



## A coastal ocean extreme bloom incubator

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[1] Novel remote sensing methods and in situ observations reveal that intense dinoflagellate blooms occur frequently in Monterey Bay, California. Blooms can contain surface chlorophyll concentrations exceeding  $500 \mu\text{g l}^{-1}$  and occupy  $\sim 5$  to  $80 \text{ km}^2$ . They occur primarily during August through November and can persist for  $> 1$  month. Maximum bloom frequency and mean intensity are in a shallow ( $< 25 \text{ m}$  depth) area of the northeastern bay, in coincidence with the warmest surface water, low wind stress, and retentive circulation. These conditions favor dinoflagellates, which can vertically migrate to acquire nutrients in the thermocline and aggregate as "red tide" near the surface. Bloom incubation areas, also indicated in other coastal upwelling systems, may disproportionately influence regional bloom ecology. **Citation:** Ryan, J. P., J. F. R. Gower, S. A. King, W. P. Bissett, A. M. Fischer, R. M. Kudela, Z. Kolber, F. Mazzillo, E. V. Rienecker, and F. P. Chavez (2008), A coastal ocean extreme bloom incubator, *Geophys. Res. Lett.*, 35, L12602, doi:10.1029/2008GL034081.

### 1. Introduction

[2] Dense accumulations of phytoplankton that imbue the surface ocean with reddish color, commonly called "red tides", are one type of extreme bloom that can negatively affect ecosystems and human health [Anderson, 1995; Glibert *et al.*, 2005; Kudela *et al.*, 2005]. Increasing global occurrence of harmful algal blooms (HABs) motivates improved understanding of natural and human influences on bloom location, frequency and severity [Hallegraeff, 2003]. Approximately 50% of all red tide forming species and 75% of all HAB species are dinoflagellates [Sournia, 1995; Smayda, 1997]. Where phytoplankton growth is limited by low surface nutrient concentrations, and stratification impedes renewal of surface nutrients by turbulent vertical mixing, dinoflagellate motility provides a competitive advantage because their populations can migrate downward at night to acquire nutrients [Cullen and Horrigan, 1981; Heaney and Eppley, 1981]. When these populations migrate up to the surface for photosynthesis during the day, their dense aggregations produce strong bio-optical signals that are detectable by satellite and airborne remote sensing.

[3] Studies have documented intense dinoflagellate red tide blooms in Monterey Bay (MB), including species known to cause harm [Ryan *et al.*, 2005; Donaghay *et al.*, 2006; Kudela *et al.*, 2008; Curtiss *et al.*, 2008; J. P. Ryan *et al.*, Influences of upwelling and downwelling winds on red tide bloom dynamics in Monterey Bay, California, submitted to *Continental Shelf Research*, 2008]. Here we apply unprecedented time-series of remote sensing and in situ data to identify and describe an "extreme bloom incubator" in an area of MB, and to examine conditions and processes underlying this phenomenon.

### 2. Data and Methods of Analysis

[4] Quantifying extreme bloom intensity and distributions using remote sensing requires measurement of the near-infrared (NIR) peak in upwelling radiance caused by such blooms [Gower *et al.*, 2005; Dierssen *et al.*, 2006]. Only one multi-spectral satellite sensor, MERIS (Medium Resolution Imaging Spectrometer), has been designed to measure NIR signal for computation of an extreme bloom index, termed the Maximum Chlorophyll Index (MCI) [Gower *et al.*, 2005; Gower and King, 2007]. We apply MCI images to illustrate synoptic bloom patterns and compute long-term statistics. The MCI image archive was screened to eliminate images having questionable signal (near cloud edges, steep view angles), producing 75 good images from August through November of 2002–2007. Of these images, 31 were full resolution (300 m), and 44 were reduced resolution (1200 m).

[5] Defining blooms as  $\text{MCI} > 0.3$ , corresponding to chlorophyll exceeding  $\sim 75 \mu\text{g l}^{-1}$  (unpublished results from model described by Gower *et al.* [2005]), we computed indices of bloom probability (detection frequency) and mean intensity. Maps of bloom statistics were constrained to well sampled pixels (at least 80% of the maximum possible sample count). Illustration of average bloom intensity was constrained to pixels for which a representative mean could be calculated (bloom frequency at least 25% of the maximum frequency).

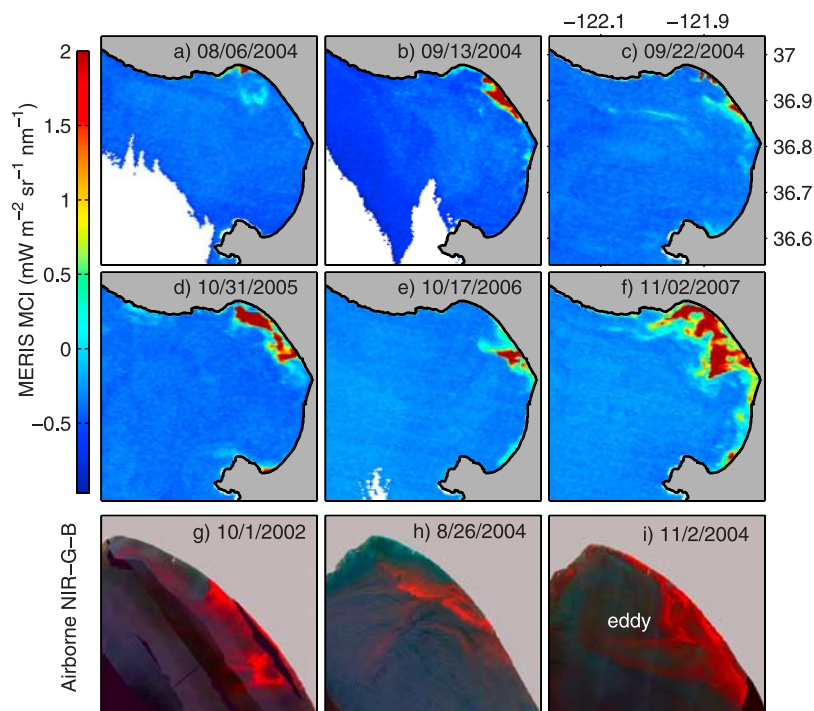
[6] To examine MCI statistics relative to oceanographic and meteorological conditions, we computed mean sea surface temperature (SST) and surface wind stress. SST images were from the MODIS (Moderate Resolution Imaging Spectroradiometer) satellite sensor for August through November of 2002–2007; details of MODIS image processing are in work by Ryan *et al.* [2008, submitted manuscript, 2008]. Surface wind stress data was from the COAMPS (Coupled Ocean/Atmosphere Mesoscale Prediction System) high-resolution (3-km, 12-hour) model of central California for August through November 2006.

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**Figure 1.** Remote sensing images of extreme blooms in Monterey Bay, California. In all images, red color indicates extreme “red tide” bloom patches. (a–f) Full-resolution (300 m) images of the Maximum Chlorophyll Index (MCI) from MERIS. (g–i) NIR-G-B composite images from hyperspectral airborne remote sensing of the NE bay. Figures 1g and 1i are from PHILLS (2 m resolution); Figure 1h is from AVIRIS (17 m resolution).

[7] Hyperspectral imaging spectrometers effectively measure the NIR reflectance peak of extreme blooms. We present NIR-G-B composite images from the AVIRIS (Airborne Visible-Infrared Imaging Spectroradiometer) and PHILLS (Portable Hyperspectral Imager for Low Light Spectroscopy) sensors, using channels centered at {711, 549, 462} and {708, 540, 458} nm, respectively. Details of the sensors and data processing are in work by *Davis et al.* [2002] and *Ryan et al.* [2005].

[8] To describe water column structure in the bloom environment, we analyzed vertical sections mapped by an autonomous underwater vehicle (AUV) between the inner shelf region of extreme bloom development and outer MB. Details of AUV sensors and sampling are in work by *Ryan et al.* [2008, submitted manuscript, 2008]. From 21 surveys during August through November of 2003–2007, we computed mean hydrographic sections. Valid means were constrained to well-sampled grid points (> 80% of maximum possible sample count).

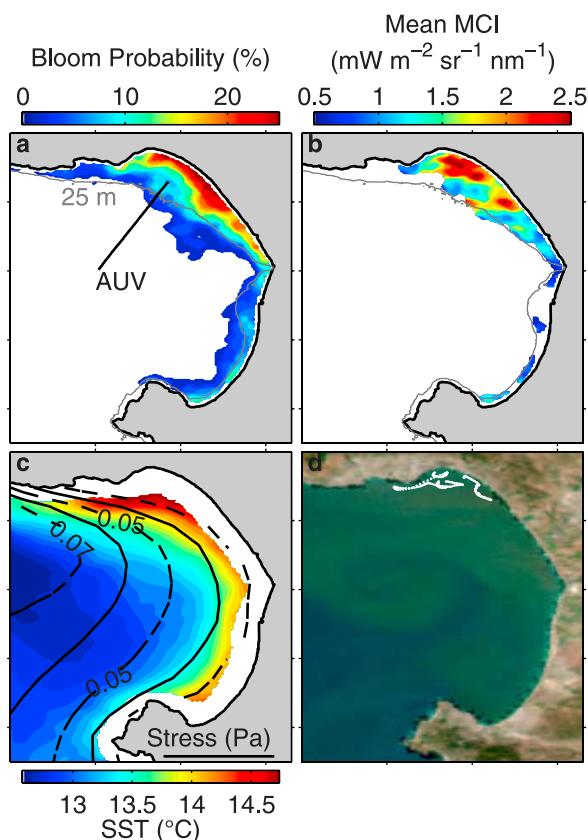
[9] During September 2007 the bloom environment was intensively studied. To track the movement of shallow waters in which dinoflagellates aggregate, we deployed satellite-tracked drifters drogued between 1 and 2 m depth. To map small-scale variability in the bloom region, we surveyed with a flow-through mapping system drawing water from 2 m depth and measuring temperature and salinity (SeaBird 45 thermosalinograph), chlorophyll fluorescence and the maximum quantum yield [*Kolber et al.*, 1998]. Phytoplankton samples included surface whole-water samples, preserved in 1% glutaraldehyde, and concentrated surface net tows (35  $\mu\text{m}$  mesh), preserved in 4% formaldehyde; samples were kept in the dark at 4°C. Whole

water samples were filtered through 5  $\mu\text{m}$  polycarbonate black filters and DAPI stained. Filters were mounted on slides with immersion oil, and cell identification and counts were performed using epifluorescence microscopy. Relative abundances of species were also estimated from net tow samples.

### 3. Results

[10] Shown in Figure 1 are images of extreme blooms in MB. The MCI images (Figures 1a–1f) show bloom scales from  $\sim 5 \text{ km}^2$  (Figure 1c) up to  $\sim 80 \text{ km}^2$  (Figure 1f). Extracted surface chlorophyll concentrations measured during blooms in 2006 (Figure 1e) and 2007 (Figure 1f) exceeded  $500 \mu\text{g l}^{-1}$ . The full MCI archive shows that extreme blooms are limited primarily to the annual period of August through November. The large 2007 bloom (Figure 1f) persisted from early October to mid-November. These examples, as well as the full archive, exhibit a preponderance of extreme blooms in the northeastern bay. High-resolution airborne imaging spectrometry emphasizes the patchiness of extreme blooms (Figures 1g–1i) and illustrates small-scale physical processes influencing bloom distributions (e.g. eddy in Figure 1i).

[11] Indices of extreme bloom probability and mean intensity show the prevalence of intense blooms in the NE bay, in waters shallower than 25 m (Figures 2a and 2b). Except for a thin border along the coast, the entire bay was well sampled, so most of the bay is accurately described by low to zero probability of extreme bloom detection. The NE bay, where bloom probability and mean intensity are high-



**Figure 2.** Bloom statistics and relevant oceanic and atmospheric conditions. (a) bloom probability (detection frequency); (b) mean bloom intensity; (c) sea surface temperature (SST) and wind stress; (d) retention of red tide shown with 9/25/2007 MODIS true color image and 9/25 to 9/28 2007 drifter tracks (white dots). AUV transect (Figure 2a) data are in Figure 3.

est, exhibits the warmest mean SST and minimum average wind stress (Figure 2c).

[12] In the area of highest mean MCI (Figure 2b), drifter studies demonstrated retention of a bloom. On September 25, 2007, remote sensing and in situ observation showed the presence of an intense surface bloom in the NE bay (reddish color in Figure 2d). Drifters released within the bloom remained in the same area for 3 days (Figure 2d). In contrast, MODIS images indicated that nearshore waters of the northern bay, south of where the drifters showed retention, were entrained out of the bay by an eddy (Figure 2d and concurrent SST and chlorophyll fluorescence line height which are not presented).

[13] The increases in bloom probability and mean intensity toward the coast (Figure 3a) correspond with thermal stratification of a shallow warm lens having the highest oxygen and lowest nitrate concentrations (Figure 3b). Relatively high salinity waters shoal toward the coast and extend into the thermocline below the warm lens (Figure 3b).

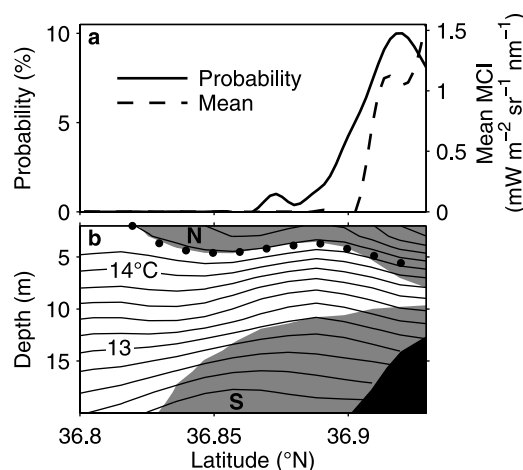
[14] A dense red tide patch in the NE bay, where mean MCI is highest (Figure 2b), exhibited not only high chlorophyll and reddish coloration, but also high maximum quantum yield (Figures 4a and 4b), indicating a healthy population. The patch was within a frontal zone, defined by

relatively strong gradients in temperature and salinity (Figures 4c and 4d). The highest dinoflagellate abundance was in the sample nearest the chlorophyll peak (Figure 4a). *Ceratium cf. divaricatum* was dominant. *Akashiwo sanguinea*, *Ceratium furca*, *Ceratium cf. lineatum*, *Cochlodinium cf. fulvescens* and *Preperidinium sp.* were common. *Alexandrium catenella*, *Prorocentrum gracilis*, *Oxyphysis oxytoides*, *Dinophysis sp.*, and *Gonyaulax sp.* were present but not abundant.

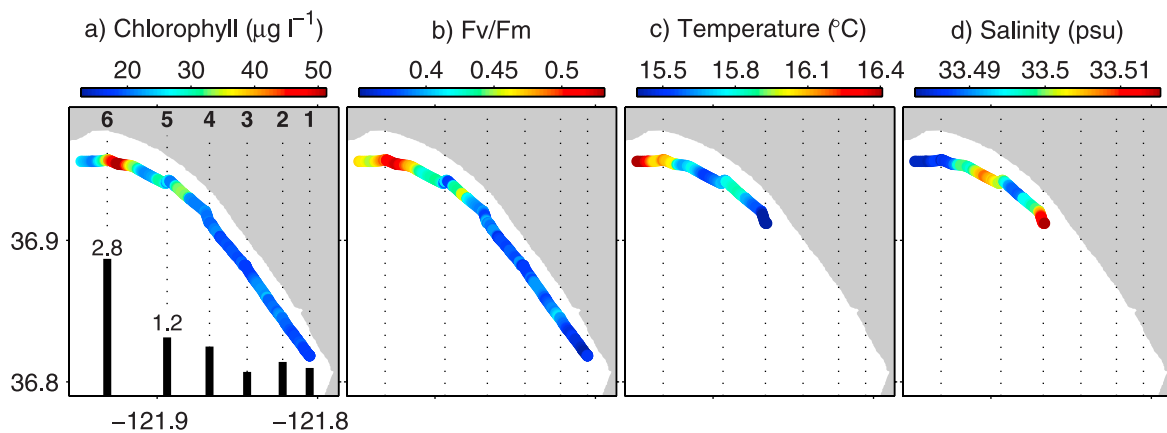
#### 4. Discussion

[15] Monterey Bay is the largest open embayment along the U.S. west coast, and an area of the bay is the site of frequent extreme blooms, particularly between August and November. New remote sensing techniques permitted this discovery and provided the impetus for closer study of this ecologically significant area. The strong bio-optical signal of these blooms is due to dense surface aggregations of phytoplankton. Dinoflagellates that most often bloom in MB, including *Akashiwo*, *Cochlodinium* and *Ceratium* [Ryan et al., 2005; Kudela et al., 2008; Ryan et al., submitted manuscript, 2008], were abundant in the diversely populated bloom patch sampled in this study. These dinoflagellates are known to exhibit strong vertical migratory behavior and aggregate near the surface [Blasco, 1978; Park et al., 2001; Donaghay et al., 2006].

[16] Observed conditions that would favor dinoflagellate blooms include relatively strong thermal stratification, locally enhanced nutrient supply in the thermocline, low wind stress, and retentive inner shelf circulation. As illustrated by studies in NE Monterey Bay, highly motile dinoflagellates like *Akashiwo* can effectively migrate into the thermocline daily to acquire nutrients [Donaghay et al., 2006]. Relatively high salinity in the thermocline beneath the bloom area presumably indicates relatively high nutrient supply, while low nitrate and high oxygen concentrations indicate



**Figure 3.** Mean water column structure underlying the extreme bloom region along the repeated AUV transect (location in Figure 2a). (a) bloom probability and mean intensity; (b) mean water column patterns: temperature (solid contours), salinity (gray shaded area labeled S is  $> 33.5$  psu), nitrate (gray shaded area labeled N is  $< 4 \mu\text{M}$ ), and oxygen (area above dotted contour is  $> 6.25 \text{ ml l}^{-1}$ ).



**Figure 4.** In situ mapping of a red tide bloom on September 19, 2007. (a) Calibrated fluorometric chlorophyll (color) and dinoflagellate cell counts at sampling stations (bars, numbers indicate cell counts  $\times 10^5 \text{ liter}^{-1}$ ); (b) maximum quantum yield (Fv/Fm); (c) temperature; (d) salinity.

relatively high nutrient utilization and productivity. Low wind stress in the NE bay promotes stratification that favors dinoflagellates and minimizes dispersal of surface aggregations by wind-driven turbulent vertical mixing. Retentive circulation minimizes dispersal by lateral advection. The bloom retention we observed in the NE bay was adjacent to eddy-forced export of waters from another part of the northern bay, and it occurred during a period of upwelling favorable winds (not shown). This is distinct from the retentive recirculation pattern described for the entire northern bay during periods of upwelling [Graham and Largier, 1997], and it emphasizes the need for studying very near-shore circulation patterns to understand bloom dynamics.

[17] Where favored by environmental conditions, dense dinoflagellate populations would have an advantage in utilizing periodic nutrient influx. The primary natural nutrient sources to MB are upwelling filaments [Rosenfeld et al., 1994] and internal tidal pumping from Monterey Canyon [Shea and Broenkow, 1982]. Shelf bathymetry may also influence nutrient transport and coupling to benthic nutrient processes. The shallow shelf area of the northern bay, where the blooms are prevalent, is much larger than that in the southern bay. Because the MB extreme bloom season overlaps with the rainy season, fluxes of nutrients and freshwater (stratification) from land drainage may at times be important to bloom dynamics. Drifter studies during fall and winter show that riverine and estuarine plumes in the central bay predominantly flow northward into the region where extreme blooms are most frequent and intense (A. M. Fischer, The structure, composition, and dynamics of a central California estuarine discharge plume, manuscript in preparation, 2008). The roles of oceanographic and land-sea nutrient supply in this region require further study.

[18] Concentration of blooms through biological-physical interactions is also indicated. Intense red tide aggregations have been observed at convergent fronts in MB [Ryan et al., 2005, submitted manuscript, 2008], and the in situ survey presented here showed a bloom patch in a frontal zone. These observations are consistent with concentration of upward-swimming populations in the downwelling zone of horizontally convergent flow.

[19] Process studies show that dense blooms in NE Monterey Bay can seed larger blooms [Ryan et al., 2005; Kudela et al., 2008; Rienecker et al., 2008; Ryan et al., submitted manuscript, 2008]. By promoting frequent development of extreme blooms, this area of the California coast may exert a disproportionately large influence on adjacent coastal regions. Drifter studies show that when upwelling favorable winds relax/reverse, the shallow waters of the NE bay can be rapidly flushed out of the bay and up the coast [Ryan et al., 2008, unpublished data, 2006, 2007]. Similar “bloom incubators” are indicated by observations from regions of other coastal upwelling systems, including northern San Luis Obispo Bay, California (M. Moline, personal communication, 2008), Lisbon Bay, Portugal [Moita et al., 2006], Paracas Bay, Peru [Kahru et al., 2004], and St. Helena Bay, South Africa [Pitcher and Nelson, 2006; Fawcett et al., 2007]. Understanding incubator regions is important to understanding red tide and HAB ecology of the larger marine ecosystems in which they reside.

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