Monitoring Annual and Seasonal Variability of Dinoflagellate Blooms in Monterey Bay, California (USA) with the Moderate Resolution Imaging Spectrometer

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Abstract - Dinoflagellate blooms in Monterey Bay, California (USA) have recently increased in frequency and intensity. Six years of satellite imagery from the Moderate Resolution Imaging Spectrometer (MODIS) is used to describe the annual and seasonal variability of bloom activity within the Bay. Three classes of MODIS algorithms were correlated against in situ chlorophyll measurements. The FLH algorithm provided the most robust estimate of bloom activity. Elevated concentrations of phytoplankton were evident during the months of August-November, a period during which increased occurrences of dinoflagellate blooms have been observed in situ. Seasonal patterns of FLH show the on- and offshore movement of areas of high phytoplankton biomass between oceanographic seasons. Higher concentrations of phytoplankton are also evident in the vicinity of the land-based nutrient sources and outflows, and the cyclonic bay-wide circulation can transport these nutrients to the northern Bay bloom incubation region.

Keywords: algal blooms, MODIS, FLH, nutrients, transport

1. INTRODUCTION

Recent advances in satellite and airborne remote sensing, such as improvements in sensor and algorithm calibrations, processing techniques (Franz et al., 2006) and atmospheric correction procedures (Wang and Shi, 2007) have provided for increased coverage of remote-sensing, ocean-color products for coastal regions. This has opened the way for studying ocean phenomena and processes at finer spatial scale, such as the interactions at the land-sea interface (Warrick et al., 2007), and coastal ocean processes and red tides (Ryan et al., 2005; Ryan et al., 2008; and Ryan et al., 2009). In addition, human population growth and changes in coastal management practices have brought about significant changes in the concentrations of organic and inorganic, particulate and dissolved substances entering the coastal ocean. There is increasing concern that these inputs have the potential to increase local concentration of phytoplankton and cause harmful algal blooms (Epply et al., 1979; Anderson et al., 2002; Spatharis et al., 2007). It is important to utilize these new procedures to characterize the increase of algal blooms that have been documented in coastal waters (Hallegraef et al., 2003) and in upwelling areas throughout the world (Kahru and Mitchell, 2008).

The phenomena of dinoflagellate blooms in Monterey Bay appear to have increased in frequency and intensity over the last five years. Jester et al., 2008 noted a shift in dinoflagellate abundance in Monterey Bay beginning in 2002, with the relative proportion of dinoflagellates out numbering other functional groups. Improved techniques of satellite and airborne remote sensing have been used to describe these phenomena and how coastal processes have influenced the development, spread and retention of these blooms. Using airborne hyperspectral imagery, Ryan et al., (2005) illustrated the development of dense aggregations of dinoflagellates in water mass and internal wave frontal zones. Ryan, et al. (2008) used snapshots from various hyperspectral airborne sensors, along with images from the Medium Resolution Imaging Spectrometer (MERIS) to illustrate synoptic patterns of "extreme blooms" within the upwelling shadow of Monterey Bay (MB) and identified a bloom incubation region within the northern waters of MB. Ryan et al. (2009) examined how the bay's bloom incubation area interacts with highly variable circulation to cause red-tide spreading, dispersal and retention. This examination used multiple remote-sensing and in situ data sets, including snapshots or daily images from the Moderate Resolution Imaging Spectrometer (MODIS). In these studies satellite imagery was mainly used to provide snapshots to describing red tide processes.

Another important element is to develop an understanding of statistically significant, long-term patterns of phytoplankton abundance and potential variability of bloom activity in the bay. No published reports have examined the applicability of MODIS for looking at variability of seasonal annual patterns of abundance and bloom activity in MB, and a limited number of studies have been published on the interpretation of satellite ocean-color imagery and the applicability of currently used satellite algorithms for the coastal waters of MB. Much of the work has focused on offshore in studies of the California Current system (Kudela and Chavez, 2000). The aim of this study is to compare the performance of various standard MODIS chlorophyll algorithms (OC3M, Carder and FLH) for the applicability of studying longer-term (seasonal and annual) variability of dinoflagellate blooms in Monterey Bay, California (USA).

2. METHODS

Six years (2002–2007) of daily MODIS L1A data were downloaded from the L1 and Atmospheric Archive Distribution System (LAADS Web) at the Goddard Space Flight Center. The MODIS data were processed from Level 1A using the SeaDAS software, by applying calibrations for ocean remote sensing developed by the MODIS Ocean Biology Processing Group (Franz et al., 2006). Of the over 3050 files downloaded from the LAADSweb and processed to level 1A, only 1369 contained coverage and contained some cloud free areas in the search area. Of the 1369 files, and 673 files or 49% were deleted due to scene contamination by cloud edges or severe distortion by extreme sensor scan angles. The remaining 696 images were processed to mapped Level 3 chlorophyll *a* and chlorophyll fluorescence products. For the atmospheric correction required to derive products (FLH, chlorophyll), we computed true 250-m aerosol retrievals, extrapolated to the visible from the 859 nm band using a fixed aerosol model (maritime 90%). Resulting image data were mapped to a cylindrical projection. The true resolution of FLH, chlorophyll 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 from low scan angle were removed from the analysis.

Ground truth measurements of chlorophyll concentrations were used to assess the accuracy of the MODIS algorithms. The Biological Oceanography group at the Monterey Bay Aquarium Research Institute has been taking extracted chlorophyll measurements at three time-series stations in MB and adjacent waters from 1989-present. Time series cruises occurred at approximately 21 days intervals. Chl a and phaeopigments were determined by the fluorometric technique using a Turner Designs Model 10-005 R fluorometer that was calibrated with commercial chl a (Sigma). Samples for determination of plant pigments were filtered onto 25-mm Whatman GF/F glass fiber filters and extracted in 90% acetone in a freezer between 24 and 30 hours. Other than the modification of the extraction procedure, the method used is the conventional fluorometric procedure of Holm-Hansen et al. (1965). Two other data sets were used to increase the number of in situ measurements in the Bay, those from the Center for Integrated Marine Technologies (CIMT) shipboard data (http://cimt.ucsc.edu) and those from Coastal Ocean Applications and Science Team (COAST) field surveys of 2006. Chlorophyll a values in these data sets were determined by the same techniques as above.

Satellite/in situ matchups were constrained to maximum 3-hour time offset. Pearson's correlation coefficients between the predictor variables (satellite algorithm) and the single common dependent variable (in situ) were computed. A test of heterogeneity among all coefficients and a confidence interval test for comparing each possible pair (FLH-OC3M, FLH-Carder, OC3M-Carder) of correlations were also conducted (Meng et al, 1992). The Fisher z transformation was applied to the correlation coefficients prior to testing to improve the normality of the correlation coefficients (Fisher, 1915). Long-term (2002-2007), annual and seasonal (oceanic, upwelling and winter) averages of daily imagery were produced for each product.

To examine forcing processes influencing the observed patterns, annual spatial means of MODIS products for MB were then compared to upwelling indices, land-based nutrient measurements and cumulative wind stress. On a monthly basis, the Pacific Fisheries Environmental Laboratory generates indices of the intensity of large-scale, wind-induced coastal upwelling at 15 standard locations along the west coast of North America. The indices are based on estimates of offshore Ekman transport driven by geostrophic wind stress. Geostrophic winds are derived from six-hourly synoptic and monthly mean surface atmospheric pressure fields. The pressure fields are provided by the U.S. Navy Fleet Numerical Meteorological and Oceanographic Center (FNMOC), Monterey, CA. Average annual and seasonal averages were calculated for 2002-2007. Land-based nutrient measurements are based on averaged measurements taken by the LOBO L01 mooring in the main channel of the Elkhorn Slough. Nitrate was measured by an in situ ultraviolet spectrophotometer (ISUS, Johnson and Coletti, 2002)). Hourly nitrate data of surface waters (0.5 m) were downloaded from the LOBO Network Data Visualization (LOBOViz 3.0) (http://www.mbari.org/lobo/loboviz.htm) website. Data processed from these stations spanned the years 2003-2007. Annual seasonal averages were calculated from these data. Cumulative wind stress was calculated by summing the square of the V component of wind stress. Wind stress data were downloaded from the MBARI live access server (http://dods.mbari.org/lasOASIS/main.pl?)

3. RESULTS

Due to varying sensor algorithm thresholds and quality flags, the number of extractive in situ chla points that matched with satellite coverage varied. Overall, the in situ chl a values ranged from 0.62 to 100.9 mg m^{-3} and the means of in situ measurements between the different algorithms were within a comparable range, 5.3, 5.2 and 6.5 mg m^{-3} for the corresponding matching points as determined by the FLH, OC3M and Carder algorithms. The correlation is higher between FLH and in situ chl a than either the OC3M and Carder algorithms (r = 0.71, n = 43, Chl = 180*FLH-0.77) (Figure 1).
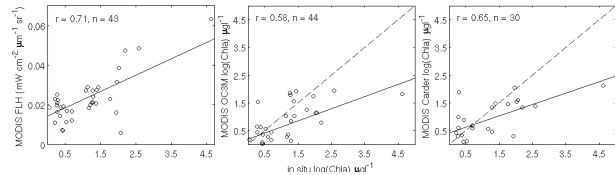

Figure 1. The relationships between FLH (left) OC3M chl a (middle) and Carder chl a (right) and log in situ chl a concentration. The best-fit line (solid) and the 1:1 line (dashed) are superposed.

However, tests of the equality of the correlation matrices indicate that the correlations are not significantly different. The first test compares correlations between two or more predictor variables (FLH, OC3M and Carder) with a common dependent variable (in situ). The matchups were first reduced to similar sample sizes, including only those satellite/in situ pairs which matched between sets. In the reduced data set, correlations were relatively similar as the full datasets (r = .71, r = .61 and r = .65 for FHL, CHL and Carder, respectively , n = 30, p>0.5). Meng et al., (1992) derivation of Hotelling's t-test to compare individual pairs correlations coefficients which have a single common dependent variable was then applied. The correlation coefficients did not differ significantly (p > 0.5).

The seasonal patterns of chl a concentration in MB were averaged across the oceanic, upwelling and winter oceanographic seasons (Pennington and Chavez, 2000) All products generally suggest that the highest concentrations of chl a and fluorescence occur during the oceanic period (August-November), with the upwelling period (March- July) being the next most productive season. The lowest concentration of chl a and fluorescence signal occurs during the winter (December - February). Both the OC3m and Carder chl a algorithms show similar spatial patterns, a shoreward increase of chl a concentrations with the overall algal abundance decreasing intensity between oceanic, upwelling and winter seasons. The Carder algorithm has a lower overall mean than the OC3M algorithm.

The seasonal FLH signal suggests a different spatial pattern than those illustrated by the chla products and appears to represent a more robust characterization of bloom activity. The rest of the analysis focuses on the FLH algorithm. In the oceanic season composite the highest FLH signal appears in the northern Bay and as a small patch in the southern Bay (Figure 2). A line of high FLH signal extends from a neashore region of the mid-Bay to the northwest corner of the Bay near Santa Cruz. This patch of high fluorescence, which appears relatively close to shore during the oceanic period moves offshore in the
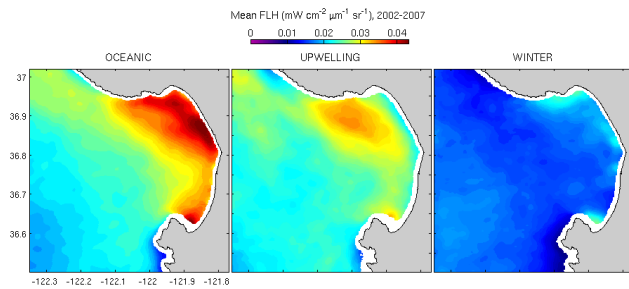
Mean FLH (mW cm⁻² μm⁻¹ sr⁻¹), 2002-2007

OCEANIC   UPWELLING   WINTER

Figure 2. Seasonal (oceanic, upwelling and winter) patterns of Fluorescence Line Height means 2002-2007.

upwelling season composite. The winter months are characterized by a low FLH signal.

The interannual signal of FLH during the oceanic period appears in Figure 3. The oceanic season is also a period of interest due to the recent proliferation of dinoflagellate blooms in Monterey Bay (Jester, 2009). Generally, during the oceanic period between the years 2002-2007, the highest FLH signal occurs in the northern Bay, with evidence of a small patch of high FLH in the pocket of the southern Bay. The highest Bay-wide signal occurred in 2002 and 2007. In 2002, 2006 and 2007, a high FLH signal appeared in the middle of the Bay near the mouths of the Elkhorn Slough and the Pajaro Rivers. This patch appears to extend in a northwesterly direction. In 2002 and 2003, the patch of high FLH extended from the mid-Bay past Santa Cruz with evidence of some of the signal being exported from the Bay. Both in 2004, 2006 and 2007, the mean signal does not extend past the northwestern most corner of the Bay, suggesting retention of algal biomass during those years. Overall, there was a very low signal throughout the entire Bay in 2003 and 2005.
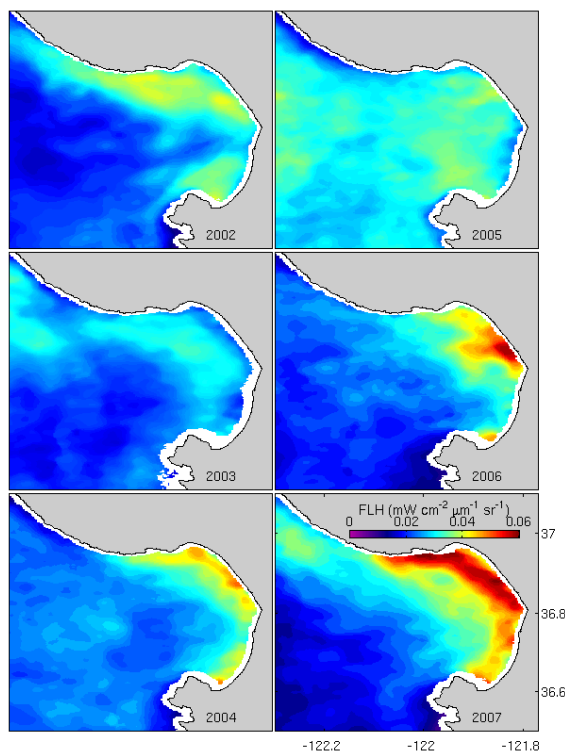

Figure 3: Interannual variability of phytoplankton fluorescence as measured by the MODIS FLH algorithm during the oceanic period (August-November) for Monterey Bay.

In an effort to understand what drives the interannual patterns of variability we examined relevant environmental variables that are commonly monitored in Monterey Bay and Elkhorn Slough against the mean FLH signal within a box drawn around the outer limits of the Bay (Figure 4). The lowest oceanic period upwelling index which occurs in 2004, did not match up with
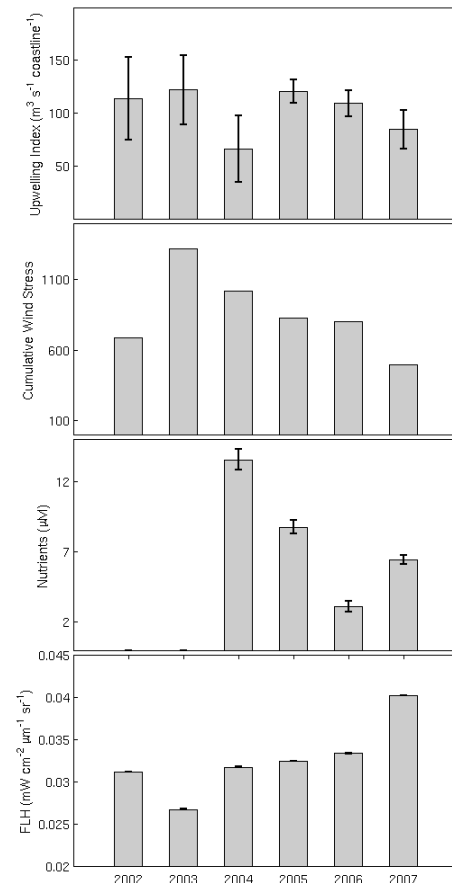

Figure 4. Annual oceanographic season means of environmental variables used to describe oceanographic phenomena in Monterey Bay. Mean upwelling index (top), cumulative wind stress at the M1 mooring (middle top), nitrate at the Elkhorn slough L01 mooring (middle bottom) and mean FLH derived from MODIS satellite imagery bottom).

the lowest bay-wide FLH signal, but it did coincide with the retention pattern of the FHL signal in the northern Bay. Consequently, the next lowest mean upwelling index, which occurs in 2007, shows a similar retention pattern but a much higher bay wide FLH signal. Cumulative wind stress during the oceanic period was highest in 2003 and 2004 and generally related to a low mean FLH signal. The bay-wide spatial patterns in 2003 and 2004 were characteristic of both the export and retention spatial patterns. Nutrient monitoring in the Elkhorn Slough, the main land-sea connection in Monterey Bay has only been in operation since 2004. The highest mean nutrient level during the oceanic period taken at the L01 mooring occurred in 2004 and decreased to > 7 mM in 2005 and ~ 3 mM in 2006. The mean concentration then increased in 2007 back up to < 7 mM. The mean Bay-wide FLH signal did does not seem to match clearly with mean concentrations of nitrate measured at L01; however, the spatial pattern of FLH, especially in 2002, but also in 2006 and 2007, suggest a link between the mid-Bay, in the vicinity of the Elkhorn Slough, and transport in a northwesterly direction to the northern Bay. Representative drifter tracks, which mark the surface transport

of outflow from the vicinity of the mouth of the Elkhorn Slough and the Pajaro River, indicate the highest signal of FLH during the oceanic period in the wake of these land-based sources of input (Figure 5).
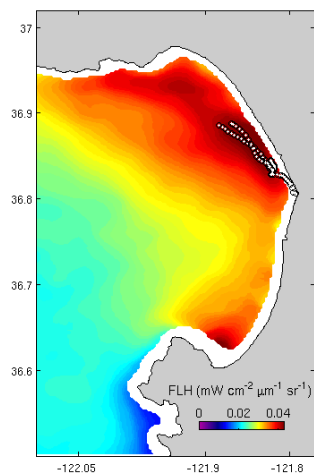

Figure 5. Mean oceanographic season FLH signal between 2002-2006 with drifter track, deployed at the Elkhorn Slough and Pajaro Rive mouths superimposed. The drifter tracks follow the highest FLH signal representing the highest phytoplankton abundance.

4. CONCLUSIONS

The purpose of this paper was to evaluate the use of MODIS Aqua imagery and in situ chlorophyll matchup data to understand which type of algorithm might serve as a better measure of algal blooms and thus serve as a more useful descriptor of seasonal and annual changes in bloom patterns throughout the Bay. Based on the results of in situ match ups with satellite data, it appears that FLH may provide a better estimate of bloom patterns for the surface waters of Monterey Bay than provided by the OC3M and Carder algorithms. However, the mean spatial patterns produced by three algorithms varied greatly and FLH means suggest more reasonable patterns in bloom dynamics and illustrate some of the coastal ocean dynamics that have been observed in Monterey Bay. (Moita et al., 2003; Ryan et al., 2008; Rosenfeld, 1994; VanderWoude et al., 2006; Roughan et al., 2006).

Seasonal patterns of FLH show the on- and offshore movement of areas of high phytoplankton biomass between the oceanic and upwelling seasons. This suggests an increase cyclonic circulation throughout the Bay during the upwelling period causing phytoplankton to aggregate alongside the upwelling fronts which sweep from the north, near Point Ano Nuevo, across the mouth of the Bay (Rosenfeld, 1994). During the oceanic period, when wind relaxation events are more common and upwelling intensity deceases, reduced cyclonic circulation allow this patch of high biomass to remain closer to the nearshore regions. A closer examination of the spatial patterns during the oceanographic period suggests the presence of land-sea linkages. Studies of a dinoflagellate blooms in Monterey Bay during the 2007 oceanic period indicated bloom inception where rain-induced flushing or agricultural lands entered the coastal ocean (Ryan, unpublished data).

It is difficult to understand whether any of the measured variables, upwelling index, cumulative wind stress or land-based nutrients directly contribute or are responsible for the observed patterns bloom activity are due to the limited time series which is currently available from MODIS. However, MODIS is one of the few sensors which has the appropriate channel to measure this fluorescence response and therefore capable of making this comparison.

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