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RESEARCH ARTICLE

Performance of the MODIS FLH algorithm in estuarine waters: A multi-year (2003-2010) analysis from Tampa Bay, Florida (USA).

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Although satellite technology promises great usefulness for consistent monitoring of chlorophyll-α concentration in estuarine and coastal waters, the complex optical properties commonly found in these types of waters seriously challenge the application of this technology. Blue-green ratio algorithms are susceptible to interference from water constituents, different to phytoplankton, that dominate the remote sensing signal. Alternatively, modelling and laboratory studies have not shown a decisive position on the use of near-infrared (NIR) algorithms based on the sun induced chlorophyll fluorescence signal. In an analysis of a multi-year (2003-2010) *in situ* monitoring data set from Tampa Bay, Florida (USA), as a case, this study assess the relationship between the fluorescence line height (FLH) product from the Moderate Resolution Imaging Spectrometer (MODIS) and chlorophyll-α.

The determination coefficient (r^2) at individual sites ranged between 0.67 (n = 28, p < 0.01) and no relationship. Overall, there was no good relationship between *in situ* chlorophyll-α and the FLH product (r^2= 0.20, n=507). Nevertheless, the low determination coefficient obtained was still eight times higher than that between *in situ* chlorophyll-α and OC3M, the standard product traditionally used to estimate chlorophyll-α in ocean waters, which is based on the blue-green section of the spectrum. A better relationship of r^2=0.4 (n=93) was obtained by using only sites located at least 5 km from shore and bridges and with depths ≥ 3.2 m. Although these results from Tampa bay did not demonstrate a consistent spatial applicability of MODIS FLH on estuarine waters, a few good determination coefficients found in particular sites (r^2 = 0.67, 0.64 and 0.49; n = 28, 11 and 13, respectively) show that good relationships can be achieved.

1. Introduction

Monitoring and assessment of water quality is critical for managing and improving the environment. Water quality monitoring requires timely and accurate data at regular intervals over sustained periods to adequately understand processes, phenomena and characteristics for regional and local water quality monitoring and management. A major factor integral to monitoring coastal water quality is phytoplankton concentration (Willen, 2007; Stoermer, 1978) and satellite imagery has proven to be a more cost effective method to provide comprehensive spatial and temporal coverage and to detect trends at a variety of geographic scales and time periods.

Several studies have proposed the use of the near-infrared (NIR) bands for estimating chlorophyll-α over the tradition blue green ration algorithms (Aiken et al., 1995; Brown et al., 2008; Evans and Gordon, 1994; McClain et al., 2004; O'Reily et al., 2000; Carder and Steward, 1985;

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Carder et al., 1999) due to the limitations of the blue-green algorithms when used to retrieve chlorophyll-α (Gitelson et al., 2007, Gons, 1999; Morel and Prieur, 1977). The advantages of using the NIR wavelengths are largely based on the assumption that no water constituents other than chlorophyll fluoresces at 683nm, so the signal at that wavelength shouldn't be affected by the presence of other optically active constituents, and the effect of those constituents on the water-leaving radiance can be neglected or considered only as small correction terms (Ruddick et al., 2006, Gitelson et al., 2009; Gitelson, 1992; Gons, 1999). This is in contrast to the visible wavelengths where it may be necessary to consider the absorption properties of dissolved organic matter and suspended particulate matter in addition to phytoplankton. Also addressing these limitations, algorithms to estimate chlorophyll-α in Tampa Bay have been recently developed using a band ratio of red-to-green Le et al, (2013a, 2013b, 2013c).

Complex processing techniques may limit the applicability of remote sensing data to specialized personnel, not commonly at the disposition of local management programs in many coastal areas of the world. The possibility of having friendly use remote sensing products would be highly desirable, consequently potential products using wavelengths less susceptible to interference caused by common constituents of coastal waters would be ideal. The FLH algorithm, which utilizes the NIR bands, is a product which can be derived from the Moderate Resolution Imaging Spectrometer (MODIS). The MODIS sensors are equipped with several bands that are specifically designed to measure the solar stimulated fluorescence of phytoplankton living in surface waters, bands 13, 14, and 15 (centered at 665.1, 676.7, and 746.3 nm, respectively, with a 10 nm bandwidth). A baseline is first formed between radiances for Bands 13 and 15, and then subtracted from Band 14 radiance to obtain the FLH (Letelier and Abbott. 1996).

The purpose of this study is to assess the prospect of using this MODIS Aqua FLH product to monitor chlorophyll-α concentration in coastal waters, using Tampa bay as a case study. This work can test in the field what has been suggested from modeling and works developed under laboratory conditions. We focus on assessing the MODIS FLH product against an eight year *in situ* sampling dataset from Tampa Bay Florida, USA. Potential linear regressions are explored.

2. Background

The usefulness of the FLH algorithm to determine chlorophyll concentrations has been extensively reported in the literature (Ryan et al., 2009; Gower and King , 2007; Ahn et al., 2007; Hu et al., 2005; Letelier and Abbott, 1996; Fischer and Kronfeld, 1990; Hoge and Swift, 1987; Gower and Borstad, 1981; Neville and Gower , 1977). However, there are also some concerns due to the inconstancy in the relationship between fluorescence and chlorophyll-α. Some studies have found that the slope of the approximate linear relationship between FLH and chlorophyll concentration varies by a factor of 2.5, Gower (1999) and the height of the fluorescence peak has been found to be affected by the concentrations of colored dissolved organic matter (CDOM) and suspended particles in the water (McKee et al., 2007; Gower et al. 1999).

In an analysis of data from the MEdium Resolution Imaging Spectrometer (MERIS) , Gower (1999) concluded that using the band at 753.75nm for the baseline would lead to significant overestimation of FLH at higher levels of suspended material due to the increasing difference in reflectance between 700nm and 750nm. Gilerson *et al.* (2006) showed that most of the emergent radiation from coastal waters is a result of scattering rather than fluorescence. He concluded, through a series of laboratory analyses, that extracting fluorescence using the baseline method could strongly overestimate values in coastal waters. Conversely, McKee et al. (2007) suggested, based on HydroLight modeling, a raised background radiance levels resulting in an estimated FLH of about only 30% of the true value of FLH. This would be due to a break down in the MODIS FLH signal when mineral suspended solids (MSS) concentrations are equal or greater than 5 mg l^{-3}. The authors showed that the MODIS FLH algorithm is relatively unaffected by increasing CDOM. Hliang *et al.* (2008), noted the best correlations between FLH and chlorophyll-α when the *in situ* chlorophyll-α concentration was lower than 4 µg l^{-1} and total suspended matter concentration was greater than 4 µg l^{-1}.

Other possible source of uncertainty in fluorescence baseline algorithms is a result of the physiological processes of the phytoplankton. Fluorescence yield is a function of photosynthesis and can vary as a function of physiological status (Falkowski and Kiefer, 1985; Kiefer et al., 1989;

Chamberlin et al., 1990; Babin *et al*., 1996; Letelier *et al*., 1997, 2000; Laney *et al*., 2005). Laboratory and field studies have shown that fluorescence is influenced by the nutrient stress (Kiefer, 1973a; Cleveland Perry, 1987; Abbott *et al*., 2000, Kiefer, 1973b; Letelier et al., 1997; Letelier *et al*., 2000), chlorophyll concentration, pigment packaging effects (Bisset et al. 1997) on light absorption, and light-dependent energy-quenching processes (Behrenfeld *et al.*, 2009). Babin *et al.* (1996) assumed that nutrient stress would increase the susceptibility of phytoplankton to excess irradiance, leading to inactivation of reaction centers and reduced fluorescence yield. Additionally, phytoplankton undergoes diurnal variations and there appears to be a midday depression in FLH emission (Falkowski and Kolber, 1995), which could be a limiting factor if coinciding with satellite time visit.

Given both the benefits and disadvantages of of using fluorescence-based algorithms it is timely to conduct a definitive empirical analysis of the applicability of this algorithm for chlorophyll determination in estuarine waters. Furthermore, in most of the experiments above, the fluorescence emission studies have been activated by artificial light supplied by the experimenter or by using numerical models that simulate natural conditions. Before the present work, few studies had looked at the empirical validity of fluorescence algorithms in coastal waters using a comprehensive long term *in situ* data set.

3. Materials and Methods

3.1 *Study Area*

Tampa Bay is located on the gulf coast of the Florida Peninsula in the southeastern United States between 27.5–28.08°N and 82.36–82.75°W (Figure 1). With a subtropical climate, air temperatures in the area range between about 4 °C in the winter and 39 °C in the summer. About 60 percent (approx. 76 cm) of the annual precipitation occurs during summer (Jun to September) (Lewis and Whitman, 1982). Tampa Bay is the largest open-water estuary in the state of Florida; covering about 1,000 km^2 at high tide and comprising the coastlines of Hillsborough, Manatee and Pinellas counties. Lewis and Whitman (1982) defined seven sections within the bay, however, all the monitoring sites used in this study are located in the four largest and more commonly understood to compose the entire bay: Old Tampa Bay (OTB), Hillsborough Bay (HB), Middle Tampa Bay (MTB), and Lower Tampa Bay (LTB). The sub-regions in Tampa Bay (Figure 1) were defined by Lewis and Whitman, 1982 mainly based on geometrical relationships between areas and shoreline lengths.

The average 3.4 m water depth of Tampa Bay constitutes a concern for possible reflectance contamination from shallow bottom especially at the blue and green sections of the spectrum. Chen et al (2007a) considered a diffusion attenuation coefficient (*Kd*) of approximately 0.33 at 645 nm for waters with medium to low turbidity and colored dissolved organic matter (CDOM) in Tampa Bay. The same authors chose a bottom depth threshold of 2.8 m following trial and error criteria to select *in situ* data in Tampa Bay at that wavelength. Four major rivers comprise up to 85% of the freshwater inflow (Lewis and Estevez, 1988): the Hillsborough River (HR), the Alafia River (AR), the Little Manatee River (LMR), and the Manatee River (MR). This is of special interest considering the potential interference to optical properties caused by CDOM and organic and inorganic detrital particles, which are constituents typically brought by rivers to estuaries. Nevertheless, these limitations are contributing conditions to make Tampa Bay a good study case to represent coastal waters, specially, when there is such an extensive amount of *in situ* data available for comparison, which makes Tampa Bay one of the most data rich water bodies in the world.

Along with marshes and mangroves, seagrass beds are among the bay's most crucial habitats as nursery and feeding grounds for a number of species and support for the tourism industry. Area cover of this important ecosystem has been used as indicative to monitor the bay water quality (TBEP, 2006). Due to the shading effect of high chlorophyll-α concentration blocking sun light penetration to segrass, this is a key water quality parameter regularly monitored *in situ* in Tampa Bay but rarely in many coastal waters in the world where there are technical and financial limitations to support sustainable field monitoring programs. Direct and indirect nutrient discharges to Tampa Bay from mining, industry, and wastewater treatment, among other examples, caused a dramatic mid-century decline in the bay water quality and a loss of seagrass coverage during the twentieth century.

Fortunately, successful watershed management efforts, among which one of the most important have been the upgrade to tertiary level in the Tampa waste water treatment plant since 1979 (Garrity *et al*., 1982), have improved the bay water quality by reducing point and non-point source nutrient loading to the bay (TBEP, 2006).

A preliminary analysis of all the *in situ* data made available for this study by the EPCHC for the period 2003-2010 showed ranges between 8 and 333.4 μg l^{-1} (Mean (μ) = 8 μg l^{-1}, Standard Deviation (σ) = 10.6) in chlorophyll-α concentration, between 0.1 and 8.8 m (μ = 2.1 m, σ = 1.1) in Secchi depth, 0 and 70 mg l^{-1} (μ = 11.7 mg l^{-1}, σ = 6) in suspended solids (SS), 0 and 39 mg l^{-1} (μ = 0.7 mg l^{-1}, σ = 1.6) in Total Nitrogen (TN), 0 and 8.7 mg l^{-1} (μ = 0.2 mg l^{-1} , σ = 0.2) in Total Phosphorus (TP), 0.4 and 31 NTU (μ = 3.1 NTU, σ = 2.1) in turbidity, and between 0 and 8.8 mg l^{-1} (μ = 1.5 mg l^{-1} , σ = 1) in Biological Oxygen Demand (BOD). Forty-four percent of the chlorophyll-α samples registered below 5 μg l^{-1}, while 82.8% of the total suspended solid measurements ranged between 5-20 mg l^{-1}. Average chlorophyll-α concentration throughout all sub-regions of the Bay exceeded 4 μg l^{-1}, from 4.18 μg l^{-1} near the mouth of the bay (e.g. LTB) to greater than 11 μg l^{-1} 170 for the more inland portions of the Bay (e.g. HB). Total suspended solids and turbidity (NTU) also showed a marked increase inland (15.5 mg l^{-1} and 4.1 NTU) from the mouth of the bay (12.9 mg l^{-1} and 2.6 NTU).

Using data from The Coastal Change Analysis Program (C-CAP), the Tampa Bay watershed (TBW) has been estimated to extend for 6,600 km^2 (Moreno-Madriñán et al., 2012), including most of the Tampa Bay Metropolitan Area, which comprises the cities of Tampa (its largest city), St. Petersburg, and Clearwater. Its economy relies primarily on tourism and port operations. The Tampa Bay area is notable by its high population growth and consequent rising environmental concerns. With a growing population of about 2.7 million inhabitants (US Bureau of Census, 2007), Tampa Bay metropolitan area is respectively the second and 21th most populous metropolitan area of Florida and the United States.

3.2 *Satellite Data*

Eight years (2003–2010) of daily MODIS Aqua L1A data (1 km resolution) were downloaded from the L1 and Atmospheric Archive Distribution System (LAADS Web) at the Goddard Space Flight Center. The criterion used to choose the Aqua satellite as opposed to Terra (both carrying a MODIS sensor in a near polar sun-synchronous orbit with 98° of inclination) was given by the daily time range during which the *in situ* data, initially available for matching, was collected. The local equatorial crossing time of Aqua is approximately 1:30 pm while that of Terra is 10:30 am. The *in situ* data initially available for comparison was collected between 9:00 am and 4:00 pm. Consequently, the Aqua time-visit better approximate an equitably division in time thus reducing the range between *in situ* and satellite measurements for the near range-limit matchup pairs.

The MODIS data were processed from Level 1A using the SeaDAS software (version 6.2), by applying calibrations for ocean remote sensing developed by the MODIS Ocean Biology Processing Group (Fu *et al*., 1998). The Ocean Biology Processing Group (OBPG) is responsible for the production and distribution of the ocean color data products from the MODIS sensor on the Aqua satellite and optimizes MODIS ocean color data by updating SeaDAS look up tables (LUTs). The LUTs are derived from analysis of a variety of measurements aboard the MODIS sensor (solar diffuser measurements, lunar observations, and onboard lamps). Additional improvements in the data products result from enhancements in the sensor calibration, atmospheric correction, and improved bio-optical algorithms.

Over 3,242 files were downloaded from the LAADS web and processed to level 1A. Files containing contamination by cloud edges, severe distortion and extensive cloud cover were eliminated from the analysis using a manual QA/QC procedure (Fischer, 2009). The remaining images were processed to mapped Level 3 chlorophyll fluorescence products (Abbott and Letellier, 2003) and the standard blue-green algorithm chlorophyll-α product (OC3M) (Campbell, 2003; Carder et al., 2003). For the atmospheric correction required to derive products (FLH, OC3M), we applied the SeaDAS default atmospheric correction algorithm (Gordon and Wang, 1994), with the addition of NIR correction for non-zero water-leaving radiance (Strumpf *et al*., 2003). The default masks of land, cloud and saturated radiance were applied between L1A and L2 processing. Resulting image data were mapped to a cylindrical projection. The true resolution of FLH and OC3M images are at best ~ 1 km at nadir; bilinear interpolation was used to generate 500 m resolution images. Images were further quality controlled, and those images containing cloud contamination or severe distortion were again removed from the analysis (Fischer, 2009).

3.3 In Situ *Data*

All *in situ* data used in this study were collected and provided by the Environmental Protection Commission of Hillsborough County (EPCHC). Data were collected monthly as part of routine water quality monitoring programs from fixed sampling sites throughout the entire Tampa Bay (Figure 1). Our analysis considered the time interval between years 2003 and 2010 to cover the period elapsed since the first full year of MODIS Aqua until the last full year of the *in situ* data available at the time of starting this study.

Analysis of *in situ* chlorophyll-α were determined by Standard Methods (SM) 10200 H (APHA, 1998), using acetone and a tissue grinder in the chlorophyll-α analysis. All *in situ* data used in this study were drawn from samples collected at mid-depth using a beta sampler. Sample containers were brown high density polyethylene bottles and lab analysis was performed in low lighting. All *in situ* data were obtained according to QA/QC rules of the National Environmental Laboratory Accreditation Program (NELAP).

3.4 *Satellite and* in situ *matchups*

Over 18,000 and 19,000 data points representing the biophysical parameters of fluorescence (FLH) and chlorophyll-α (OC3M), respectively, were derived from the MODIS imagery and were initially available for comparison with over 7,552 data points from the *in situ* data set. 507 Matchup pairs of data with a bottom depth equal or greater than 2.8 m and within a time window of ±6 hours were selected for an overall coefficient of determination (r^2) between the predictor variables (satellite algorithm) and the single common dependent variables (*in situ*) chlorophyll-α. The 2.8 m threshold criterion was chosen following a trial and error procedure. This criterion was also used by Chen *et al.* (2007a, 2007b) and Moreno-Madriñán *et al*. (2010). Both of these studies showed no further improvement satellite/*in situ* comparisons by including samples with shallower bottom depths. As mentioned earlier, Secchi depth ranged between 0.1 and 8.8 m (μ = 2.1 m, σ = 1.1). Chen *et al.* (2007a) used the same 2.8 m threshold to estimate turbidity of Tampa Bay water with MODIS surface reflectance at 645 nm. The authors found this value to be very close to the light penetration depth as predicted from a diffuse attenuation coefficient (*Kd*) of approximately 0.33 m^{-1} at 645 nm. This depth was not expected to interfere the signal at the 665.1-746.3 nm wavelength used by the FLH algorithm since the depth of light penetration is lower at longer wavelengths in this section of the spectrum (Botha *et a.l*, 2013) due to the strong absorption of light by water molecules (Pope and Fry, 1997). Similar trial and error procedure was followed to choose the ±6 h time window criterion, since further decreasing this time window did not improve the relationship. Le *et al*. (2013a, 2013b) used time windows of 3 and 24 h for chlorophyll-α estimation using the algorithms based on the blue/green band ratios (Le *et al.* 2013a, 2013b, 2013c).

In situ chlorophyll-α value were log transformed, as chlorophyll-α concentration tend to be log normally distributed (Campbell et al., 2003). A long term (2003-2010) annual mean was calculated for each of the MODIS products (FLH and OC3M) along with the chlorophyll-α *in situ* data. Areas which had less than 25% satellite coverage were excluded from the final mapped products. Lastly, correlations between *in situ* chlorophyll-α and the remotely sensed products FLH and OC3M were compared.

4. Results

4.1 *Satellite and* in situ *matchups*

No satellite data could be generated for 15 out of the 54 *in situ* sampling sites (Figure 1). Most of these sites were located adjacent to the coastline. Out of the 39 sites that generated satellite data, 35 had dates matching *in situ* chlorophyll-α data collection. The chlorophyll-α concentration of the matched *in situ* data ranged from 0.3 to 37.5 µg l^{-1} (μ = 4.6 µg l^{-1}, σ = 3.7). Sixty-nine percent of the chlorophyll-α samples matched with satellite data registered below 5 µg l^{-1}. Twenty-two sites showed statistically significant relationships when the FLH product was matched with *in situ* chlorophyll-α data but only two sites had coefficients of determination (r^2) greater than 0.6 (Table 1).

The r^2 within sites ranged between 0.67 (n=28, p<0.01) (Figure 2a) and no correlation. There was one unexplained case (station LTB96) where the relationship was negative, r^2= -0.45 (n=12, p=.016). Sites that exhibited the best relationships included MTB14 (r^2=0.67, p<0.01, n=27), HB7 (r^2=0.64, p<0.01, n=11) OTB68 (r^2=0.49, p<0.01, n=13) and MTB32 (r^2=0.48 p<0.01, n=28) (Figure 2a, b, c, respectively). While the HB sub-region had only one statistically significant station for the 12 *in situ* sampling locations, MTB, OTB and LTB had 8, 7, and 6 significant sites, for the 13, 18 and 11 sites in the respective sub regions. The percentage of sites by sub-region that produced statistically significant results was 8, 61, 39, and 55% for HB, MTB, OTB and LTB, respectively. The mean determination coefficients (r^2) of the statistically significant sites by sub-region were 0.64, 0.40, 0.38 and 0.16, for HB, MTB, OTB and LTB, respectively.

While the average distance to shoreline (including bridges) for the statistically significant stations was 3,386 m and 2,160 m, respectively, the average distance for the non-statistically significant stations was 1,309 m and 813 m, respectively. The average bottom depth for the statistically significant sites was 5.0 m while that of the non-significant sites was 4.3 m. Overall, including all matchups pairs available in all sites, and after removing matching pairs with a bottom depth less than 2.8 m, there was no important relationship between FLH and *in situ* chlorophyll-α concentrations (r^2 = 0.21, n = 507, p < 0.01) (Figure 3a). Nevertheless it was 8 times greater than that between FLH and the standard MODIS blue-green ratio (OC3M) product (r^2=0.0272, n=507, p<0.01. This seems to corroborate studies showing that the global MODIS empirical algorithm (OC3M) breaks down in coastal waters producing an overestimate ranging from 50% to as much as 20 fold (Wozniak and Stramski, 2004).

The poor overall correlation found between FLH and *in situ* chlorophyll-α (r^2= 0.2) seems to support the modeling results of McKee *et al*. (2007) according to which the FLH signal breaks down in turbid waters where mineral suspended solids are greater than 5 mg l^{-3}. The authors explained this to be caused by the raised background radiance levels created by the suspended material. Their study further states that the FLH signal detected by satellite based sensors reaches only 30 % of the true value of FLH. In addition, Hlaing et al. (2008) noticed a noticeable spatial structure correlation between satellite-based chlorophyll and fluorescence maps for areas with chlorophyll concentration lower than 4 µg l^{-1}. Average *in situ* chlorophyll-α and total suspended solids measurements in Tampa Bay exceeded respectively 4 µg l^{-1} and 5 mg l^{-1}. However, no improvement was obtained after considering only matching pairs with *in situ* chlorophyll-α concentration lower than 4 µg l^{-1} and total suspended matter concentration greater than 4 µg l^{-1}. Some improvement in the relationship was achieved when the analysis was limited to matching pairs from sites located at least 5 km from shoreline and bridges (r^2=0.4, n=93, P< 0.01) (plot closer to linear regression, Figure3b). Some of these bridges have four lanes in each direction besides the shoulders of the road and abundant vegetation along the sides of the embankment to both ends. Thus these structures may have an impact contaminating the pixels.

4.2 *Spatial patterns*

The spatial patterns of the long term means (2003-2010) for the FLH and OC3M product are shown in Figure 4 along with that of the *in situ* data for comparison. The blue-green ratio OC3M product mean displayed a higher chlorophyll-α concentration in OTB and in general increasing eastward throughout the full extent of OTB, MTB, and LTB. Similar eastward pattern was observed on water turbidity estimation using the surface reflectance MODIS Terra product (MOD09GQ, 620-670nm) (Moreno-Madriñán *et al*., 2010) and appears to be related to river discharge as the four major rivers (HR, AR, LMR and MR) discharge their waters at the east side of Tampa Bay. A possible direct association between higher OC3M estimation of chlorophyll-α and water turbidity may be explained by the associated concentration of CDOM discharged by these four rivers and the high absorption of CDOM in the blue wavelength. Since coastal waters commonly have high concentrations of CDOM, this aligns with studies showing that the OC3M algorithm can overestimate measurements in coastal waters by as much as 50% to 20 fold (Wozniak and Stramski, 2004). No major river discharges into OTB but a number of minor streams and storm water runoff from watershed scale precipitation can be important sources of CDOM for this bay sub-region.

Conversely, the FLH product, estimated higher concentration of chlorophyll-α westward throughout all sub-regions of Tampa Bay. Both remote sensing products showed a decreasing spatial trend in chlorophyll-α from the upper bay sub-regions to the lower sub-regions. This trend agrees with the *in situ* data and may be associated with adjacent more dense urban areas influencing the northern side of the bay (Xian *et al.*, 2007; Moreno-Madriñán *et al.*, 2012) transitioning southwards to the influence of the clear waters from the Gulf of Mexico at the south (Weisberg and Zheng, 2006) as also suggested by Le *et al.* (2013b).

Similarly to the FLH product and contrary to the OC3M product, the geographical distribution of the *in situ* data (Figure 4) confirmed that the chlorophyll-α concentration was in fact higher toward the western portion of OTB. For both the OC3M and FLH products, lower satellite coverage for HB (<25%) produced a limited data set. Therefore, not enough matchup data points were available to analyze spatial distribution trends in HB as it can be appreciated from the large proportion of masked area covering this sub-region of the bay in Figure 4. Due to the absence of monitoring sites adjacent to the western shoreline of MTB, it was not possible to confirm if the pattern of the *in situ* data would coincide with the FLH product showing higher chlorophyll-α concentration along that shoreline.

5. Discussion

This analysis utilizes a long-term *in situ* data set from Tampa Bay, Florida (USA) and assesses the validity the MODIS FLH algorithm to monitor chlorophyll-α concentrations in coastal/estuarine waters. The *in situ* data set contains a range of values from multiple water quality parameters that characterize an optically complex estuarine body of water and provides the opportunity to assess algorithm performance across a range of variables and conditions. Despite the fact that the overall correlation between the FLH product and *in situ* chlorophyll-α measurements was about 8 times greater than that between OC3M (blue-green ratio) algorithm and *in situ* chlorophyll-α, it was still not useful.

Stray light contamination from the brighter, adjacent land pixels, may have contributed to the overall poor FLH-*in situ* relationships within Tampa Bay whose width is only ~16.5 km at its widest point. The impact of this adjacency effect over inland and coastal water pixels can be very strong in the NIR channels, for which water is very dark and land pixels normally present a high reflectance, and can even be noticed in visible channels under certain conditions (Odermatt *et al*. 2008). As a result, a significant portion of the recorded signal from the MODIS sensor can originate from outside the area represented by that pixel. In addition, artifacts introduced by the along-scan transition of AQUA from bright (land) to dark (ocean) pixels compromises the reflectance signal in coastal areas less than 5 km from the coast (Chuanmin Hu, pers. comm.).

It is important to mention that the 93 matchup pairs from sites at 5 km or more from shoreline and bridges (r^2 = 0.4) (Figure 3b) had bottom depths ≥ 3.2 m. As a matter of fact, the site with the second best relationship between the FLH product and *in situ* chlorophyll-α (HB7, r^2 = 0.64) (Figure 2b) was located ~1.3 km from the shoreline with an average bottom depth of 3.6 m. This good relationship was followed by r^2 = 0.49 in OTB68 (Figure 2c) and r^2 = 0.48 in MTB32 (Figure 2d) with ~1.5 and ~3 km from shore, respectively. Average bottom depths for both sites were respectively 4.8 and 7.5 m. This suggests that the timid improvement in the relationship achieved with increasing distance from shore may be also helped with increasing depth. Confirming both hypotheses (bottom depth and distance from shore), the best relationship (MTB14) was observed at > 5 km from shore and with a deep bottom of 7.4 m (Figure 2a). Remarkably, the three monitoring sites with the best relationships observed between the MODIS Aqua FLH product and *in situ* chlorophyll-α were also reported with the best relationships between the MODIS Terra surface reflectance product (MOD09GQ) and *in situ* water turbidity (Moreno-Madriñán et al, 2010). The coefficients of determination observed in that study were 0.86, 0.77 and 0.66 respectively for OTB68, MTB14 and HB7. The fact that each one of these monitoring sites is located in a different sub-region of the Bay, suggests the usefulness of using them in representation of their respective sub-region to monitor water quality with remote sensing.

To understand if the low relationships between FLH and chlorophyll-α could be explained by turbidity interfering with the FLH signal, a determination coefficient between the FLH product and water turbidity was computed for 417 available matchups. This resulted in an $r^2 = 0.06$, which does not seem to support turbidity as the determining factor for a low relationship between the FLH product and *in situ* chlorophyll-α. Lastly, given that the near polar, sun-synchronous orbit of the Aqua satellite crosses the equator at approximately 1:30 pm and since emission of chlorophyll-α fluorescence is depressed at noon (Falkowski and Kolber, 1995) roughly coinciding with the satellite time visit to Tampa Bay, this could be argued as a strong contributor to explain the low relationships found in most of the sites. The average *in situ* sampling time for the 507 matchup pairs with bottom depth ≥ 2.8 m was 12:33 pm. As mentioned earlier, this shorter range between *in situ* and satellite measurements was the criterion to choose Aqua as opposed to Terra. However, the average sampling time for the sites with the best observed relationship MTB14, HB7, OTB68 and MTB32, were respectively 11:14 am, 10:24 am, 1:51 pm and 11:10 am; only one of them closer to Aqua time visit as compared to Terra. Nevertheless, even in the case that the time of satellite visit could explain low relationships between FLH and *in situ* chlorophyll-α determinations, the question remains about why there are still few sites with good relationships. Good part of the answer to this question may come from undertaking similar study based on data generated by the MODIS sensor on Terra. It is important to mention, however, that 10:30 am would be still within the period of low FLH fluorescence signal and alternatively fluorescence measurements taken at night would require night *in situ* sampling for comparison.

6. Conclusions

Overall, these results line up with the lab and modeling studies suggesting that the FLH product may have difficulties to quantify *in situ* chlorophyll-α concentration and/or water quality for estuarine waters. Nevertheless, it is suggested a possible role played by the time of satellite visit to the sites. Although in a broad sense, and based solely on this Tampa Bay case and satellite visit time, these results are not favourable to recommend the use of MODIS FLH algorithm for the measurement of chlorophyll-α concentration in estuarine waters. Yet they show that in particular sites this product can draw good estimations, which exposes the need for further research addressing the factors that determine this difference between bad and good sites. An approach to use this product in estuarine waters would imply an initial period of *in situ* monitoring to identify sites with good determination coefficients. Once these sites are identified, a monitoring program with satellite technology could continue. This approach would allow temporal consistency in water quality monitoring, although would be deprived of consistent spatial distribution for analysis across larger areas of the estuary.

It can be reasonably deduced that improvements regarding spatial consistency can be made when simultaneously considering certain conditions like distance between monitoring sites and shore along with bottom depth. The low but still better relationship between *in situ* chlorophyll-α and the FLH product as compared with the blue-green ratio OC3M, confirms possibilities for continuing search for improvements using the fluorescence signal and the NIR section of the spectrum to estimate chlorophyll-α in estuarine waters. It would be valuable to perform a similar study using the data generated from MODIS Terra, given the earlier daily time visit of the Terra satellite, thus avoiding the fluorescence emissivity depression of chlorophyll-α at midday.

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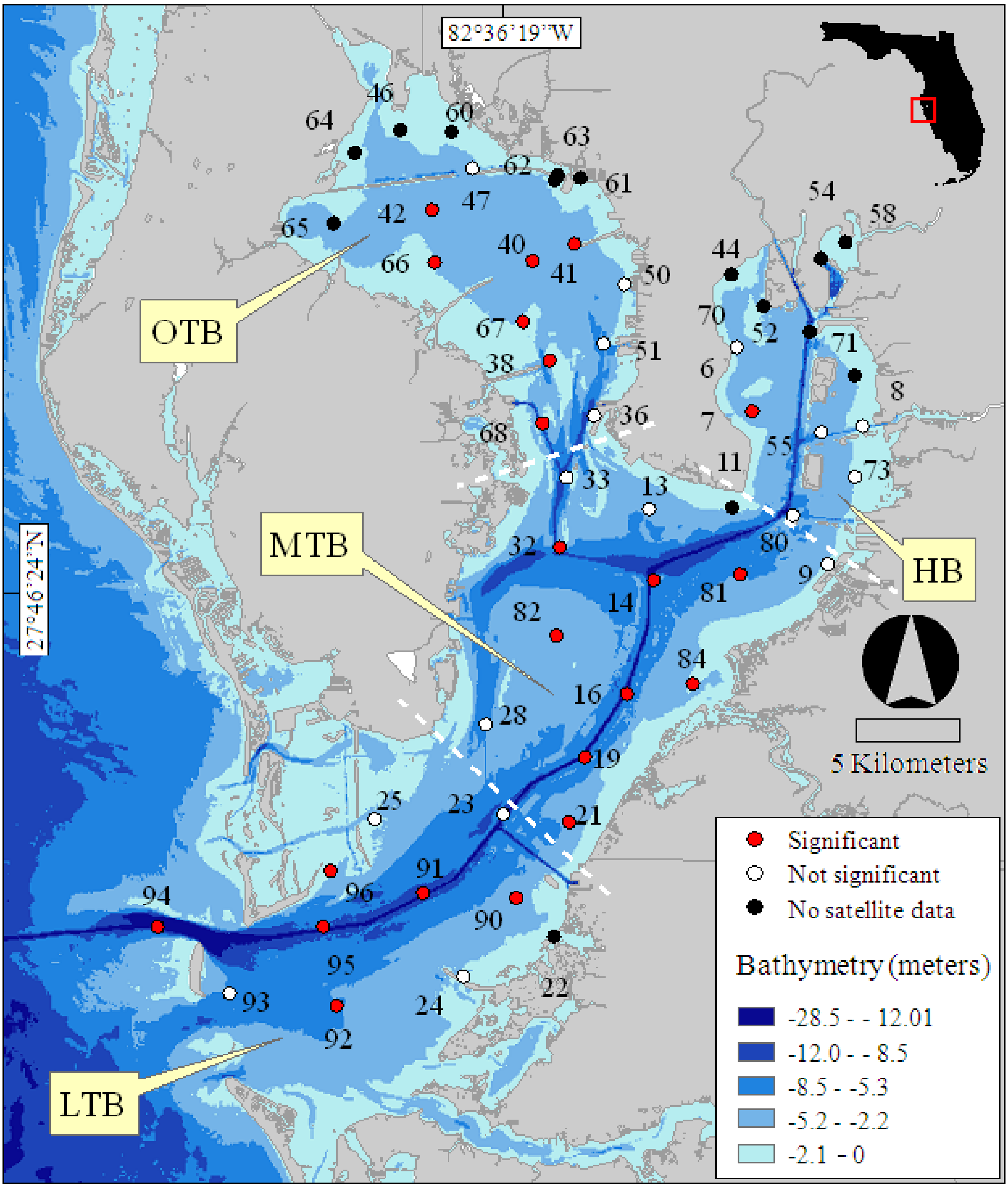

Figure 1. Map of Tampa Bay, U.S.A., showing the 54 sites monitored by the Environmental Protection Commission of Hillsborough County (EPCEC) used in this study, the four main sub-regions of the bay and an inset showing the location of this estuary in the state of Florida. The sub-regions are Old Tampa Bay (OTB), Hillsborough Bay (HB), Middle Tampa Bay (MTB), and Lower Tampa Bay (LTB). Monitoring sites marked in red (22 sites) were those having a statistical significant relationship between satellite data (FLH) and *in situ* chlorophyll-α ($p \leq 0.05$). Sites marked in white (17 sites) either had not significant relationships between satellite data and chlorophyll-α ($p >$ 0.05, 13 sites) or did not present match ups between both parameters (4 sites). Those sites marked in black denote those for which no satellite data was obtained (15 sites).

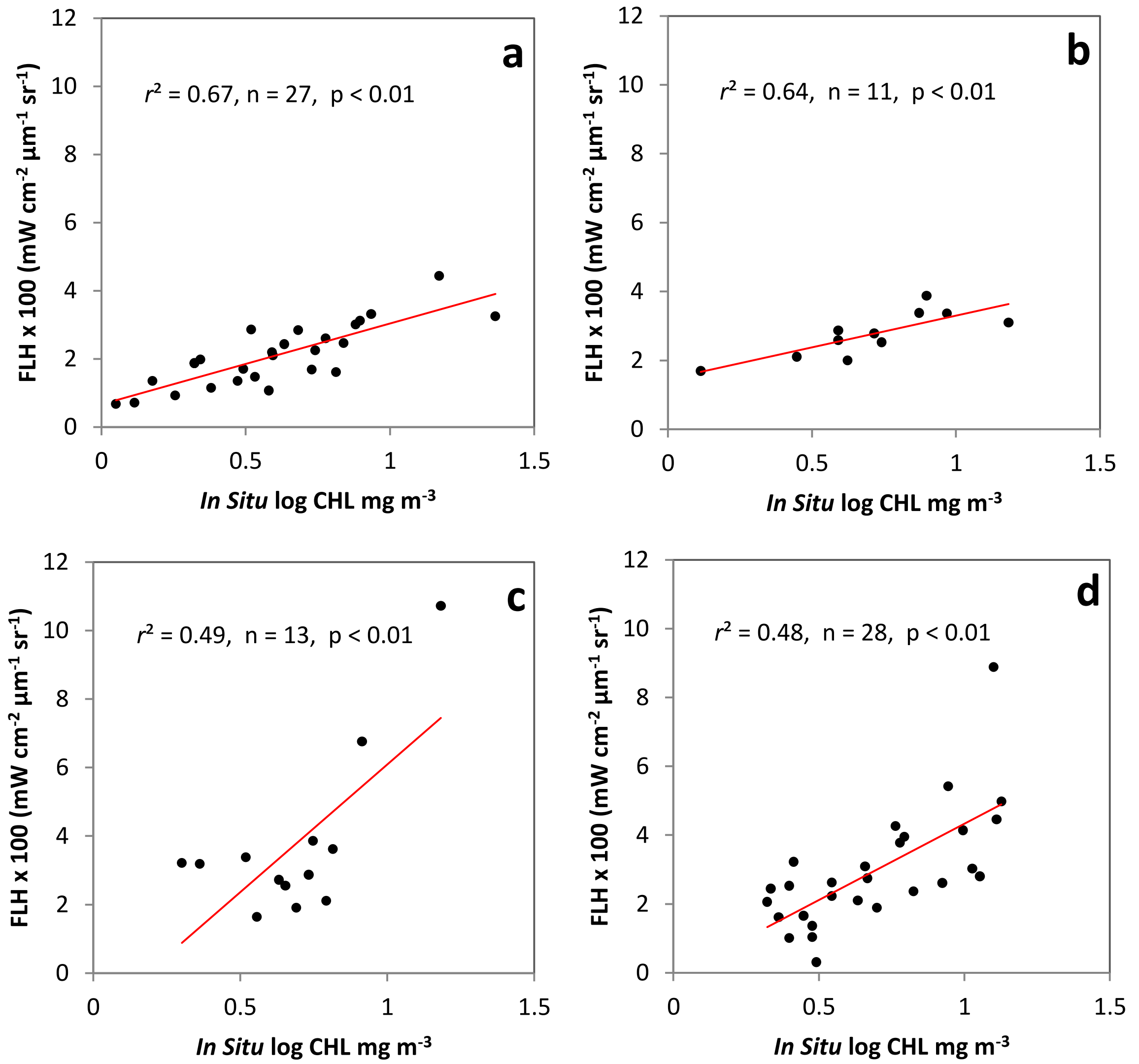

Figure 2. Relationship between *in situ* log chlorophyll-α and satellite based FLH measurements for monitoring sites: (a) MTB14, (b) HB7, (c) OTB68, and (d) MTB32.

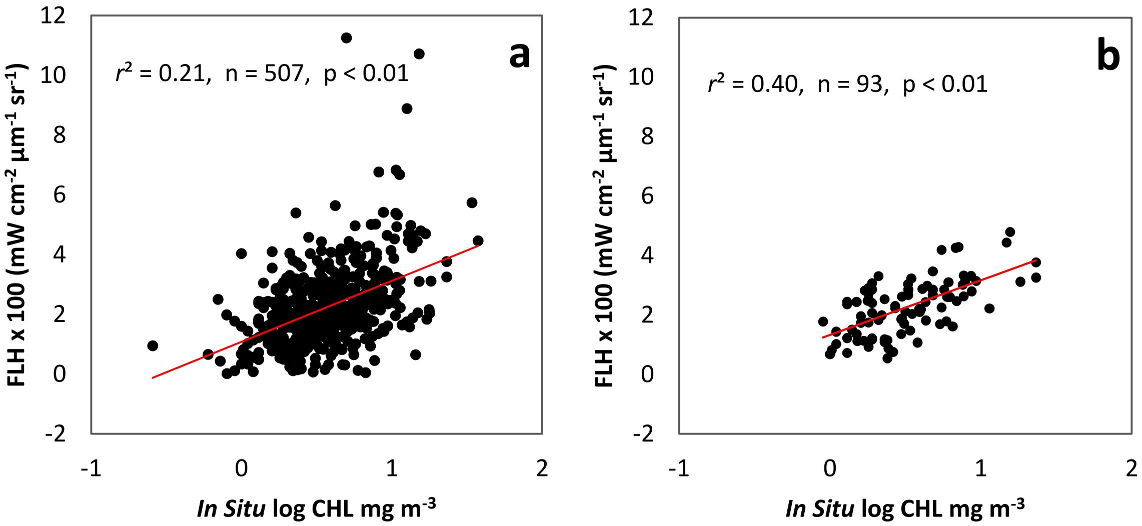

Figure 3. Overall relationship between *in situ* log chlorophyll-α and satellite based FLH measurements for all available *in situ* sampling sites according to the following criteria: (a) all matchup pairs associated to a bottom depth ≥2.8 m and (b) all matchup pairs from sites located ≥ 5 km from shore and bridges and associated bottom depth ≥ 3.2 m.

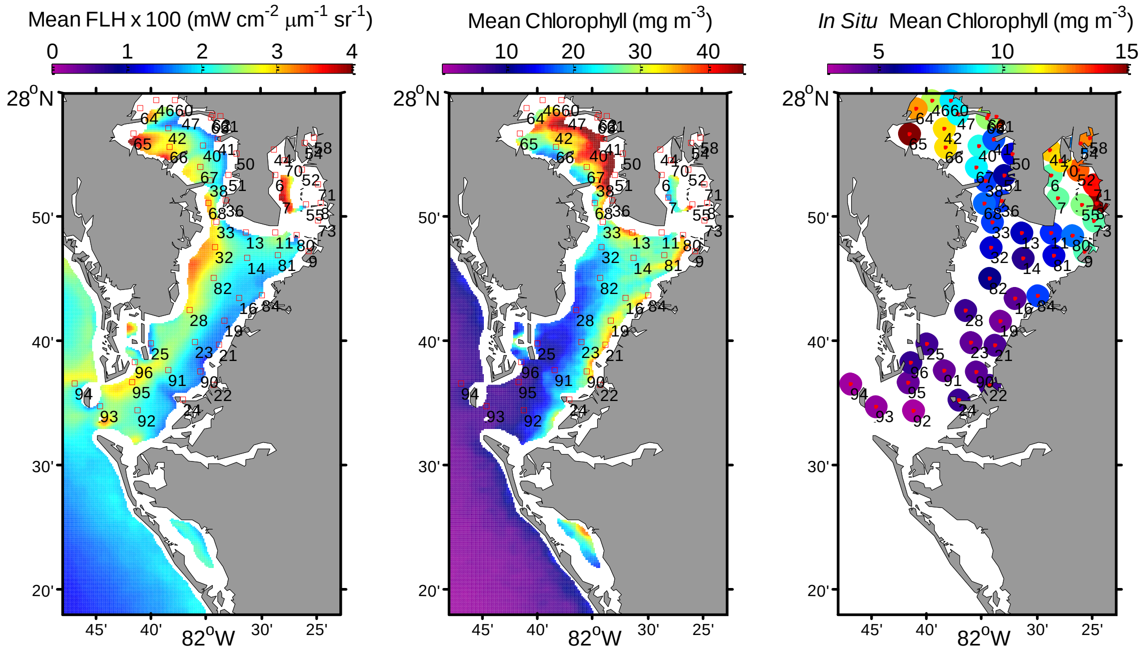

Figure 4. The long term mean FLH (left) and chlorophyll (OC3M) (middle) MODIS products from 2003-2010 in Tampa Bay, Florida (USA), along with mean log-chlorophyll (right) for individual *in situ* sampling sites for the same time period. The red squares or dots indicate the *in situ* sampling sites with the associated sites numbers.

Table 1. Summary of determination coefficients (r^2) between the MODIS FLH and OC3M products x *in situ* chlorophyll-α concentrations, average site depth and distance from shore, sorted by decreasing correlation between FLH x chlorophyll-α, for the 35 sampling sites with matchup data in Tampa Bay, Florida (USA) throughout the sampling period (2003-2010), *n* = matchup pairs, * P<0.05, ** P<0.01, † = inverse correlation.

Sampling Site	**Depth (m)**	**Distance to shore or bridge (m)**	r^2 **(FLH x chl-α)**	***n***	r^2 ***(OC3M x chl-*α)**	*n*
MTB14	7.4	5600	0.67**	28	0.01	26
HB7	3.5	1180	0.64*	11	0.36†	9
HB55	5.3	1130	0.57	3	0.47†	4
OTB68	4.8	1530	0.49**	13	0.28†	11
MTB32	7.5	3000	0.48**	28	0	28
LTB96	2.3	624	0.46*†	12	0.15	15
OTB40	4.8	72	0.44**	28	0	24
OTB41	3.5	110	0.43**	15	0.24	12
OTB67	2.5	72	0.42**	26	0	25
OTB38	2.3	590	0.40**	23	0.03	25
MTB81	7.5	3520	0.38**	23	0.27*	21
MTB82	3.8	5130	0.37**	34	0.08	32
LTB21	4.9	1765	0.35*	16	0	18
MTB19	7.8	2800	0.34*	21	N/A	0
LTB92	5.8	5080	0.34**	32	0.06	38
LTB90	4.4	1860	0.31*	16	0	21
MTB84	1.8	1150	0.29*	15	0.05	13
MTB16	*7.5*	2800	0.29**	28	0.01	27
LTB94	3.6	800	0.28*	38	0.14*	41
LTB95	8.2	1890	0.26*	25	0.52	25
OTB42	3.4	1638	0.26*	18	N/A	0
OTB36	5.5	100	0.24	5	0	8
LTB91	9.1	4290	0.23*	33	0.19*	34
OTB66	2.6	2010	0.23*	25	0.04	23
OTB51	4.8	112	0.06	11	0	9
LTB93	5.8	1208	0.06	7	0.32	10
MTB13	4.0	2100	0.04	7	0.24	7
MTB33	8.4	2130	0.03	9	0.39	6
LTB23	9.0	3900	0.01	29	0.08	32
LTB25	2.4	915	0.01	7	0	7
MTB28	3.5	2990	0.00	16	0	17
HB73	2.3	1800	N/A	2	0.29†	4
HB80	3.5	142	N/A	1	0.01	3
OTB47	4.40	187	N/A	1	N/A	0
HB6	2.2	312	N/A	1	N/A	0

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