and validation of the Carder algorithm, *in situ* data sets were compartmented into 2 regions. In the first, the pigment packaging would not be expected, and a second one where this packaging effect would probably occur more frequently or more intensely. Besides, a global average algorithm was developed to be used in conditions where the packaging effect is unknown or transitional. The algorithm also alternates between the empirical and the semi-analytical formulation, using different coefficients for the varying levels of pigment packaging.

2.5 Statistical comparisons

The comparisons obtained between the *in situ* CHL and those estimated with MODIS data were calculated inside a window of 12 hours window. The pairs of data were composed between the CHL_{insitu} and the median value of a 3 x 3 pixels (9 km²) centered on the geographical position of the sampling station in the equivalent MODIS image. The fluorometric data were statistically compared to the satellite estimates, above-water radiometric data and LIDAR data, through linear regression analysis, root mean square error, and transformed-rmse ($rmse-L$)¹⁰.

3. RESULTS AND DISCUSSION

CHL_{insitu} values varied between 0.077 and 0.197 mgm⁻³ with a mean value of 0.12 (±0.04) mgm⁻³. These low values are typical of the oligotrophic waters of the Brazil Current (BC) as observed previously by other authors^{13,14}.

In general, the empirical algorithms applied to the *in situ* radiometric data overestimated CHL_{insitu} (Figure 2). OC3M and OC4v4 presented a similar performance, with lowest $rmse-L$ (0.28) and $rmse$ (0.93) than OC2v4 (0.40 and 1.36, respectively) (see Table 1).

For illustration, examples of MODIS images processed using with the 3 algorithms tested in this study are shown (Figure 3). In the 11/25/2004 image, the oligotrophic waters of the BC are observed offshore, over the slope region, in dark blue colors (OC3M<0.08 mgm⁻³; GSM01<0.08 mgm⁻³; Carder<0.1 mgm⁻³). A surface signature of a mesoscale eddy with a mean diameter of 75-80 km was identified in front of Cape Sao Tome between 22.00°S - 22.65°S, and 39.9°W - 40.77°W, with relatively higher CHL values (0.1<OC3M<0.15 mgm⁻³; 0.08<GSM01<0.13 mgm⁻³; 0.2<Carder<0.3 mgm⁻³).

Table 1. Comparison between different *in situ* and satellite estimates of surface chlorophyll-*a* concentration in the Brazilian Southeastern continental shelf and slope waters in November 2004. (N= number of observations; RAD=*in situ* radiometry; SAT= MODIS data).

Algorithm/LIDAR	<i>rmse-L</i>	<i>rmse</i>	N
OC2v4 _{RAD}	1.36	0.40	17
OC4v4 _{RAD}	0.93	0.28	17
OC3M _{RAD}	0.93	0.28	17
OC3M _{SAT}	0.36	0.11	10
GSM01 _{SAT}	0.28	0.08	10
Carder _{SAT}	1.14	0.34	10
CSM _{LIDAR}	0.48	0.14	14

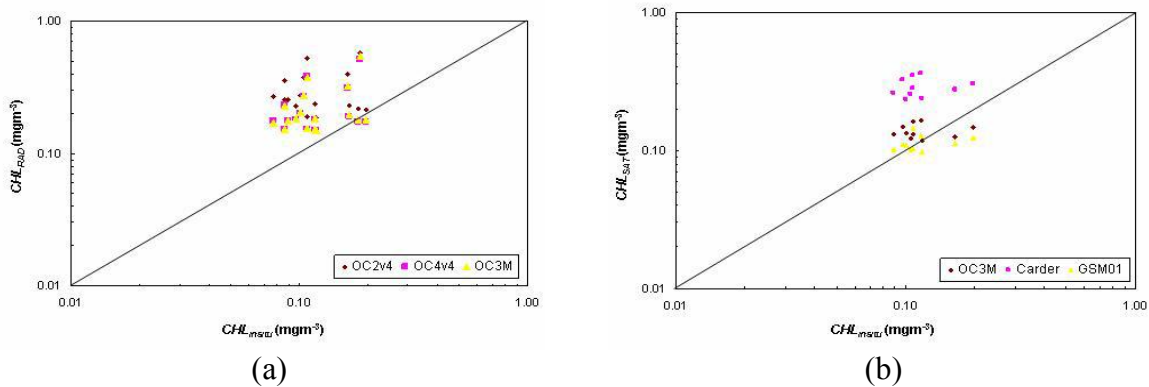


Fig. 2. Scatter plots of chlorophyll concentration estimates obtained with (a) above-water radiometric data (3 algorithms), and (b) MODIS ocean color remote sensing data (3 algorithms) against *in situ* fluorometric estimates.

Ocean color satellite estimates also overestimated the values of CHL_{insitu} (Figure 2), although the algorithms GSM01 and OC3M have underestimated the relatively higher concentrations. The best performance was obtained with the semi-analytical algorithm GSM01, with the lowest values of *rmse-L* (0.28) and *rmse* (0.08), respectively (see Table 1). The empirical algorithm OC3M also presented a good performance, with *rmse-L* equal to 0.36 and *rmse* of 0.11.

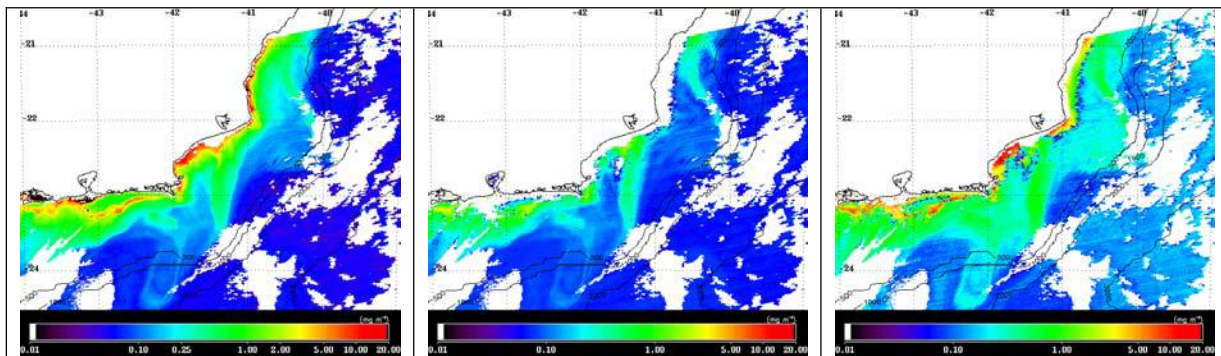


Fig. 3. Surface distributions of chlorophyll concentration estimated with OC3M (left), GSM01 (center), and Carder (right) algorithms applied to MODIS data acquired on 11/25/2004 (see text for details). Isobaths in meters. Color table in logarithmic scale. Land and clouds are masked in white.

The spectral distributions of R_{RS} measured in 31 stations are shown on Figure 4. In general, all the spectra are typical of Case 1 oceanic and oligotrophic waters with low chlorophyll concentrations. At station I03 (yellow on Figure 4) the highest chlorophyll value was obtained with the LIDAR (0.22 mgm^{-3}), which was similar to those estimated by the OC3M and OC4v4 algorithms applied to the *in situ* radiometric data (0.18 and 0.19 mgm^{-3} , respectively). The noise also

observed at station E05 (dark blue on Figure 4) was due to the low light level at the time of data acquisition. The different shape of the spectrum at station E21 corresponds to more coastal waters, with relatively higher chlorophyll concentration (0.54 mgm^{-3} OC3M) and with the probable presence of other optically active components.

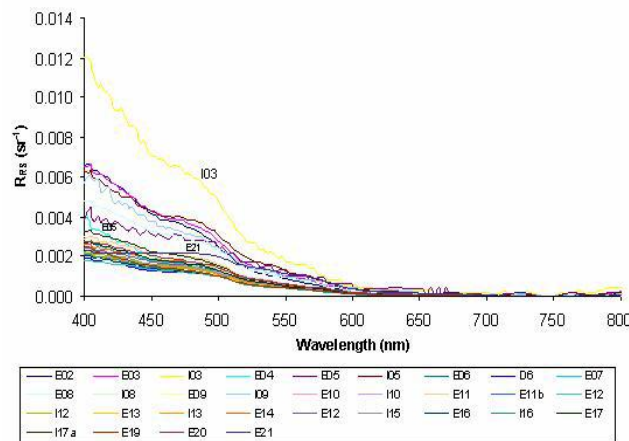


Fig. 4. Surface Remote sensing reflectance spectra obtained by above-water radiometry during the cruise FITOSAT I cruise, November 2004, in the Brazilian Southeastern continental shelf and slope. Water sampling, above-water radiometry and LIDAR stations labeled with an “E”. Stations without water sampling labeled with an “T” (see text).

The fluorescence spectra processed from the LIDAR data are presented on Figure 5. The chlorophyll concentrations estimated with the LIDAR (CSM_{LIDAR}) at the stations with simultaneous water sampling for fluorometric analysis varied between 0.064 and 0.0163 mgm^{-3} , with a mean value of $0.12 (\pm 0.03) \text{ mgm}^{-3}$, very similar to CSM_{insitu} . In fact, a paired t-test confirmed that the two mean values are statistically equal. The performance of the LIDAR was similar to that obtained by the *in situ* fluorometric and radiometric methods, with *rmse* and *rmse-L* values of 0.14 and 0.48 , respectively.

4. CONCLUSIONS

To our best knowledge this is the first published result of simultaneous measurements of surface chlorophyll concentration in the Brazilian Southeastern continental shelf and slope region using *in situ* fluorometric, above-water radiometry, and LIDAR, complemented with ocean color remote sensing MODIS imagery.

Chlorophyll concentrations were reasonably well estimated by the methods utilized, even though, the empirical algorithms applied to the *in situ* radiometric and satellite data have slightly overestimated the CHL values. The semi-analytical GSM01 algorithm applied to MODIS data presented the best performance in relation to the OC3M and Carder algorithms.

Other comparisons between the above-water radiometric data, LIDAR and satellite data are being conducted in order to better explore those sampling techniques and to advance in the ecosystemic study of the interest area.

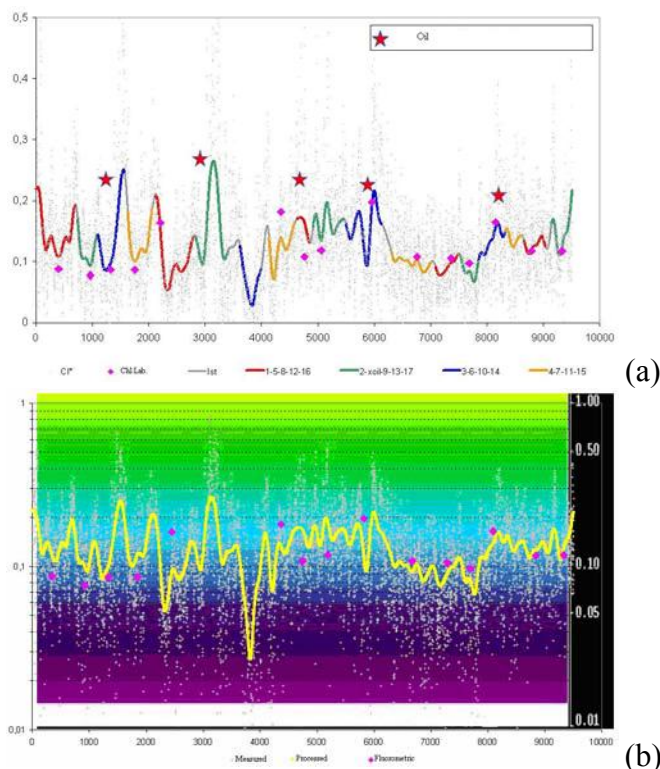


Fig. 5. Surface along-track chlorophyll concentration estimated with the LIDAR during the cruise FITOSAT I cruise, November 2004, in the Brazilian Southeastern continental shelf and slope. (a) Colors indicates the water sampling stations; stars indicates the occurrence of oil slicks; (b) LIDAR estimates superposed to the logarithmic scale used for MODIS images. Purple diamonds represent the fluorometric estimates.

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