A Coastal Ocean Extreme Bloom Incubator

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Abstract

Novel remote sensing methods and in situ observations reveal that intense phytoplankton blooms occur frequently in Monterey Bay. These events can contain surface chlorophyll concentrations exceeding 500 $\mu g\ l^{-1}$ and occupy ~5 to 80 km^2. They occur primarily during August - November and can persist for > 1 month. Maximum bloom frequency and mean intensity are in shallow (< 25 m) water of the northeastern bay, in coincidence with the warmest surface water, low wind stress, and retention of shallow waters. These conditions favor dinoflagellates, which can vertically migrate to acquire nutrients in the thermocline and aggregate as “red tide” near the surface. High-resolution mapping and sampling in the bloom area indicate that concentration of dinoflagellate blooms can occur in frontal zones. This bloom area receives nutrients from natural oceanographic processes and agricultural land drainage. Such coastal bloom incubation areas may disproportionately influence regional bloom ecology.

Introduction

Dense accumulations of phytoplankton that imbue the surface ocean with reddish color, commonly called "red tide", 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; *Donaghay et al*., 2006]. 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.

Studies have documented intense dinoflagellate red tide blooms in Monterey Bay, including species known to cause harm [*Ryan et al*. 2005; *Donaghay et al*. 2006; *Kudela et al*. 2008; *Curtiss et al*. 2008; *Ryan et al*., 2008a]. 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 Monterey Bay, and to examine conditions and processes underlying this phenomenon.

Data and Methods of Analysis

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; *Schalles*, 2006]. Only one multi-spectral satellite sensor, MERIS (Medium Resolution Imaging Spectrometer), has been designed to permit computation of an extreme bloom index, termed the Maximum Chlorophyll Index (MCI), using the NIR signal [*Gower et al*., 2005; *Gower and King*, 2007]. We apply MCI images to illustrate synoptic bloom patterns and to compute long-term bloom statistics. The MCI image archive was screened to eliminate images having questionable signal in Monterey Bay near cloud edges or at steep satellite viewing angles, resulting in 75 good images in the August – November periods of 2002 - 2007. Of these images, 31 were full resolution (300 m), and 44 were reduced resolution (1200 m).

To compute bloom statistics from MCI images, we define blooms as MCI > 0.3, which corresponds to chlorophyll concentrations exceeding ~30 $\mu g\ l^{-1}$ [*Gower et al,* 2005]. We computed indices of bloom probability (detection frequency) and mean intensity. Maps of bloom statistics were constrained to pixels that were well sampled through the time series (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, defined as pixels having a bloom frequency of at least 25% of the maximum frequency.

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 – November of 2002 - 2007; details of MODIS image processing are in *Ryan et al*. [2008a]. Surface wind stress was from the COAMPS (Coupled Ocean / Atmosphere Mesoscale Prediction System) high-resolution (3-km, 12-hour) model of central California for August – November 2006.

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 flown on aircraft over Monterey Bay during the extreme bloom season. Details of these sensors and data processing for coastal ocean studies are found in *Davis et al*. [2002] and *Ryan et al*. [2005]. NIR, green and blue channel center wavelengths were {711, 549, 462} nm for AVIRIS and {708, 540, 458} nm for PHILLS.

To describe water column structure in the bloom environment, we analyzed a time-series of vertical sections mapped by an autonomous underwater vehicle (AUV) between the inner shelf region of extreme bloom development and outer Monterey Bay. From 24 surveys during August through November of 2003 - 2007, we computed mean hydrographic sections. Details of AUV sensors and sampling are in *Ryan et al*. [2008b]. Valid means were constrained to well-sampled grid points (at least 80% of maximum possible sample count).

During September 2007 the bloom environment was studied using multi-platform observations, including drifter deployments, surface property mapping from a small boat, and phytoplankton sampling. To track the movement of shallow waters in which red tide dinoflagellates aggregate, satellite-tracked drifters were drogued between 1 and 2 m

depth. The flow-through mapping system drew water from 2 m depth and measured temperature and salinity (SeaBird 45 thermosalinograph), chlorophyll fluorescence and the maximum quantum yield [*Kolber et al.,* 1998]. Surface phytoplankton samples were immediately preserved with 1% glutaraldehyde and kept in the dark at 4ºC. Samples were filtered through 5μm polycarbonate black filters and DAPI stained. Filters were mounted on slides with immersion oil, and cell counts were performed using epifluorescence microscopy.

Results

Shown in Figure 1 are remote sensing images of extreme blooms in Monterey Bay. The MCI images (Figure 1a-f) show bloom scales from ~ 5 km^2 (Figure 1c) up to ~ 80 km^2 (Figure 1f). Extracted surface chlorophyll concentrations measured during blooms in 2006 (Figure 1e) and 2007 (Figure 1f) exceeded 500 $\mu g\ l^{-1}$. The large 2007 bloom (Figure 1f) persisted for more than a month, from early October to mid-November. These examples, as well as the full image series, exhibit a preponderance of extreme blooms in the northeastern bay. Images from all months show that extreme blooms are limited primarily to the annual period of August – November. Airborne imaging spectrometry provides less frequent coverage, but its high spatial resolution emphasizes the patchiness of such extreme blooms (Figure 1g-i), as well as small-scale physical processes influencing bloom distributions (e.g. eddy in Figure 1i).

Indices of extreme bloom probability (Figure 2a) and mean intensity (Figure 2b) show the prevalence of intense blooms in the NE bay, in waters shallower than 25 m. The entire bay except a thin border along the coast 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 highest, exhibits the warmest mean SST during the extreme bloom season (Figure 2c). These warm waters are adjacent to the swath of coldest average SST, which is due to filaments of recently upwelled water that enter the bay from the north [*Rosenfeld et al*., 1994]. Surface wind stress is also lowest over the inner bay, and the warm waters of the NE bay are in a region of minimum average wind stress.

In the area where mean bloom MCI is highest (Figure 2b), drifter studies demonstrated retention of a red tide bloom. On September 25, 2007 remote sensing and in situ observation showed the presence of an intense surface bloom in the NE bay (Figure 2d; note the reddish color in the MODIS image). Drifters released within the bloom waters were retained in the same area for three days, despite the nearby influence of an eddy that entrained waters from other areas of the bay (Figure 2d). MODIS chlorophyll fluorescence line height for 9/25/2007 (not presented) indicates eddy entrainment from nearshore waters of the northern bay, south of where the drifters showed retention. This retention pattern contrasts with other drifter studies, which show that surface waters in the NE bay can be rapidly transported ~50 km in three days out of the bay and northward along the coast [*Ryan*, unpubl. data].

The in situ climatology from the AUV survey line (Figure 2a) shows that the increases in bloom probability and mean intensity toward the coast (Figure 3a) correspond with thermal stratification of a shallow warm lens (Figure 3b). Further, relatively high salinity waters shoal toward the coast and extend into the thermocline

below the warm lens (Figure 3b), presumably indicating relatively high nutrient availability in the thermocline on average.

In situ surface observations showed patterns consistent with the description from remote sensing. A very dense red tide patch was observed in the NE bay (Figure 4a), in the region where mean bloom MCI is highest (Figure 2b). The patch exhibited not only high chlorophyll and strong reddish discoloration, but also high maximum quantum yield (Fv/Fm; Figure 4b), indicating a healthy bloom population. The intense red tide patch was within a frontal zone, defined by relatively strong gradients in temperature and salinity (Figure 4c,d). The highest dinoflagellate abundance of 2.8×10^5 cells l^{-1} was found in the sample nearest the peak in chlorophyll (Figure 4a). Dinoflagellate species sampled in this bloom area included *Akashiwo sanguinea, Alexandrium catenella, Ceratium divaricatum, Ceratium furca, Cochlodinium fulvescens, Preperidinium sp., and Protoperidium sp.*

Discussion

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, especially in the fall 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 containing exceptionally high chlorophyll concentrations. Dinoflagellates that aggregate near the surface during the day have been observed with remote and in situ sensing during these extreme blooms in NE Monterey Bay [*Ryan et al*., 2005; 2008a; *Kudela et*

al., 2008; *Rienecker et al*., 2008], and this specific type of bloom presumably underlies the characterizations from remote sensing.

Observed natural conditions that would favor dinoflagellates include relatively strong thermal stratification, low wind stress (promoting maintenance of stratification), and high nutrient availability in the thermocline. Dinoflagellates would be favored because they can migrate into the thermocline to acquire nutrients, an ecological phenomenon illustrated by studies in Monterey Bay [*Donaghay et al*., 2006]. Frequent observation of dense surface aggregations also implies relatively weak dispersal. Low wind stress in the NE bay would minimize dispersal by wind-driven turbulent vertical mixing. Drifter studies showed reduced dispersal by lateral advection (i.e. enhanced retention) of a red tide bloom in the NE bay. The example of bloom retention we observed in the area of highest average bloom intensity is distinct from the recirculation pattern described for the entire northern bay during periods of upwelling [*Graham and Largier*, 1997]. This emphasizes the need for studying very near-shore circulation patterns in understanding bloom dynamics.

Where favored by environmental conditions, dense dinoflagellate populations would have an advantage in utilizing periodic nutrient influx. The primary natural nutrient sources to this region are upwelling filaments [*Rosenfeld et al*., 1994] and internal tidal pumping from Monterey Canyon [*Shea and Broenkow*, 1982]. The northern shelf is distinguished from the southern shelf by stronger influence of recently upwelled waters (Figure 2c) [*Rosenfeld et al*., 1994]. 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. The roles of natural nutrient supply processes and shelf bathymetry require further study to evaluate their relative importance in the sustenance of these extreme blooms.

Monterey Bay coastlands also host intensive agriculture, and these lands drain into rivers and a tidally forced estuary that connect with the bay. MERIS images show nearshore bloom patches located at riverine and estuarine outflows. The first MERIS detection of the extensive 2007 bloom was over a nearshore area between riverine and estuarine outflows, shortly after the first major rain of the fall season. This rain event resulted in very high nutrient loading that was measured by moored sensors near the estuarine outflow. Drifter studies during fall and winter show that the outflow plumes in the central bay flow predominantly northward into the region where extreme blooms are most frequent and intense [*Fischer*, 2008]. The potential for bloom initiation by agricultural nutrient inputs exists, and the potential role of this ecosystem perturbation must be examined.

Beyond growth, accumulation and low dispersal, active concentration of bloom biomass through biological-physical interactions likely plays a significant role in the intensity and patchiness of some of these extreme bloom aggregations. One interaction involves concentration in convergence zones, where populations of motile species can overcome downwelling by swimming toward the surface. Convergent fronts in this region have been associated with particularly intense red tide aggregations [*Ryan et al.*, 2005]. The in situ survey presented here also showed an intense, strongly colored, dinoflagellate bloom patch in a frontal zone, consistent with this mechanism of concentration. Biological-physical interactions may also influence the bloom environment itself. Color loading due to dense aggregations of phytoplankton and high

concentrations of colored dissolved organic matter intensifies shallow absorption of solar insolation, thereby promoting thermal stratification [*Cahill et al.*, 2008].

Process studies show that dense blooms in NE Monterey Bay can seed larger blooms as populations are advected [Ryan et al., 2005; 2008a; Kudela et al., 2008; Rienecker et al., 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, the shallow waters of the NE bay are rapidly flushed out of the bay and northward along the coast [*Ryan et al*., 2008b; *Ryan*, unpubl. data]. Similar "bloom incubators" are indicated by observations from other sheltered regions of coastal upwelling systems, including northern San Louis Obispo Bay on the California coast [*M. Moline*, personal communication] and Lisbon Bay on the Iberian coast [*Moita et al*., 2006]. Understanding the ecology of such incubator regions, where natural and human influences can both be significant, is important to understanding red tide and HAB ecology of the larger marine ecosystems in which they reside.

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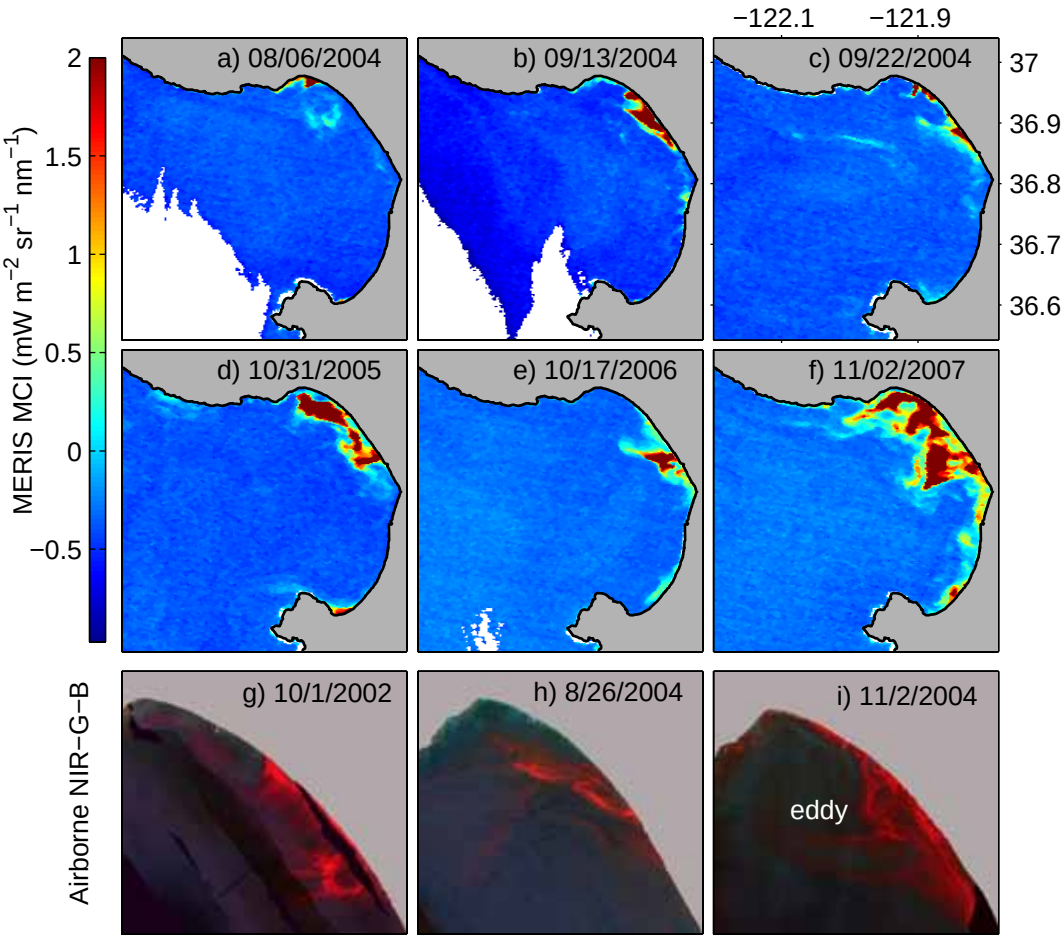
Figure Captions

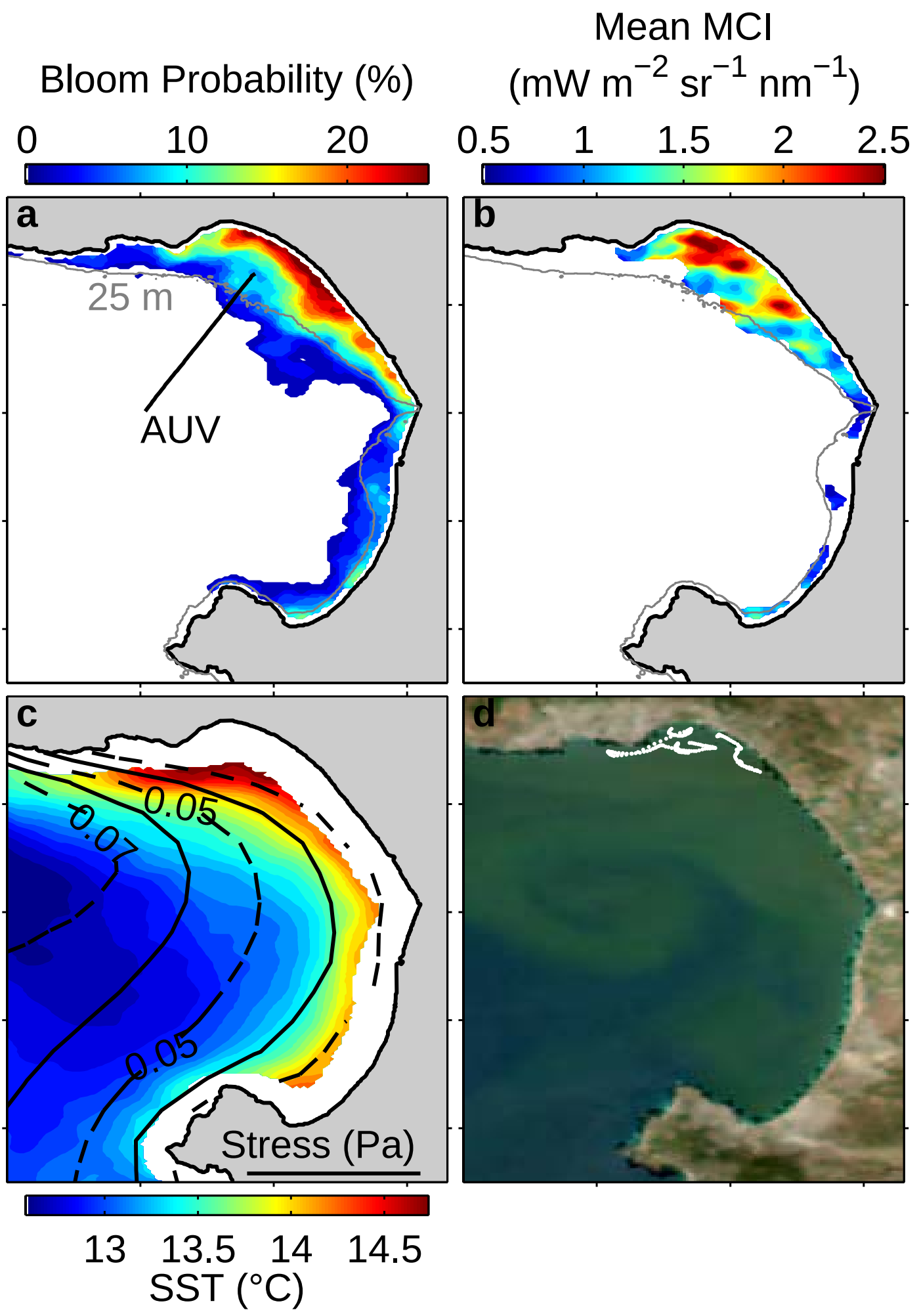
Figure 1. Remote sensing images of extreme blooms in Monterey Bay, California. In all images, red indicates extreme "red tide" bloom patches. (a-f) Full-resolution (300 m) images of the Maximum Chlorophyll Index (MCI) from the MERIS satellite sensor. (g-i) NIR-G-B composite images from hyperspectral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

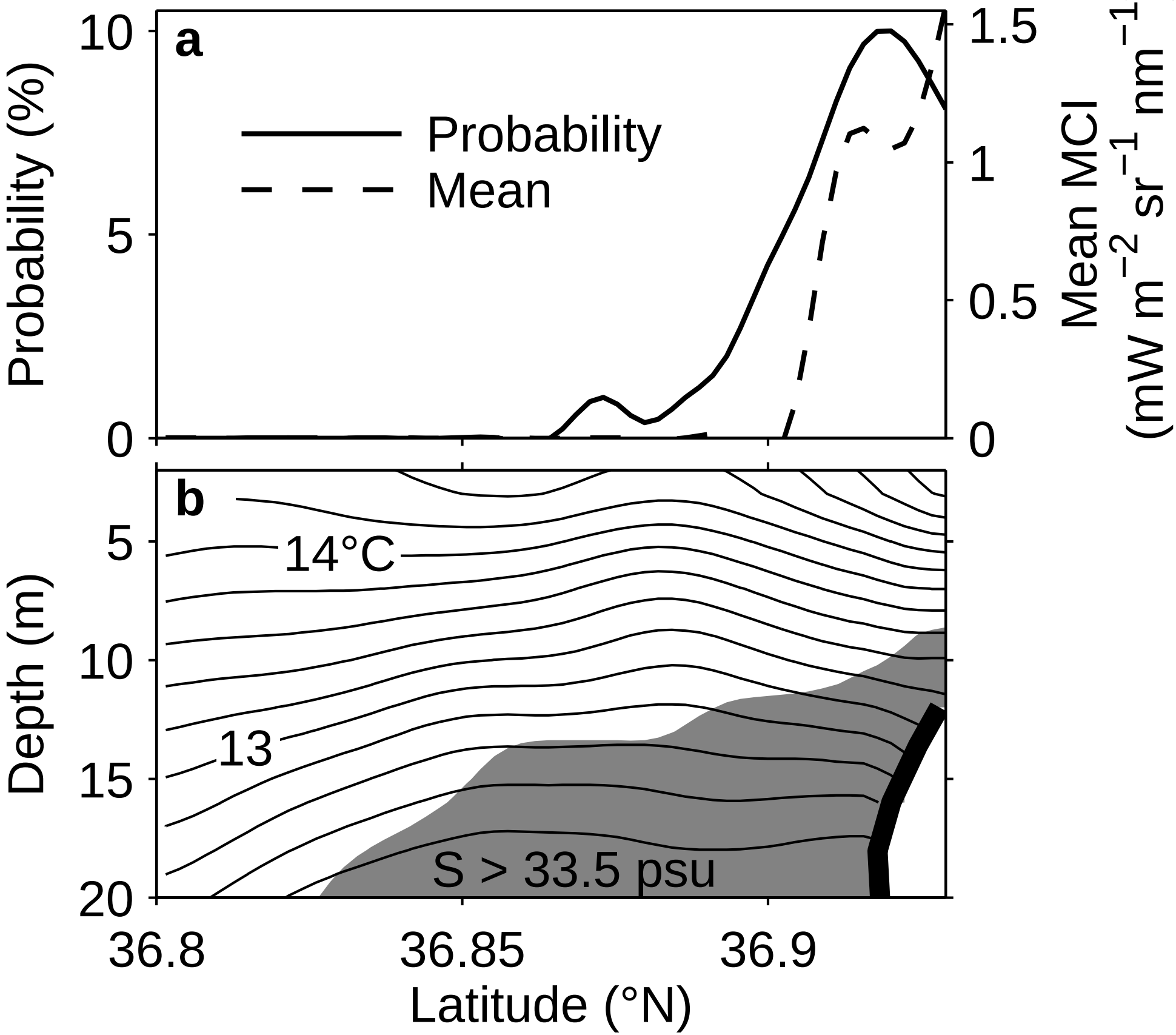
Figure 2. Bloom statistics and relevant oceanic and atmospheric conditions. (a) bloom probability (detection frequency); (b) mean bloom intensity; (c) sea surface temperature (SST) and wind stress; (d) retention of red tide shown with 9/25/2007 MODIS true color image and 9/25/2007 to 9/28/2007 drifter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

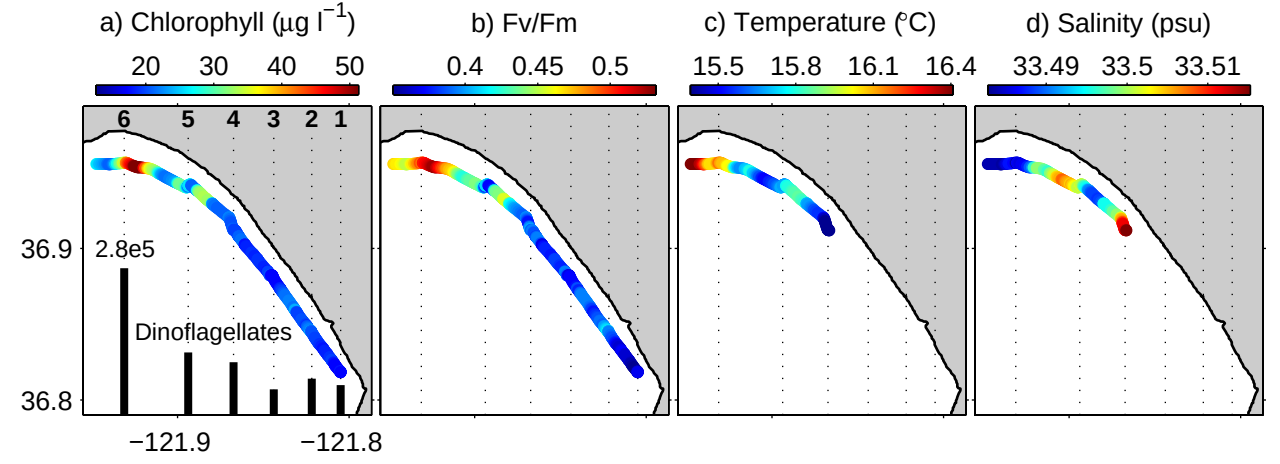
Figure 3. Mean water column structure underlying the extreme bloom region along the repeated AUV transect (location in Figure 2a). (a) bloom probability and mean intensity; (b) mean water column temperature (contours) and salinity > 33.5 psu (shaded).

Figure 4. In situ mapping of bloom scales, species, and relationships to hydrography. Survey was conducted on September 19, 2007. (a) Calibrated fluorometric chlorophyll and dinoflagellate cell counts at sampling stations; (b) maximum quantum yield (Fv/Fm); (c) temperature; (d) salinity.


−122.1
−121.9
a) 08/06/2004
b) 09/13/2004
c) 09/22/2004
d) 10/31/2005
e) 10/17/2006
f) 11/02/2007
g) 10/1/2002
h) 8/26/2004
i) 11/2/2004
eddy
MERIS MCI (mW m−2 sr−1 nm−1)
2
1.5
1
0.5
0
−0.5
37
36.9
36.8
36.7
36.6
Airborne NIR−G−B


Bloom Probability (%)
0
10
20
Mean MCI
(mW m^{-2} sr^{-1} nm^{-1})
0.5
1
1.5
2
2.5
a
25 m
AUV
b
c
0.05
0.07
0.05
Stress (Pa)
d
13
13.5
14
14.5
SST (°C)


a
b
Probability
Mean
Probability (%)
Mean MCI
(mW m^{-2} sr^{-1} nm^{-1})
Depth (m)
14°C
13
S > 33.5 psu
Latitude (°N)
0
5
10
0
0.5
1
1.5
5
10
15
20
36.8
36.85
36.9


a) Chlorophyll (μg l^{-1})
20 30 40 50
b) Fv/Fm
0.4 0.45 0.5
c) Temperature (°C)
15.5 15.8 16.1 16.4
d) Salinity (psu)
33.49 33.5 33.51
6 5 4 3 2 1
2.8e5
Dinoflagellates
36.9
36.8
−121.9
−121.8