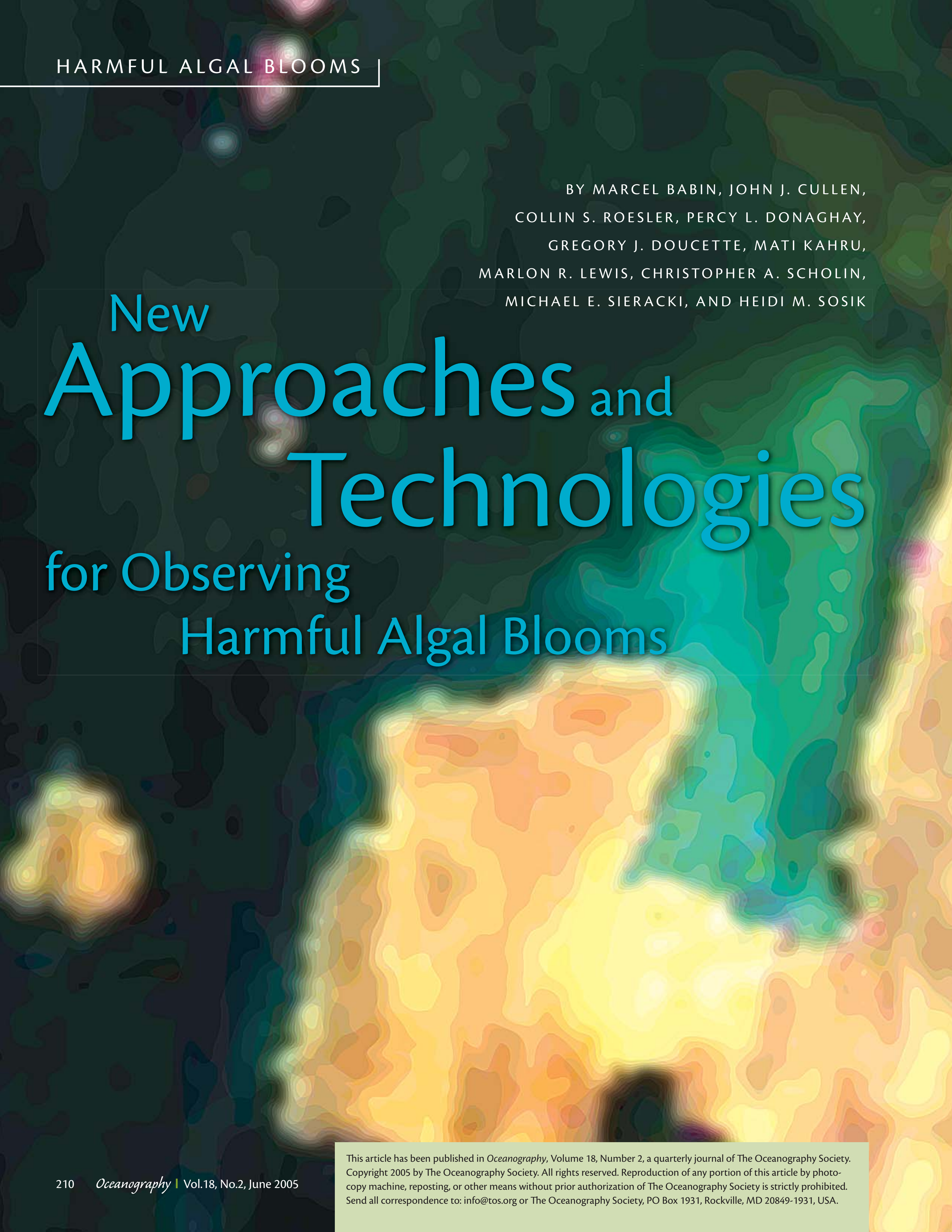

New Approaches and Technologies for Observing Harmful Algal Blooms

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Harmful algal blooms (HABs) represent a diverse range of phenomena that universally share only two characteristics: they produce effects on ecosystems or food resources that humans perceive as harmful, and their progression is fundamentally a process of population dynamics under oceanographic control. Because of the complexity, scales, and transient nature of HABs, their monitoring and prediction requires rapid, intensive, extensive, and sustained observations at sea. These requirements cannot be met with traditional approaches that depend on ships for sampling and laboratories for chemical or biological analyses. Fortunately, new sensing technologies that operate autonomously *in situ* will allow, in the near future, the development of comprehensive observation strategies for timely detection of HABs. In turn, developments in modeling will support prediction of these phenomena, based directly on real-time measurements.

Enabling ocean-observation technologies that have emerged during the last decade reflect advances in optical imaging, molecular biology, chemistry, acoustics, phytoplankton physiology, and marine optics. Now, sensors are increasingly deployed from various platforms such as *in situ* profilers, autonomous underwater vehicles (AUVs), and moorings to derive a broad range of quantitative and qualitative information about the pelagic environment. For example, optical sensing, used for decades to measure photosynthetically available radiation and to estimate concentrations of suspended particles from turbidity or phytoplankton from chlorophyll fluorescence, has been greatly enhanced to provide much better measures of the light field and seawater constituents, plus indicators of the species composition, cell size, and physiological properties of phytoplankton. Also, *in situ* analysis of nutrient concentrations is now a reality, complementing established methods for measuring temperature, salinity, and oxygen concentrations with submersible sensors.

Many of the new approaches and technologies are unfamiliar to potential users, therefore, they are not immediately useful to them. Hence, we organized a "Workshop on Real-Time Coastal Observing Systems for Ecosystem Dynamics and Harmful Algal Blooms" in Villefranche-sur-Mer (France), held 11-21 June 2003, to review the new technologies and platforms appropriate for autonomous and *in situ* observation of HABs. We provided the participants with both the theory relevant to understanding the basic principles of real-time observation and modeling tools, and tutorials to explain the use of these tools. The proceedings of this workshop ("Habwatch") appear in two forms. First, all invited lectures and contributed talks, and most posters, are available on the workshop web site (www.obs-vlfr.fr/habwatch); oral talks are available as slide shows with voice. Second, chapters based on invited lectures will be published in a peer-reviewed volume of the UNESCO series *Monographs on Oceanographic Methodology* (Babin et al., in press).

Here, we present an overview of the major observational technologies described during the Habwatch workshop, referring the reader to detailed reviews on specific topics, which form the chapters of the Habwatch proceedings. We conclude by suggesting some priorities for the development of observational tools within the framework of the Global Ecology and Oceanography of Harmful Algal Blooms (GEOHAB) program (see www.geohab.info/).

AVAILABLE AND EMERGING OBSERVATIONAL TECHNOLOGIES

Many technologies show promise for real-time observation of HABs and the oceanographic processes that in large part determine their dynamics. Some enhance existing capabilities while others can provide information *in situ* that until recently could be obtained only through hands-on analysis of samples.

Detection of Phytoplankton at the Group or Species Level

The harmful effects of HABs are generally attributable to single species. It is thus necessary to discriminate phytoplankton at the group or species level for the detection, early warning, and oceanographic characterization of HABs. This is traditionally done by microscopic examination or analysis for toxins, both of which are laborious and generally performed in the laboratory; these approaches are not suitable for real-time observation. There are, however, new and emerging technologies derived from those traditional methods that allow autonomous and/or near real-time detection of phytoplankton at the species and group levels. One such commercial technology is Flow-CAM, a particle analyzer and imager that combines aspects of microscopy and flow cytometry (Figure 1) (Sieracki et al., 1998). This instrument measures light scattering, and fluorescence from chlorophyll and phycoerythrin, on individual particles larger than 5 µm. Its CCD camera is triggered by, for instance, the chlorophyll *a* fluorescence signal; digital silhouette images are stored on disk. Data analysis allows enumeration of targeted morphotypes with semi-automatic shape recognition. This particle analyzer is especially good in the microplankton size range (20 to 200+µm) where morphology is an important identification feature. Benchtop, portable, and submersible versions are available. Jaffe (in press) reviews other optical imagers that could be used in HAB research and monitoring.

Many technologies show promise for real-time observation of HABs and the oceanographic processes that in large part determine their dynamics.

Sensitive to cells smaller than Flow-CAM's limit, flow cytometers can be used to discriminate phytoplankton groups based on pigment fluorescence and light scattering as an index of size. Automated submersible flow cytometers have been developed and deployed successfully to obtain significant results on phytoplankton population dynamics (Figure 2). With sample preparation, flow cytometers can identify cells labeled with specific markers (e.g., for proteins, bulk DNA, or gene probes).

In many cases, phenotypic attributes of cells (e.g., morphology, pigment composition) are insufficient to discriminate among HAB species. Thus, unique genetic signatures (DNA, RNA) targeted by molecular probes have been increasingly used for detection of microorganisms at the species level, including the discrimination of potentially toxic from non-toxic species of a genus (e.g., *Pseudo-nitzschia* spp.). However, simply the presence of a toxigenic species provides no information on the associated toxicity, as toxin levels can vary widely as a function of environmental effects on the organism's physiology. Ideally, the potential impacts of a toxic HAB should be assessed

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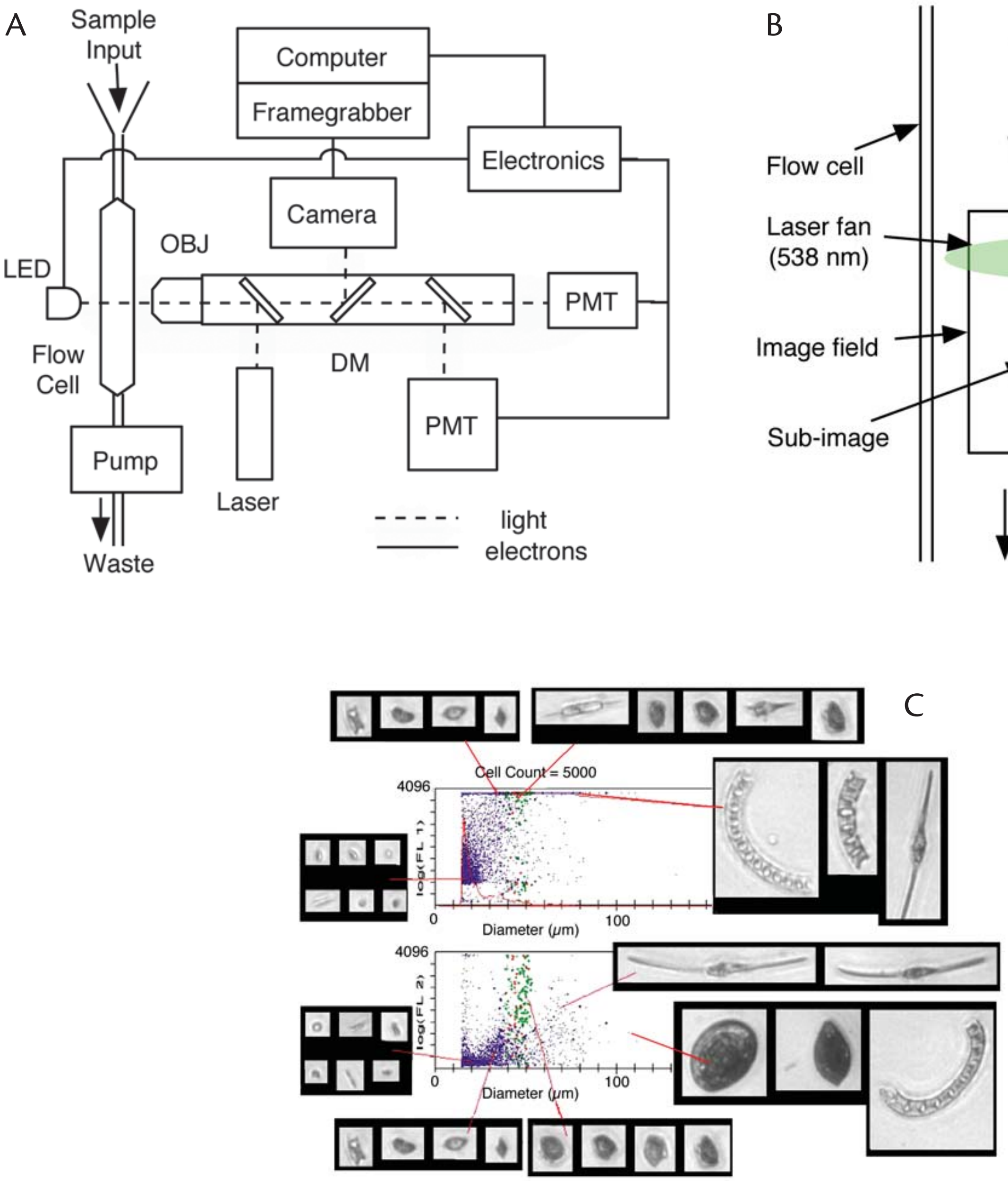

Figure 1. Schematic diagrams and results from the FlowCAM imaging-in-flow system (Fluid Imaging Technologies, USA; www.fluidimaging.com). Sample fluid is pulled through the flow cell at rates up to 4 mL/min. (A) When a cell enters the field of view, fluorescence is excited by a fan of laser light. Epifluorescence optics are used that employ dichroic mirrors (DM) to split the light signals. Different objectives (OBJ) can be used for different magnifications (e.g., 4X to 20X). The fluorescence signal is detected by photomultiplier tubes (PMT) and triggers a light emitting diode (LED) to flash and backlight the flow cell. The camera image is digitized by the frame grabber. The cell is located within the image and measured, and a subimage is stored on disk in real time. Particles can also be detected by light scatter (detector not shown for simplicity). (B) Details of the field of view of the flow cell. (C) These images are linked to the size and fluorescence values and results can be browsed using the interactive scattergram. The dot plot shows fluorescence versus size and populations can be investigated by selecting points and the corresponding images are displayed.

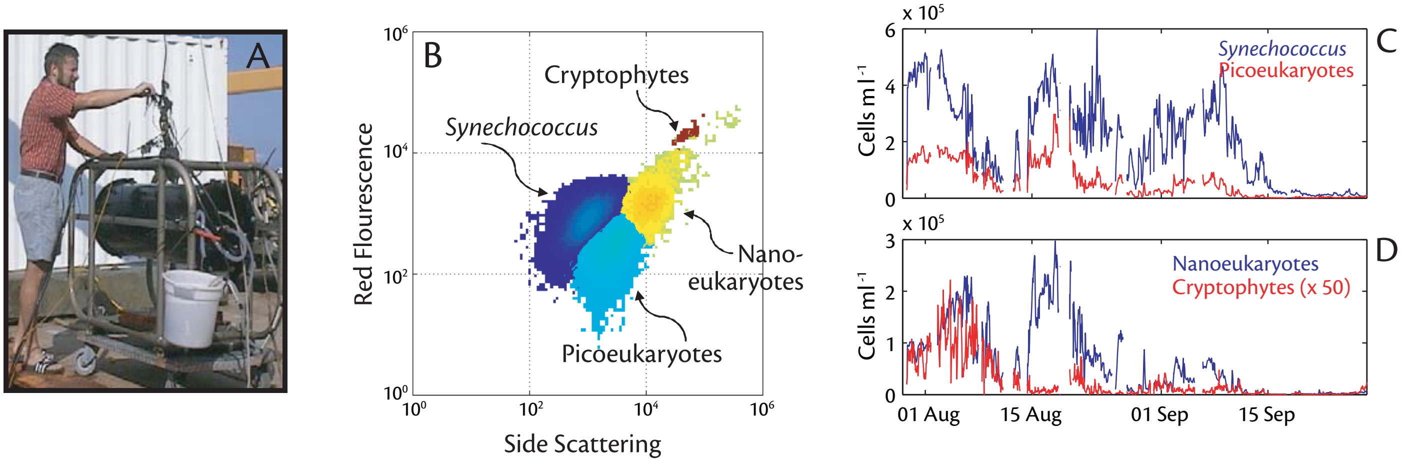

Figure 2. FlowCytobot (A), an automated submersible flow cytometer designed and built at the Woods Hole Oceanographic Institution (Olson et al., 2003), has been successfully deployed at coastal cabled observatory sites on the U.S. East Coast. FlowCytobot makes nearly continuous measurements of pico/nanophytoplankton abundance, cell scattering, and cell fluorescence characteristics (B, typical data from 1 hour of sampling; classification of cells considers all measured properties including orange fluorescence, critical for discrimination of *Synechococcus* and cryptophytes). A two-month deployment at the Long-Term Environmental Observatory off New Jersey in 2001 reveals a high level of temporal variability in abundance of *Synechococcus*, cryptophytes and other pico- and nanophytoplankton (C, D), some of which can be explained on the basis of changes in population growth rates inferred from FlowCytobot-based observations of diel changes in cell size distributions (Sosik et al., 2003). An autonomous flow cytometer is now commercially available in portable, floating, and submersible versions (CytoBuoy b.v., The Netherlands; http://www.cytobuoy.com).

with integrated detection of organisms and toxins using *in situ* sensors in real- or near-real time. Toward this end, the Environmental Sample Processor (ESP) has been developed (Figures 3 and 4). A prototype of this autonomous, *in situ* system has performed DNA probe array analyses when deployed at sea (Scholin et al., in press). An ELISA-based (enzyme-linked immunosorbent assay) toxin array deployable on this same autonomous sampling platform can detect *Pseudo-nitzschia's* toxin, domoic acid. The toxin array has undergone initial laboratory testing (Figure 4) and will soon undergo field trials. Once operational, the next-generation ESP will be capable of providing concurrent data on the abundance of a HAB species and its toxin. Other approaches such as molecular imprinting and *in situ* mass spectrometry also show promise for autonomous detection of toxins (Scholin et al., in press).

Improved Detection of Phytoplankton Biomass and other Bulk Properties of Surface Waters

The new technologies for detection of phytoplankton at the group and species levels are not presently suited for synoptic or highly resolved sampling on the scales of HABs. Fortunately, such specialized measurements can be complemented with synoptic remote sensing and continuous, *in situ* deployments of other instruments to provide essential oceanographic context. For example, fluorometers, transmissometers, or turbidometers on a variety of platforms can continuously detect phytoplankton or particles on the vertical and horizontal scales of the physical and chemical processes that influence HAB dynamics. However, the optical sensors in wide use measure bulk properties of the water and do not allow much discrimination beyond measures of algal biomass or particle load. This shortcoming is largely compensated by the amount of information generated over a broad spectrum of temporal and spatial scales. New optical sensors described at the Habwatch workshop can provide much more information on the same scales. They measure a range of optical properties that can be related directly to phytoplankton and other constituents of the water.

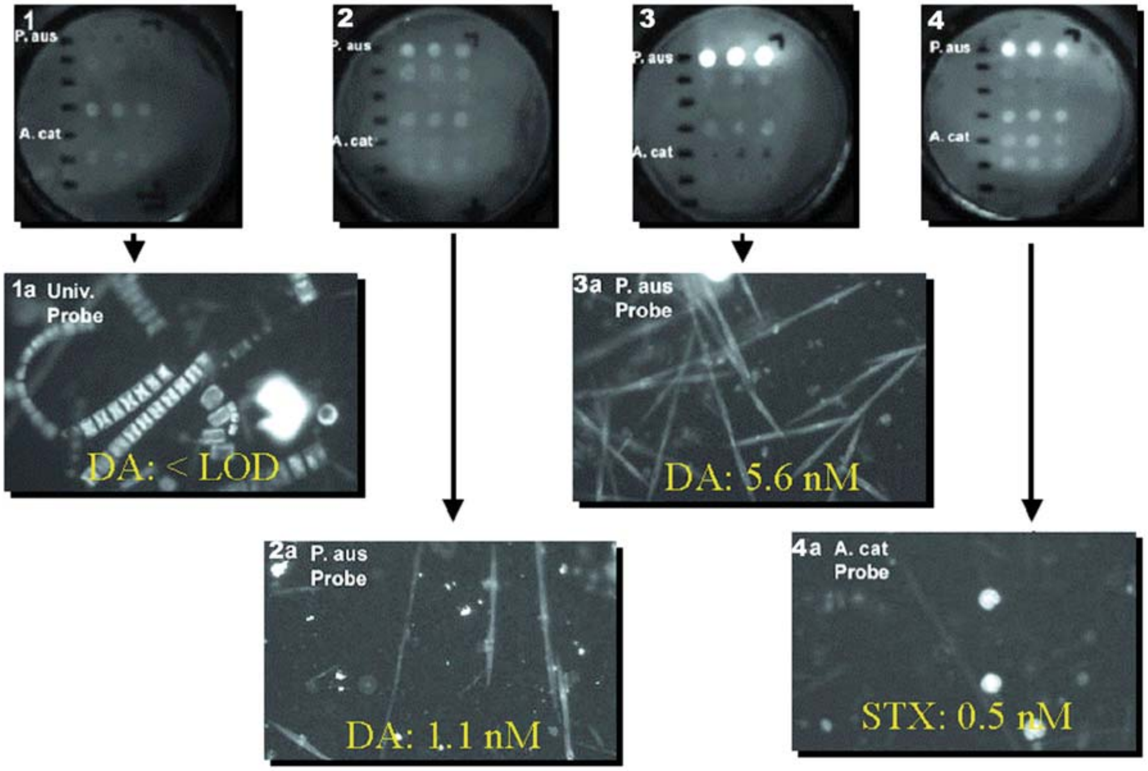

Figure 3. Use of the Environmental Sample Processor (ESP) to detect phytoplankton species in near real-time and to archive aliquots of the same samples for fluorescent *in situ* hybridization (FISH) and toxin analyses (for details see Scholin et al. in press; http://www.mbari.org/microbial/ESP). These examples show how a given sample can be interrogated for HAB species and toxins using a variety of molecular analytical techniques. For probe arrays, the ESP concentrated phytoplankton, homogenized that material, and passed the homogenate over a custom oligonucleotide probe array to reveal ribosomal RNA (rRNA) molecules indicative of a variety of HAB species (e.g., Figure 4). An image of the resulting array was recorded using a CCD camera, providing a near real-time indication of presence and abundance of selected species. For FISH, a sample corresponding to that used to develop the array was collected, preserved, and stored onboard the ESP. Later, the ESP was programmed to process that archived sample with any one of a number of fluorescently labelled probes. Once the hybridization process was completed, the sample filter was recovered and viewed using conventional epifluorescence microscopy. Finally, the ESP was used to archive samples for determinations of either domoic acid or saxitoxin activity. In the examples presented here, images of the probe arrays are shown in the top row (frames 1 to 4) and corresponding micrographs showing results of FISH assays are shown in the bottom two rows (frames 1a to 4a). Locations of probes on the arrays for *Pseudo-nitzschia australis* and *Alexandrium catenella*, spotted in triplicate, are denoted "P. aus" (labels rRNA specific to *P. australis*) and "A. cat" (labels rRNA specific to *A. catenella*), respectively. Different rRNA probes were used for FISH analysis depending on the sample: "Univ." (targets rRNA from all organisms), as well as fluorescent versions of "P. aus" and "A. cat" similar to those on the arrays. Domoic acid or saxitoxin activity associated with a sample was determined using a receptor binding technique, and values obtained are printed at the bottom of the respective micrographs.

One group of commercially available, *in situ* optical instruments uses carefully designed light sources and detectors to measure the inherent optical properties (IOPs) of the substances contained in seawater: the coefficients of absorption, attenuation, scattering, and backscattering, at an increasing number of wavelengths. Because phytoplankton, non-algal particles, and colored dissolved organic matter (CDOM) have different optical properties, spectra of absorption and scattering can be deconvolved to retrieve estimates of their respective concentrations (Roesler and Boss, in press; Sosik, in press). Sometimes, species composition can be retrieved. It has been shown by Kirkpatrick et al. (2000) that the toxic dinoflagellate *Karenia brevis* can be detected by analyzing the shape of the phytoplankton absorption spectrum, measured *in situ* with a flow-through spectrophotometer, in comparison with a known absorption spectrum for the species in question (Schofield et al., in press).

Submersible IOP sensors now exist in different formats, ranging from bulk hyperspectral to miniature multispectral instruments. They can be deployed on virtually all *in situ* platforms (e.g., towed vehicles, moorings, and AUVs) and provide data at various spatial and temporal scales, depending on the platform (Chang and Dickey, in press; Griffiths, in press). An example of high-frequency and high-resolution vertical profiles of the absorption coefficient is shown in Figure 5, from a study of the dynamics of thin layers formed by *Pseudo-nitzschia* spp. in East Sound, WA and Monterey Bay, CA (USA). The potential for using IOPs in the detection and study of HABs is huge: fulfillment of this potential will require further development of theory and measurement technology, but more importantly the education of a broader community in relevant principles of bio-optics.

A second group of optical instruments includes passive sensors that measure irradiance or radiance, and thereby the apparent optical properties (AOPs) of seawater, namely the vertical diffuse attenuation coefficient (K_d) and water reflectance (*R*; the ratio of upward radiance or irradiance to downward irradiance) at different wavelengths from the UV to the near-infrared. Because they depend on the sun for illumination rather than on internal optics, AOP sensors cannot measure spectral absorption or scatter directly, or at night. But the attenuation coefficient is strongly a function of absorption, and reflectance depends on the ratio of backscatter to absorption, so the constituents of the water can be retrieved from AOPs. AOP inversion models discriminate phytoplankton from CDOM and non-algal particles, and may even identify pigment-based taxonomic groups if the sensors are hyperspectral (Figures 6 and 7). Like the IOP deconvolutions, these models are based on a forward model with assumptions about the spectral shapes of IOPs for the different constituents. But, the inversion is more complex since it is necessary to first derive IOPs from AOPs. This is another reason why the use of new optical approaches for monitoring and research requires some knowledge of bio-optics.

Radiometric sensors that measure AOPs are calibrated in an absolute sense against international standards; mea-

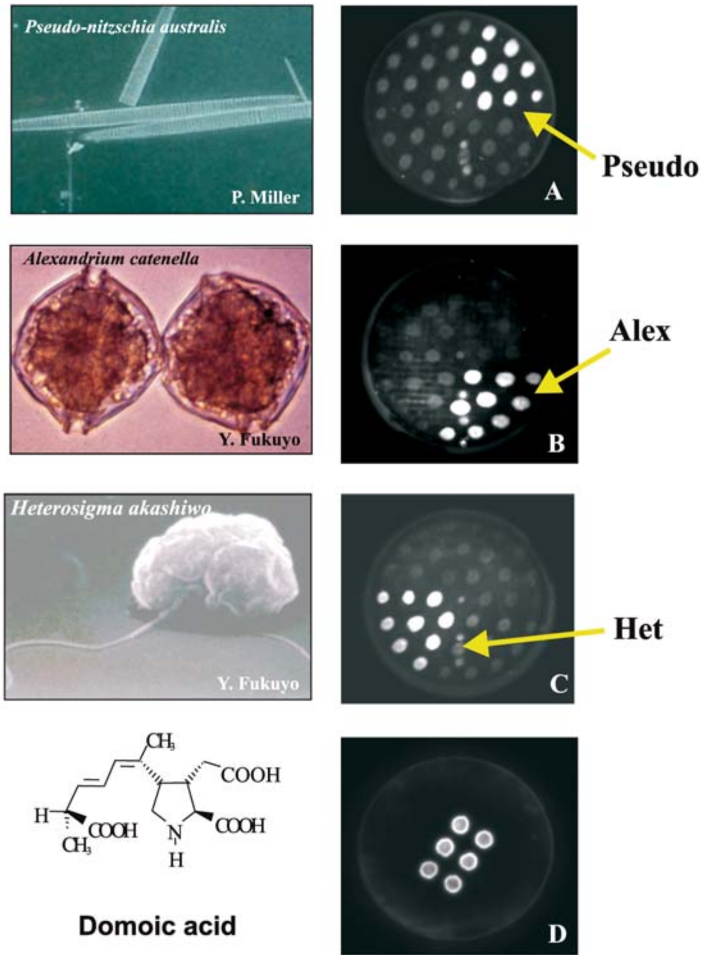

Figure 4. A)-(C). Custom DNA probe arrays printed on filters and developed autonomously on board the Environmental Sample Processor. Images show target organisms and corresponding array image (Scholin, unpublished; images of cells kindly provided by P. Miller and Y. Fukuyo). (D). Prototype domoic acid (DA) toxin array printed on a filter and showing binding of DA-specific antibody to toxin-protein conjugate following conduct of a competitive ELISA (G. Doucette, C. Mikulski, and C. Scholin, unpublished).

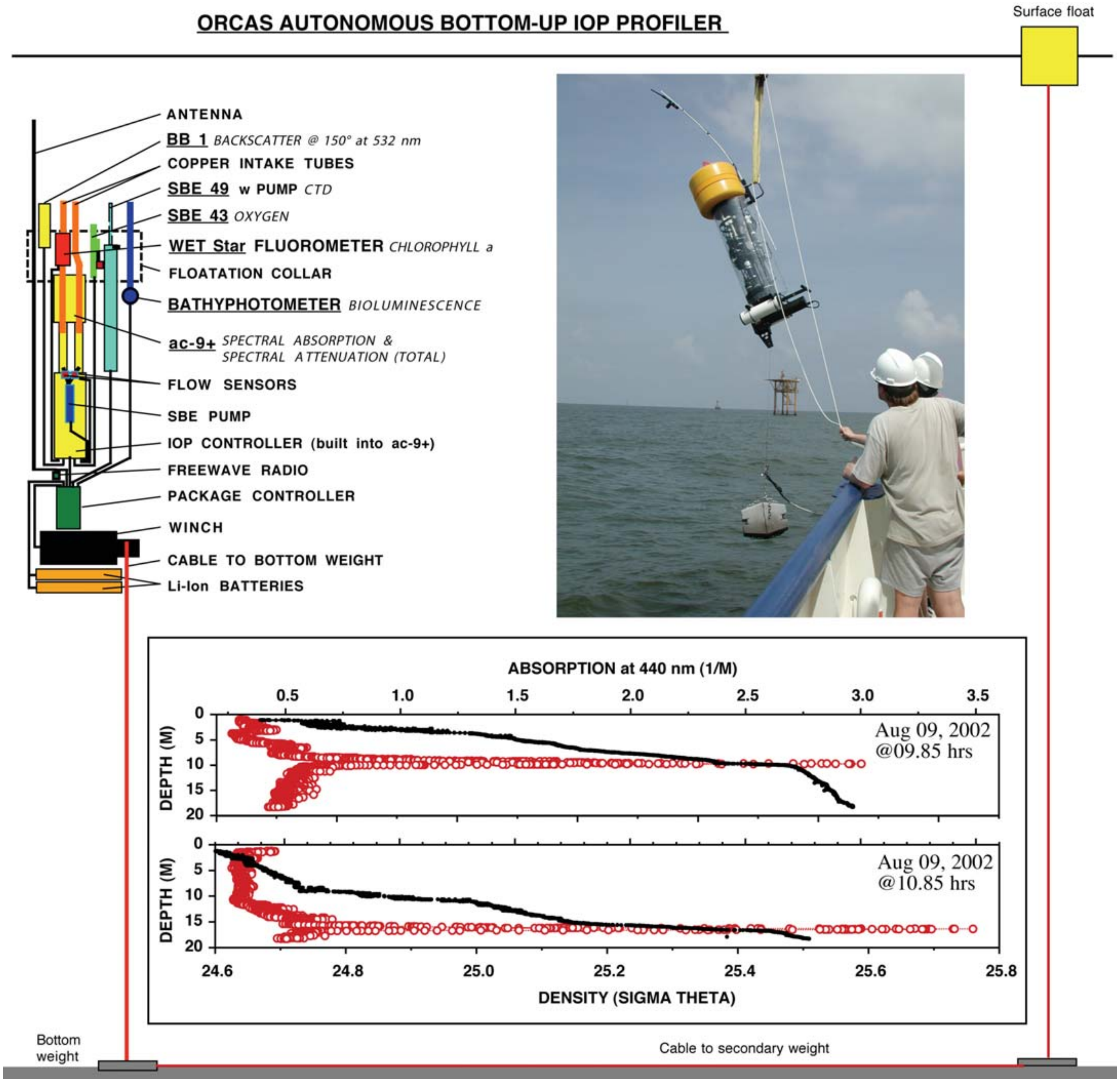

Figure 5. The Ocean Response Coastal Analysis System (ORCAS) autonomous bottom-up profiler used to collect a week-long time series of vertical profiles in northeastern Monterey Bay, CA. The profiler design and picture are illustrated at the top of the figure along with 2 of the 187 sequential vertical profiles of absorption at 440 nm (the wavelength of peak absorption by chlorophyll *a*) (red circles) and density (black dots). This thin layer was dominated by *Pseudo-nitzschia* and persisted for 5 days. The profiler uses a positively buoyant sensor package and a small underwater winch to profile fine scale physical, chemical, and optical structure from the bottom up. These profilers, co-developed with WET Labs (www.wetlabs.com), are fully self-contained with onboard microprocessors, controllers, batteries, and radio communication systems. They can characterize vertical structure on the scale of cm using sensors for spectral absorption, spectral attenuation, spectral scatter, chlorophyll *a* fluorescence, optical backscatter, and mechanically stimulated bioluminescence.

surements of irradiance or radiance taken at one location or time can be quantitatively compared to measurements taken elsewhere or through long time series. AOP sensors are therefore especially appropriate for extensive and sustained monitoring, and for applications with diverse participants, such as the Global Ocean Observing System (GOOS). Additionally, quantities such K_d and R can be derived without absolute calibration, providing the opportunity for development of low-cost applications.

AOP sensors can be placed on many different platforms, although their deployment needs some care regarding measurement geometry (Morel and Lewis, in press). One of the most spectacular approaches for AOP measurement is ocean color remote sensing from space. There are now several operational sensors in flight providing global and recurrent coverage, with spatial and spectral resolution that has progressively improved with newer sensors. Ocean color remote sensing has been successfully used, in a limited number of cases, to detect HABs (Ruddick et al., in press; see the examples in Figure 8). Current limitations of this technique are related to atmospheric corrections and interpretation of the signal in coastal waters where interference from CDOM and suspended sediment can confound conventional algorithms.

The optical signal of chlorophyll *a in vivo* fluorescence, stimulated by sunlight, is another powerful tool for detecting phytoplankton in seawater despite the large variability of the fluorescence quantum yield always observed in the natural environment (Babin, in press).

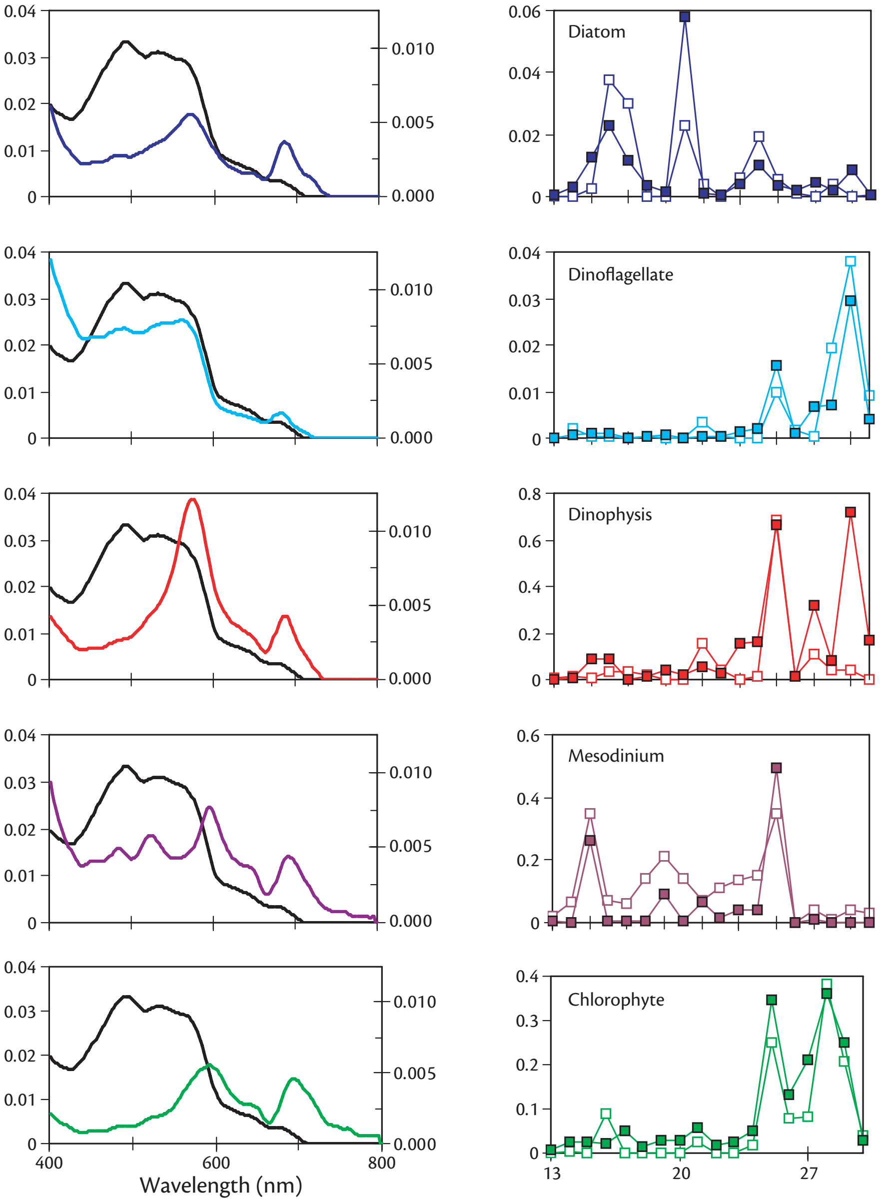

Figure 6. Example of taxonomic identification from a hyperspectral surface reflectance time series collected during an extensive red tide bloom off the west coast of South Africa in the Benguela upwelling zone in March 2001. Left panel: Sample reflectance spectra of pre-HAB conditions (black curve, left axis) and near-monospecific conditions (colored curve, right axis) observed over the 17-day time series. Right panel: Time series of phytoplankton absorption coefficients (676 nm, m^{-1}) for five separable taxonomic groups derived from inversion of hyperspectral reflectance (solid symbols, Roesler and Boss, 2003) and computed from microscopic cell counts, cell size, and cellular absorption efficiency (Roesler et al., 2003). X-axis is date in March 2001, correlation coefficients between reflectance- and microscopy-derived estimates are from top to bottom: 0.63, 0.90, 0.62, 0.84, and 0.93, respectively.

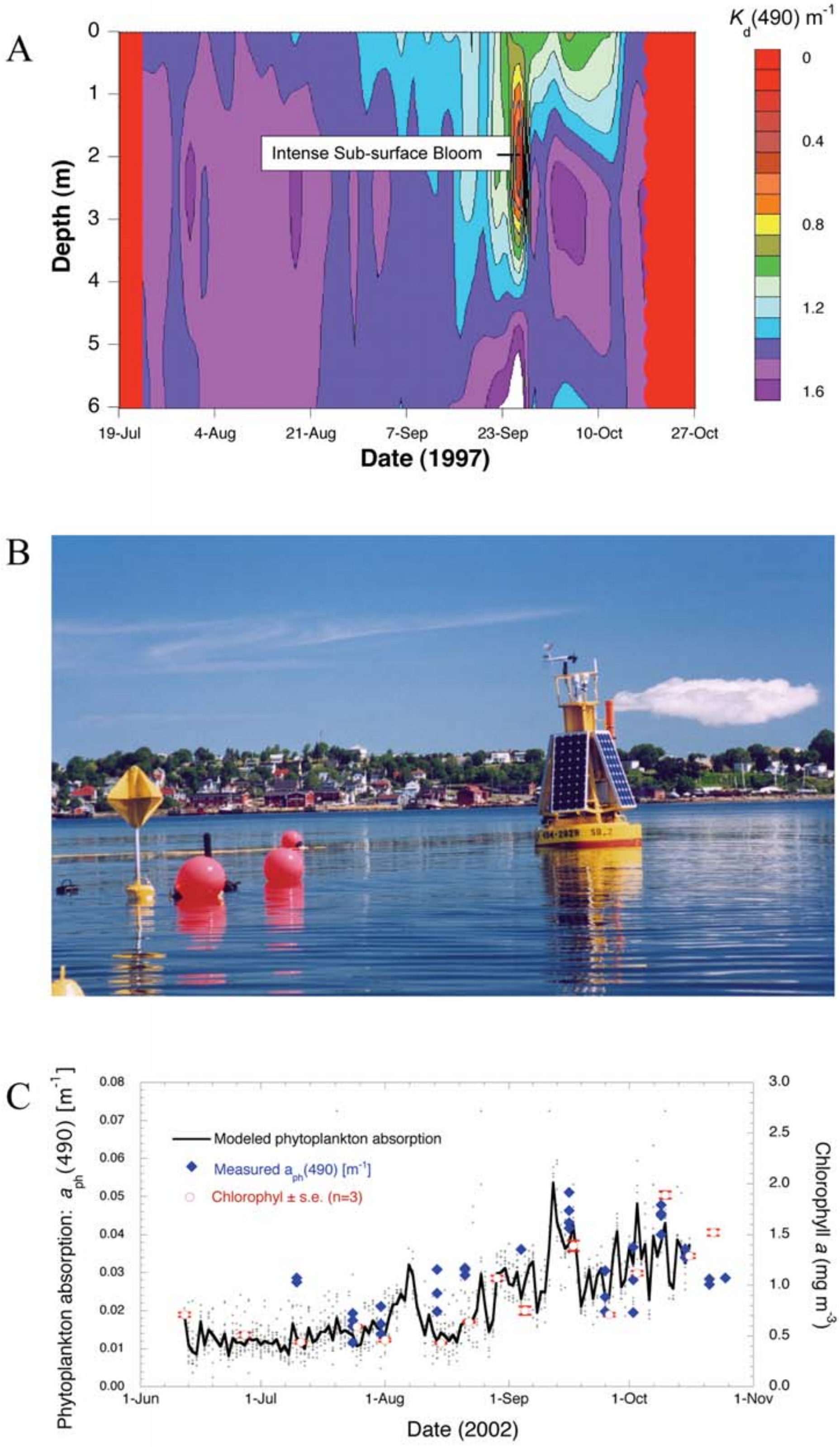

Figure 7. Detection of bloom dynamics with measurements of light attenuation. (A) A moored chain of upward-looking irradiance sensors (490 nm K-chain) was used to estimate the attenuation of irradiance as a function of depth in a coastal embayment (Bedford Basin). An intense, but ephemeral, sub-surface bloom of dinoflagellates was observed; the surface manifestation was much weaker. Moored K-chains are thus useful for detecting intense blooms, even below the surface (M. Lewis and J. Cullen). (B) The Marine Environmental Prediction System-Bay (www.cmep.ca/bay) has three moorings in Lunenburg Bay, Nova Scotia with salinity-temperature chains, current meters, and meteorological and optical sensors, including spectral K-chains; a data assimilation model is being developed to incorporate these data and other local observations into a real-time, coupled atmosphere-ocean simulation of the bay (photo by P. Kuhn). (C) Nearly continuous measurements of hyperspectral ocean color were analyzed by C. Brown and Y. Huot (unpubl.) with an inverse model, generating estimates of phytoplankton absorption (black dots) corrected for the substantial contribution of CDOM and other constituents of the water. The black line is a locally weighted least squares regression to indicate trends. Blue symbols show direct measurements of phytoplankton absorption (filter pad method, corrected for detritus) and open red symbols are determinations of extracted chlorophyll. Large blooms were absent and absorption by phytoplankton at 490 nm was much less than that by CDOM, so subsurface gradients of phytoplankton were masked by CDOM.

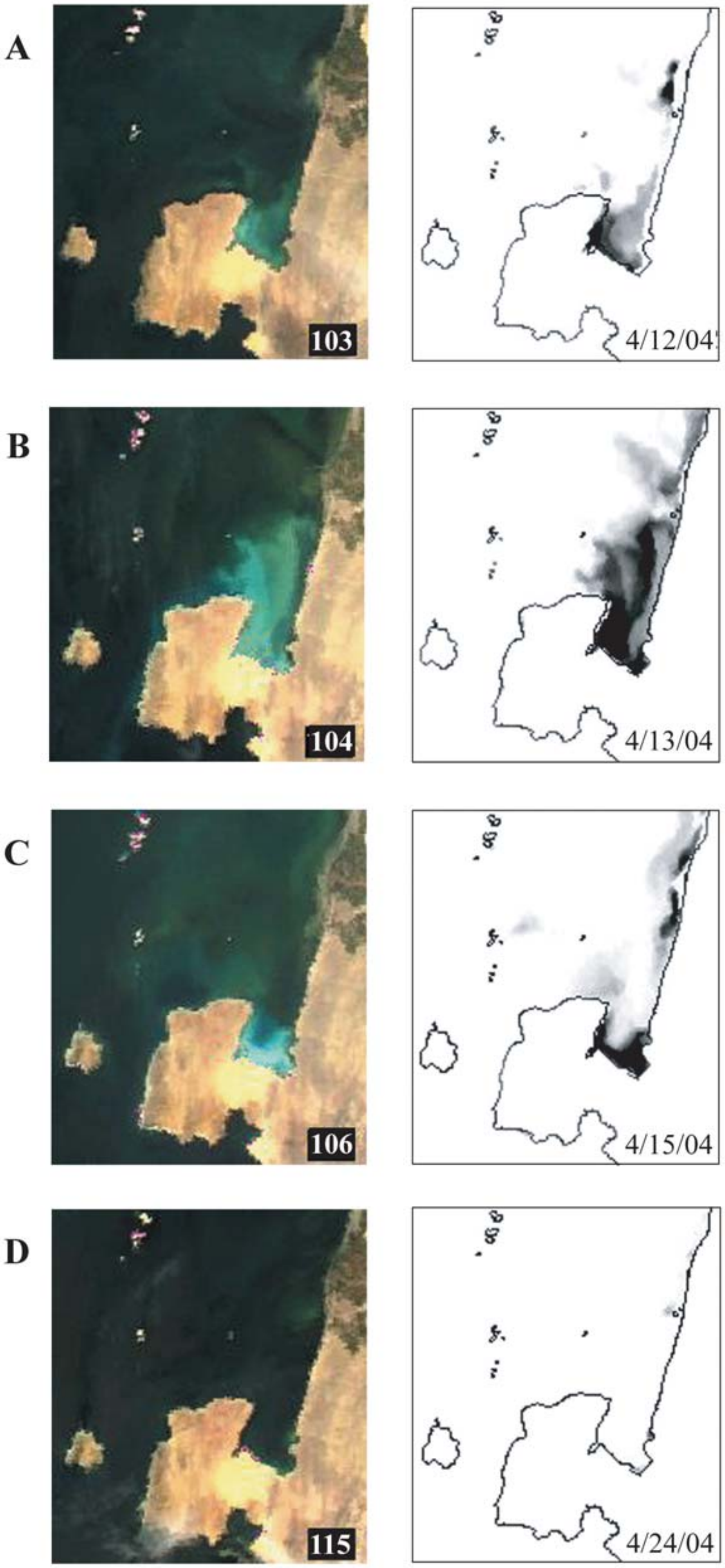

Figure 8. A harmful phytoplankton bloom dominated by the dinoflagellate *Gymnodinium sanguineum* in Paracas Bay, Peru in April 2004 caused estimated economic damage of US$28.5 million. While standard ocean color products of SeaWiFS and MODIS satellites were of little use in this case due to insufficient resolution and problems in atmospheric correction and radiance inversion, MODIS medium-resolution bands provided valuable information with empirical processing algorithms (Kahru et al., 2004). The image, republished from *Eos*, *Trans.* AGU. 85: 465-472, shows the application of two empirical products in monitoring of the devastating bloom in Paracas Bay. The left column shows that the true-color (red-green-blue) images using, respectively, MODIS bands 1 (red), 4 (green), and 3 (blue) can clearly identify the distribution of the bloom in the bay by its conspicuous bright color. The right column shows the turbidity index, a semi-quantitative measure of the amount of particulate material in the near-surface water. Darker areas show higher turbidity. Julian day is shown for the true-color images, and the corresponding date (month/day/year) is shown for the turbidity images. While turbidity is not specific to algal blooms, it is a quantitative estimate of the intensity of the bloom once the existence of the bloom is detected by the true-color images. During the rise and fall of the bloom in the bay, turbidity was inversely correlated with oxygen concentration. Oxygen depletion caused most of the damage to the benthic communities. The top panel (A) shows the bloom in the increasing phase, panel (B) shows the maximum extent of the bloom, panel (D) shows the decreasing phase of the bloom, and the bottom panel (E) shows the normal conditions after the bloom.

More traditionally, fluorometers with internal light sources are used to detect phytoplankton. New applications have been developed. *In situ* spectrofluorometry provides a direct measurement of the shape of the phytoplankton absorption spectrum and allows discrimination of phycobilin-containing phytoplankton groups (mostly cyanobacteria and cryptophytes) from others. A more sophisticated physiological analysis of chlorophyll *a* fluorescence from a special class of fluorometer provides quantitative information on the status of the photosynthetic apparatus (e.g., Kolber et al., 1998), and can be used to estimate primary production (Kolber and Falkowski, 1993), vastly increasing the information potential from *in situ* fluorometry.

Nutrient Sensors

In many cases, nutrients play a central role in controlling population and community dynamics of HABs. This is, of course, especially true for eutrophication, but vertical nutrient structures may play important roles in the development of HABs that occur as vertically migrating populations or subsurface thin layers. Submersible chemical analyzers using wet chemistry have recently been commercialized. They can measure nutrient concentrations continuously *in situ* and thus can provide data on vertical or horizontal nutrient structure. Commercial versions of these systems can be deployed from ships for vertical profiling or on towed bodies and AUVs for spatial mapping (reviewed by Hanson and Moore, 2001). The submersible chemical analyzers can measure nitrate, nitrite, phosphate, silicate, and iron. Issues limiting the application of these in HAB research include ease of use by non-chemists, storage of reagents, calibration, length of deployment, and power consumption. An alternative new type of commercial nutrient sensor uses absorption in the UV to measure nitrate concentration (Johnson and Coletti, 2002). Although this nitrate sensor is easier to use and calibrate, and has excellent long-term stability, it cannot be used to measure other types of nutrients. More research is needed to adapt autonomous nutrient analyzers to a variety of *in situ* platforms and to resolve the above issues that currently limit their application. More work is also needed to dramatically extend their sensitivity down into the nanomolar range where nutrient concentrations may affect competition between species.

BIOFOULING

Technology has its limits, and the ocean often defines them. All *in situ* sensors are sensitive to biofouling, which can range from a thin organic film to heavy incrustation with a community of microbes, plants, and animals. Depending on the application and environment, sensors can be rendered useless by fouling in a few days, or they may operate for many months without significant problems. Any detecting surface or transducer can be compromised by fouling, but optical sensors are especially sensitive because the validity of their calibration relies upon the cleanliness of the windows. Heavy fouling alters the chemical environment near a sensor, so measurements of nutrients or oxygen are not immune. Many remedies have been developed and some are quite successful (see Lehaître et al., in press; Chang and Dickey, in press), but the intense biofouling in rich coastal environments still prohibits long-term deployments without maintenance.

PLATFORMS FOR INSTRUMENT SYSTEMS

Having the tools for observing oceanographic phenomena is one thing, but using them effectively is another. As we have shown, a new generation of sensors is now available for autonomous deployment in ocean and estuarine observing systems targeted at characterization of HABs and the factors that influence them. Effective use of sensors requires clear definition of the scales that should be observed (Chang and Dickey, in press) and installation of the appropriate sensors on platforms that can observe these scales. There is now a wide array of platforms appropriate for the observation of HABs at various scales, for instance, airplanes, satellites, moorings, bottom-up profilers, towed vehicles, powered AUVs, gliders, various kinds of floats, and ships of opportunity (see Chang and Dickey, in press; Griffiths, in press). Some of the cheapest and most accessible platforms are ships of opportunity, including ferries. Their use for sustained HAB monitoring has proven to be valuable, for instance, in the Baltic Sea (see www.itameriportaali.fi). Nonetheless, to describe the different relevant scales of HABs and the processes that influence them, it is necessary to develop an observation program combining the use of multiple platforms in strategic deployments suited for the HAB phenomena of interest.

STRATEGIES FOR OBSERVING DIFFERENT TYPES OF HAB

The scales of variability for HABs are among the most important factors to consider when designing an observation strategy (Chang and Dickey, in press). The important spatial scales relate not only to the distributions of target species in horizontal and vertical dimensions (for which taxonomic identification and physiological characterization would be important), but also to the physical, chemical, and community processes that affect the population dynamics of the HAB species, including the interactions between behavior (sinking, floating, swimming) and circulation (Franks, 1997, and in press). The physical processes that can affect the spatial-scale characteristics of HABs include turbulence, waves, wind-driven vertical mixing, convection, light distribution, tides, thermohaline vertical gradients, fronts, eddies, bathymetry-related circulation, climate oscillations, and climate change. The full spectrum of physical processes covers scales of micrometers to thousands of kilometers, but some of these processes are more significant for given HAB species and these must be identified when designing a targeted observation strategy. The same is true for chemical (e.g., nutrient concentration and ratios, allelopathy) and community (e.g., grazing) processes.

A minimum temporal resolution of sampling corresponds to each of the above-mentioned physical, chemical, and community processes. In addition, physiological mechanisms such as growth, diel vertical migration, circadian clocks and the cell cycle, acclimation processes, and life-cycle events such as encystment and excystment, can strongly affect the dynamics of a HAB. Consequently, the spectrum of temporal scales relevant to HABs ranges from a second or so to hundreds of years; however, as it is the case for spatial scales, some of them are more significant for given HAB phenomena.

Technical advances are rapidly transforming oceanography, but technology alone cannot solve pressing environmental challenges such as the need to detect and predict harmful algal blooms.

Although technology is advancing rapidly, it will never be possible to measure everything continuously and synoptically. Observation strategies must be designed to make the most of limited resources. As proposed by Cullen (in press), a coarse classification of HABs can be useful as an initial guide to identify relevant scales and appropriate observation strategies for local or regional observation programs. The classification is summarized here, with suggestions for observation strategies.

Widespread HABs Dominated by One Species: Extensive, Progressive Coastal Blooms

There are several examples of nearly monospecific and often toxic, extensive blooms that appear in coastal waters and progress along the shoreline. Some examples include blooms of *Karenia brevis* in the Gulf of Mexico, *Alexandrium catenella* off the western coast of South Africa in 2002, *Karenia mikimotoi* (formerly *Gyrodinium aureloum* or *Gymnodinium mikimotoi*) in northern European shelf waters, the toxic bloom of *Chrysochromulina polylepis* in Scandinavian waters in 1988, blooms of *Heterosigma* in the Strait of Georgia and adjacent waters in western Canada, and the dramatic bloom of *Karenia digitata* in Hong Kong waters during April 1998. Hypotheses about bloom dynamics focus on the processes of initiation, including transport of populations from offshore, and interactions of populations with surface circulation during the progression of a bloom.

Many environmental properties must be measured for effective early warning, monitoring, and prediction of blooms progressing along a coast. For early warning, species- or group-level observation technologies are generally necessary (Figures 1 to 4, Figure 6). Once the species forming a bloom is known, and when conditions permit, remote sensing from satellites and aircraft can provide key information on distributions and transport of biomass (Ruddick et al., in press; Stumpf et al., 2003), especially when supplemented by observation networks that include direct sampling, for instance, for microscopic examination (Figure 7) (Johnsen et al., 1997). Even if surface distributions of developed blooms are resolved with remote sensing, early stages and subsurface distributions signatures must be described by other means. In particular, vertical distributions of phytoplankton should be well resolved because the interaction of swimming, sinking, or floating with frontal features, aggregation of seed populations in subsurface layers near the pycnocline, and changes of behavior in mixed waters landward of a front (possibly associated with nutrition) all may be important in initiation, maintenance, and transport of extensive, progressive, coastal blooms (Donaghay and Osborn, 1997; Cowles, 2003). Consequently, for early warning and monitoring, observation systems must resolve vertical distributions of phytoplankton in relationship to temperature, salinity, and currents, and they must have the means to detect target species (and, optimally their toxins) *in situ*. Because nutrient availability can influence toxicity and depletion of nutrients can terminate a bloom, the nutrient regime should also be assessed as part of monitoring and modeling strategies.

Progressive coastal blooms move with coastal currents and can appear or disappear on the time scale of days. Effective monitoring thus requires nearly continuous measurements, and mitigation responses (such as the movement of aquaculture cages) require communications in near-real-time. Strategies for management, such as controls on coastal nutrient loading or site selection for aquaculture, depend on sustained observations over many years to determine the relationships among environmental variability (e.g., climate change), human influences (e.g., nutrient loading), bloom occurrences, and their impacts.

Widespread HABs: Extensive Blooms in Open Waters

For a second class of HABs, our interest is focused on harmful or potentially harmful blooms that occur in open waters in semi-enclosed seas or near coasts where they can influence coastal ecosystems and be affected by terrestrial inputs of freshwater and nutrients. The Baltic, North Sea, and Bohai are exemplary. In the Baltic Sea, summer blooms of nitrogen-fixing cyanobacteria are common. The hepatotoxic *Nodularia spumigena* forms conspicuous HABs in open waters; during the latter stages of a bloom, filaments form highly visible aggregates at the surface that can be detected from space (Kahru et al., 1994). Harmful effects include nitrogen enrichment as well as toxicity upon landfall. Blooms of *Phaeocystis* in the North Sea are influenced by nutrient loading from rivers; they can deliver prodigious quantities of noxious foams to beaches, with significant economic impact. Finally, China's Bohai is strongly affected by widespread HABs, sometimes clearly detectable from space.

For extensive blooms in open waters, long records that can characterize fundamental changes in both the physicochemical environment and the ecological system, including the frequency, duration, and extent of blooms, are needed for observation and prediction. Predictions could include long-term trends in bloom frequency and yearly projections of probabilities. Except for properties like N:P ratios and deep water salinity and oxygen, periodic surveys are inadequate for developing and testing predictive models because transient and patchy events cannot be resolved. The strategy of continuous sampling from ferries and remote sensing, supplemented with research cruises, appears to be on the right track. Although this does not reach the ideal of continuous and synoptic observations, data obtained through these approaches can be used to describe the variability of phytoplankton with unprecedented temporal and spatial resolution, so the occurrence of HABs can be related directly to environmental forcing, including climate change and nutrient loading from terrestrial sources.

Widespread HABs Dominated by One Species: Localized Blooms

When they occur, HABs cause local problems, regardless of regional extent. Within regions (defined as the next larger scale that must be observed to understand the local scale of interest; Intergovernmental Oceanographic Commission [IOC], 2003) some locations experience recurrent, though not necessarily predictable, HABs, while other nearby locations may be spared. Even though localized HABs are likely related to larger-scale forcings, local conditions must have a strong influence on their occurrence and impacts and thus merit direct focus in the development of observation and prediction systems for monitoring and management. A few of many examples include:

- Blooms of *Heterosigma akashiwo* or *Alexandrium tamarense* in Hiroshima Bay, which can be related to patterns of eutrophication and local hydrography interacting with cyst dynamics, growth, and behavior of the algae;
- PSP toxicity in oceanic bays (rias) of northwest Spain, where *Gymnodinium catenatum* is transported from elsewhere but exerts its effects on local mussel farms due to interactions among longshore transport, estuarine circulation under the influence of winds, and swimming behavior of the dinoflagellates; and
- Brown tides of the pelagophyte *Aureococcus anophagefferens* in U.S. mid-Atlantic coastal waters, which are recurrent and persistent, but not predictable—explanatory hypotheses invoke preferences for organic nitrogen and other nutrients that could be elevated when estuarine flushing is reduced, and also top-down control as influenced by suppressed grazing.

Description and prediction of localized blooms require assessment of their extent and duration in relationship to local conditions, quantification of exchanges with adjacent waters, and enough observations of nearby systems to explain why the HABs occur in one location and not another.

Blooms Strongly Influenced by Buoyancy or Swimming Behavior

Some of the most dramatic photographs of blooms depict strong discoloration of water near frontal features in coastal waters. These phenomena can have significant impacts, for example, when they impinge on aquaculture sites or decay in restricted inlets, causing anoxia. Dense aggregations of phytoplankton, such as those at fronts, surface scums, concentrated subsurface layers, and transient surface accumulations due to diel vertical migration, are all associated with interactions between vertical movements of phytoplankton and discontinuities in the water column (cf. Franks, 1997 and in press). Consequently, detection and description of these blooms require effective sampling of phytoplankton and physical-chemical properties on the scales of the biological-physical interaction, and modeling to describe the consequences of these interactions in three dimensions.

Subsurface layers illustrate the challenges of observation and modeling. Many phytoplankton taxa, including dinoflagellates, the prymnesiophyte *Chrysochromulina polylepis*, and diatoms of the genus *Pseudo-nitzschia*, can form subsurface thin layers, thereby evading detection with conventional sampling (Rines et al., 2002; Holliday et al., 2003). Considering that thin layers are commonly found if appropriate sampling is conducted, and that specialized sampling and analysis have not been widely employed, it is reasonable to expect that many toxic species (and other phytoplankton species) will be found in thin layers of stratified coastal waters. Highly resolved vertical profiles, for example, with special samplers and moored, towed, or autonomous underway profiling systems (e.g., Figure 5), are required to describe the distributions of subsurface blooms. Because buoyancy and swimming behaviors of phytoplankton are strongly influenced by nutrition, the association of subsurface layers with nutrient gradients is quite likely, though rarely explored on this scale of thin layers. Fine-scale determination of nutrient concentrations, as well as temperature, salinity, and currents, is thus needed to resolve causes and dynamics of blooms influenced by buoyancy or swimming behavior.

Toxic HABs

Toxic HABs merit special consideration for several reasons: they can have harmful effects even if the species is not dominant; effective detection at the species level and discrimination from other species is often required; and the production of toxin is under physiological control and can vary among strains within a species and with environmental conditions during the course of a bloom. Toxicity must therefore be detected in concert with distributions of the toxic species (Figure 4) and, if possible, assessment of their physiological state. The effects of toxic HABs depend on the toxin, the targets, and how the toxin gets to the targets. Pathways and efficiencies of transfer between trophic compartments, as well as exchanges between pelagic and benthic communities, must be understood and assessed.

As a result of these issues, the task of observing and predicting the dynamics of toxic HABs starts with the approaches described for blooms on the appropriate scales as described above, but should include several more components: detection and physiological characterization at the species level; measurement of toxin; assessment of toxic effects; and description of how toxins reach various target species (Doucette et al., in press). Toxic effects on competitors, grazers, or predators that feed back on population dynamics should also be explored.

Examples of toxic species illustrate the difficulties that are encountered when trying to detect and predict toxic HABs. The toxic species of the diatom genus *Pseudo-nitzschia* cannot be distinguished on the basis of gross morphology or pigmentation. Its presence can be inferred through the use of specific probes or analysis of samples for domoic acid; however, an uncoupling of organisms and toxin is not unusual given the wide potential fluctuations in cellular toxicity (Scholin et al., in press). Species such as *Alexandrium fundyense* in the Gulf of Maine can cause significant toxicity in shellfish even when present at low concentrations, representing only a fraction of the phytoplankton assemblage. In these cases, routine detection is a major problem. In general, observation and prediction of algal blooms is a challenge that requires a multidisciplinary approach to detect phytoplankton and to describe physical-biological interactions. With the inclusion of toxic effects as a factor, the problem becomes even more multidisciplinary, complicated and challenging (Scholin et al., in press).

PREDICTION OF HABS

Prediction is the stated objective of most plans for real-time coastal observation systems. It can be defined as the estimation of properties that are not observed directly with known certainty (IOC, 2003). This broad definition includes hindcasts, nowcasts, and forecasts. The latter two are key products of real-time systems, but their development and evaluation depends on the former. Nowcasts serve as the best possible assessment of current conditions, useful in early warning. Also, as a time series, nowcasts provide a record of environmental change that is richer than a compilation of direct observations alone; this is the future of coastal monitoring (Cullen, in press). Forecasting of HABs, however, is clearly an ultimate goal.

All prediction depends on models, which include conceptual descriptions of ecological relationships, statistically based empirical models, and a range of numerical models of varying complexity. For many, the Holy Grail is the coupled, physical-biological, ocean-atmosphere, data assimilative model of coastal dynamics including HABs. A broad range of modeling approaches was addressed at the Habwatch workshop and is reported in the proceedings. In the context of our discussion here, it is important to recognize that all predictions depend on observations, and the observations should provide not only the input to the models, but also the data for validating the predictions and estimating error. Consequently, the scales of observations and models should match.

> Integration is the answer: molecular biology and bio-optics with ocean observation technology; physiological ecology with oceanography and numerical modeling; real-time observing systems with ongoing efforts in monitoring and research.

SUMMARY AND GUIDANCE FOR THE GEOHAB PROGRAM

The scientific goal of the GEOHAB program is to "improve prediction of HABs by determining the ecological and oceanographic mechanisms underlying their population dynamics, integrating biological, chemical, and physical studies supported by enhanced observation and modeling." The specific objectives of GEOHAB for observation are:

- To develop capabilities to observe HAB organisms *in situ*, including their properties and the processes that influence them;
- To develop and evaluate systems for long-term monitoring of HAB species;
- To develop capabilities for real-time observation and prediction of HABs.

According to the GEOHAB Science Plan, "GEOHAB will foster the development of new observation technologies and models to support fundamental research on HABs, improve monitoring, and develop predictive capabilities. Because capabilities in coastal observation and modeling are advancing rapidly on many fronts, coordination and cooperation among the different elements of the GEOHAB program are essential. The intention is to ensure rapid and effective integration of knowledge, technical capabilities, and data across disciplines and regions." The Habwatch workshop contributed strongly to the latter, and based on the proceedings we offer two recommendations as guidance for the GEOHAB program.

Encourage Further Advances In Species-Specific Detection

Many of the new, powerful, and exciting tools for observation of HABs have widespread oceanographic applications and merit strong, broad-based support. Some of the most promising approaches for early warning and for studying HAB species are those employing molecular-based methods. Prototypes of rRNA probe arrays for *in situ* and autonomous deployment have been tested and several new toxin detection technologies may be amenable to *in situ* platforms. GEOHAB should encourage development of a broad range of tools for observations of HABs, with a priority on the development of species-specific sensors.

Promote The Development of Integrated Observation Systems

Populations of HAB species develop in different environments (e.g., bays, fjords, open ocean), and at various temporal and spatial scales (e.g., patches, large blooms, thin layers). Some form high-biomass blooms while others do not. Observations serve many purposes in the study, monitoring and prediction of harmful algal blooms: (1) early warning; (2) description of population and ecosystem dynamics; (3) model development, including parameterization and validation; (4) determination of model initial and boundary conditions; (5) data assimilation in predictive models; and (6) time-series analysis. A growing arsenal of sensors can provide observations to serve these purposes, but many sensors operate only in specific conditions (e.g., clear skies for ocean color remote sensing) and with different spatial and temporal resolutions. So, a combination of platforms and sensors is necessary to observe and predict HABs. Observation strategies must be developed for each HAB phenomenon using knowledge of oceanography and bloom dynamics to design a system making the best use of available platforms and sensors to serve identified scientific and management goals. We therefore recommend that, within the framework of GEOHAB, high priority be given to research on integrated observation strategies tailored to the specific phenomena being studied.

Workshops such as Habwatch and programs such as GEOHAB foster the interdisciplinary and international interactions that will result in new capabilities to observe and predict HABs.

CONCLUSION

Technical advances are rapidly transforming oceanography, but technology alone cannot solve pressing environmental challenges such as the need to detect and predict harmful algal blooms. Integration is the answer: molecular biology and bio-optics with ocean observation technology; physiological ecology with oceanography and numerical modeling; real-time observing systems with ongoing efforts in monitoring and research. Workshops such as Habwatch and programs such as GEOHAB foster the interdisciplinary and international interactions that will result in new capabilities to observe and predict HABs. Continued commitment to communication and collaboration across disciplines and sectors will ensure rapid progress.

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