

The Monitoring of Harmful Algal Blooms through Ocean Observing: The Development of the California Harmful Algal Bloom Monitoring and Alert Program

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1. INTRODUCTION AND BACKGROUND

Phytoplankton are at the base of the food chain in most freshwater and marine systems. These single-celled photosynthetic algae provide many positive benefits including production of about half the oxygen on the planet, and transformation of sunlight and inorganic elements into the organic material and energy that drives our productive aquatic ecosystems. The dominance of cells of one or several species of phytoplankton can form an algal bloom, either through rapid growth or minimal

loss (e.g., grazing, physical advection, or sinking). Though blooms are often harmless or beneficial to the functioning of marine and freshwater ecosystems, there is increasing awareness that blooms can also be indicative of eutrophication, ecosystem disruption, or altered environmental states.^{1–3}

Some algal blooms can have negative impacts to the environment, human and aquatic health, and the economy (such as aquaculture, fisheries, and tourism) and are thus termed harmful algal blooms (HABs). HABs negatively affect many freshwater systems and the majority of coastal regions worldwide. There is consensus that the impact of such blooms has grown over the last few decades, causing harm to public health, ecosystem function, fisheries and aquaculture, and recreation/tourism industries.⁴ Despite the broad consensus that HAB impacts are increasing, it is challenging to describe the research, management, and mitigation strategies coherently because the term HAB encompasses a wide, and sometimes bewildering, array of species, life histories, ecosystems, and impacts. There is no unifying ecological or evolutionary theme in the organisms considered to form HABs. They span the majority of algal taxonomic groups, including both eukaryotes and prokaryotes; some produce potent toxins, and others cause harm through a variety of other mechanisms. The dinoflagellates account for the majority (75%) of HAB species, but there are HAB representatives from nearly every algal taxon.⁵

To categorize the many groupings of potentially harmful algae, HABs are often first divided into toxic versus high-biomass blooms. Although they comprise a minority of the phytoplankton assemblage, toxic species can and do have significant impacts on human, marine life, and ecosystem health.⁶ In California and along the US West Coast, toxic species are the most frequently encountered HABs; they consist primarily of the dinoflagellate genus *Alexandrium* (Paralytic Shellfish Poisoning) and the diatom genus *Pseudo-nitzschia* (Amnesic Shellfish Poisoning and Domoic Acid Poisoning).⁷ Less frequently observed, but emerging as serious potential threats, are the dinoflagellates *Dinophysis* (which can cause Diarrhetic Shellfish Poisoning^{8,9}) and *Gonyaulax* and *Lingulodinium* (Yessotoxin producers^{10,11}), whereas the freshwater cyanobacteria *Microcystis* (a Microcystin producer) threatens not only the terrestrial environment but also estuarine and coastal waters.^{12,13} Other toxic species have been encountered in California, but this relatively short list comprises the majority of significant toxic HAB issues seen to date.

In contrast to blooms of toxic species, high-biomass blooms cause negative impacts through the sheer abundance of cells.³ This can lead to physical disruption of other organisms via gill irritation, viscosity, and gelatinous barriers that lead to gill clogging, production of allelochemicals, and anoxia or hypoxia following the decay of large blooms. Impacts to humans include disruption of desalination systems and drinking water supplies, as well as impacts to tourism due to accumulation of dead organisms, foul smells, foam production, and discoloration of the water. Many of these HABs fall under the general term ecosystem disruptive algal blooms (EDABs^{14,15}). This group includes emergence of organisms previously thought to be harmless such as the dinoflagellate *Akashiwo sanguinea*, which can produce foam with surfactant properties resulting in the large-scale mortality of marine birds,¹⁶

as well as organisms such as the dinoflagellate *Cochlodinium* (fish killer^{17–19}) and the raphidophyte *Heterosigma akashiwo* (fish killer^{20,21}), which until recently have not been as problematic in California compared to other regions.⁸

This considerable diversity in organisms, impacts, mechanisms, and potential solutions led to the realization that there is no single solution to understanding, monitoring, predicting, or mitigating HAB problems within California or along the US West Coast. Though California has been highly successful at minimizing human health impacts through the establishment of the marine Biotoxin Monitoring Program by the California Department of Public Health, this program was not intended to address the wide array of emerging issues that includes impacts to ecosystem and wildlife health, emerging toxins, and HAB dynamics driven by both terrestrial and marine processes. Research efforts funded by agencies such as California Sea Grant and the NOAA competitive HAB programs ECOHAB and MERHAB provided significant funding leading to advances in understanding and monitoring HABs in California, but these programs were necessarily focused on specific regions, organisms, and impacts. Discussions between the NOAA competitive HAB program, disparate phytoplankton monitoring efforts, agencies managing HAB impacted resources, and the Southern California Coastal Water Research Program (SCCWRP) identified a needed statewide capacity for monitoring and HAB alerts that encompasses all of the existing and emerging HAB issues. It is within this context that the NOAA Center for Sponsored Coastal Ocean Research, SCCWRP, and the California Ocean Science Trust convened the first workshop in 2008 that developed the California Harmful Algal Bloom Monitoring and Alert Program, or CalHABMAP.²²

The 2008 workshop participants included the leading HAB researchers in California and representatives with a wide variety of stakeholders, such as water quality management representatives, public health officials that manage the shellfish industry, animal rescue communities, universities, and state and local agencies. These participants strongly agreed that there was a need for a coordinated HAB alert system. Thus, the goal of CalHABMAP is to implement a proactive HAB alert network that will provide algal bloom forecasts and facilitate information exchange among HAB researchers, managers, and the general public. Crucial decisions on how to respond to HAB events, how to mitigate their impacts, and how to predict them, require knowledge of their occurrence and their impacts along our coast. Instituting a statewide alert network is a critical first step in moving toward an operational forecast and prevention program.

CalHABMAP created an integrated, statewide HAB monitoring and alert network by coordinating organizations and researchers currently collecting HAB data and created a centralized portal for the dissemination of this information. The program also established an ambitious set of goals including studies to normalize the diverse methodologies employed to identify toxin and toxic algal species in coastal waters, and development of an economic analysis of resources along the California coast and the potential impact of HABs on these resources. Thus the main goal of CalHABMAP is to ultimately implement a statewide

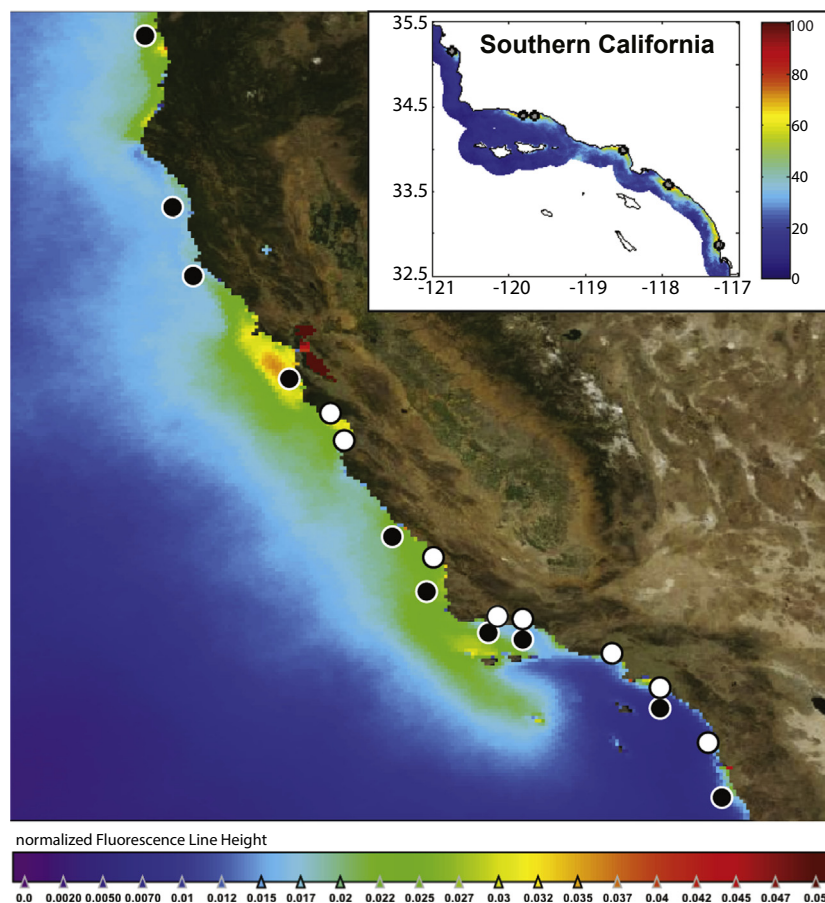
HAB network and forecasting system for California, and potentially the US West Coast, by implementing the following specific objectives:

- Design an HAB network that will meet the needs of, and will be accessible to, all HAB stakeholders.
- Create a web portal within the California Ocean Observing System's programs and act as a mechanism to bring these two programs together. The portal would be a centralized location where HAB data and predictive information could be used by many groups throughout the state.
- Conduct a comparison of analytical methods for toxin analysis and harmful algae identification and enumeration, and review and disseminate the results through a workshop. The method comparison information will be critical to establish guidelines for comparing different data sets currently collected, and it will help determine the finalized design for the CalHABMAP network.
- Conduct an economic analysis of the potential impacts of HABs along the California coast.
- Collaborate with the Water Quality Monitoring Council to ensure that HAB information and data are included in and accessible from water quality websites.

2. THE CalHABMAP NETWORK

At the heart of CalHABMAP is the development of a grassroots-driven, voluntary network of HAB researchers, managers, and other volunteers who share and disseminate information about HABs in California. The first step was to develop a CalHABMAP listserv to provide an efficient mechanism for all of the interested parties to communicate. The listserv provides the following types of data and information:

1. Results from weekly phytoplankton monitoring samples are collected and the results are published to the list in a standardized report format. These weekly HAB Monitoring Reports are posted from the following locations (see also [Figure 1](#)):
 - a. Santa Cruz Municipal Wharf, Santa Cruz
 - b. Monterey Wharf, Monterey
 - c. Cal Poly Pier, San Luis Obispo
 - e. Goleta Pier, Goleta
 - f. Stearn's Wharf, Santa Barbara
 - g. Santa Monica Pier, Santa Monica
 - h. Newport Pier, Newport
 - i. Scripps Pier, La Jolla
2. Monthly Biotoxin Report provided by California Department of Public Health, Plankton Monitoring Program
3. General comments and an open forum to discuss current HAB conditions or marine mammal and bird strandings

**FIGURE 1**

Locations of existing CalHABMAP stations (white circles) and proposed new stations (black circles) overlaid over the background of mean normalized fluorescence line height, a proxy for phytoplankton biomass. New station locations were conditioned on the continued existence of the existing CalHABMAP stations. The addition of the new stations improves probability of identifying an HAB from $\sim 20\%$ to $\sim 70\%$. The inset shows the spatial map of HAB coverage for the existing stations in Southern California. Warmer colors indicate the region represented by the station information, whereas blue indicates the regions for which the shore station information is inadequate.

An important component of the listserv is that it *integrates* groups across the region, and it can accommodate expansion to include both Mexican observations (already in place) and observations from the other western states. Though the majority of oceanographic stations and sampling locations are maintained and operated by the Southern California Coastal Ocean Observing System (SCCOOS), the Central

and Northern California Ocean Observing System (CeNCOOS), and the California Department of Public Health (CDPH), all of the data are collated and presented as part of CalHABMAP.

Whereas the network is based primarily on historical locations where HABs were monitored, a second component of CalHABMAP is the assessment of an “ideal” network. Toward this end, Frolov et al.²³ and Kudela et al.²⁴ identified the optimal network for monitoring HABs in California. That analysis found that only the CDPH network, with 50 sites routinely sampled, had sufficient spatial and temporal coverage to capture 60% of potential blooms. In contrast, the SCCOOS/CeNCOOS networks capture only 20% of the variability, but do so at economically and ecologically important sites. However, with the inclusion of just 10 additional optimally placed stations (some of which are on the continental shelf rather than at the shore) to complement the eight occupied by CeNCOOS/SCCOOS, 73% of the variability could be captured, including offshore (more than a few km from the coast) sites that are particularly relevant with the permitting of Catalina Sea Ranch offshore aquaculture farm by the California Coastal Commission in 2014. This represents the first large-scale offshore aquaculture facility in California, and will likely not be efficaciously covered by the existing CDPH network. The results of a more quantitative analysis of an optimal HAB monitoring program demonstrate that better coverage can be achieved with fewer stations while simultaneously extending the program to cover nearshore waters.

In addition to the listserv, CalHABMAP proposed to develop a single web portal that would integrate observations from members, providing a single location where end users could acquire information (Figure 2). This has been more challenging than anticipated because many groups are required to or find it desirable to maintain individual web pages and databases. Nonetheless, a significant accomplishment from CalHABMAP has been the development of a data portal that merges the two Ocean Observing System datasets seamlessly. This portal is hosted at <http://www.habmap.info>, with financial support from CeNCOOS, SCCOOS, and the California Ocean Protection Council. Data are hosted and maintained by SCCOOS using a common format and web-enabled database. This system allows for data exploration and real-time information, as well as supporting peer-reviewed research on the status and trends of HABs within California (e.g.,^{7,23,25}). A similar web-based graphical approach has been taken by CDPH for dissemination of the Marine Biotxin Monitoring Program data, used by the State to regulate marine biotoxins (Figure 3).

Recognition that HABs are a major contributor to poor health and strandings of marine mammals^{26–28} has pushed the development of a coordinated monitoring effort for marine mammals as well.²⁹ There is no national program for monitoring marine animal health, despite the numerous monitoring initiatives maintained by private groups, and federal and state agencies. To facilitate this effort Axiom Consulting & Design, working with CeNCOOS and in collaboration with SCCOOS, the Marine Mammal Center, and other agencies, is developing an interactive Marine Mammal Health Map (Figure 4). A separate but coordinated

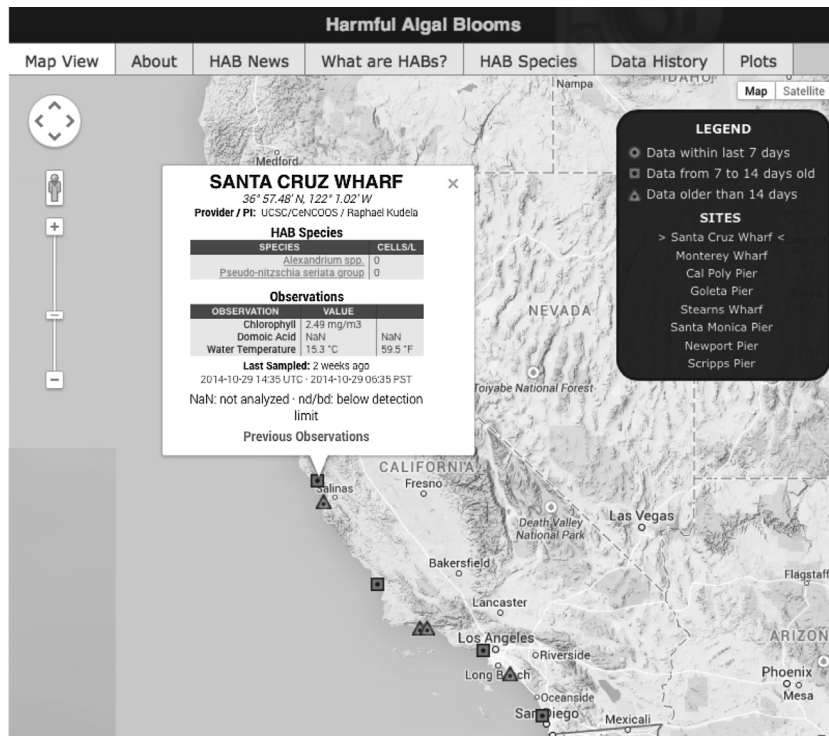


FIGURE 2

The HAB data portal for CalHABMAP, maintained by SCCOOS. The interactive map provides access to the near real-time data from each site and links to historical data. The maps can be accessed at <http://www.habmap.info/data.html>.

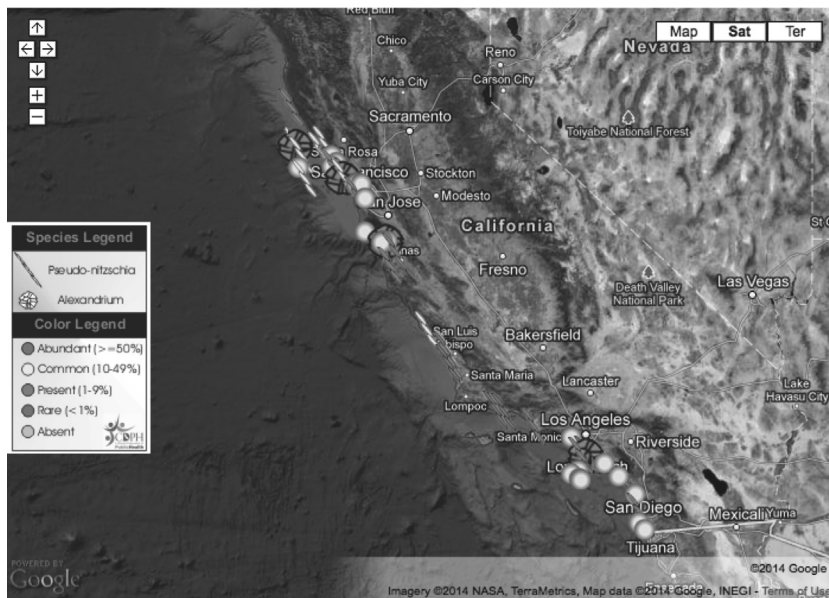


FIGURE 3

HAB location and abundance data provided by the California Department of Public Health for the fourth week of September, 2014. The interactive map can be accessed at <http://www.cdph.ca.gov/HealthInfo/environhealth/water/Pages/Toxmap.aspx>.

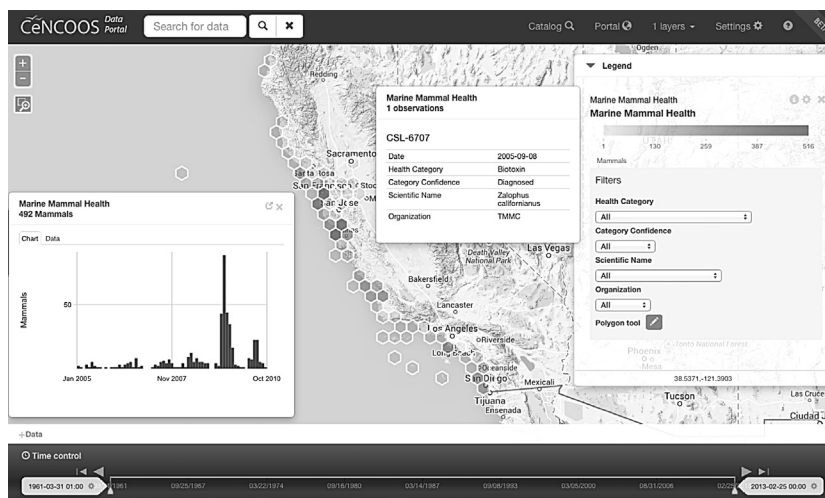


FIGURE 4

A screenshot from the beta version of the Marine Mammal Health Map, hosted by CeNCOOS. The map provides easy visual representation of marine mammal stranding data geographically (polygons) with shading (red in the original) indicating the number of impacted animals. The inset boxes show examples of data available by clicking on polygons. Additional layers, such as numerical model data, satellite imagery, or other oceanographic information can be added to provide context and exploratory data analysis.

program has introduced marine mammal strandings to the Jellywatch Website (<http://www.jellywatch.org>), creating a crowd-sourcing component that directly engages the public in identifying the impact of HAB events.

3. DEVELOPMENT OF AN HAB FORECASTING CAPABILITY

A significant advancement toward an operational California HAB forecast has been the transition of a research-based forecast system for the toxic diatom *Pseudo-nitzschia*^{6,24,30} toward an operational forecasting system. As reviewed by Anderson et al.,⁶ there are many ways to implement a regional forecast of HABs based on empirical, statistical, and/or numerical models. Preliminary empirical studies on HABs in the California Current System (CCS) provide the basis to forecast blooms and toxin production using statistical models (Figure 5).

Anderson et al.³⁰ extended a previous study on the Santa Barbara Channel (SBC), located at the northern extreme of the Southern California Bight,^{31,32} and they identified several variables to be good predictors of *Pseudo-nitzschia* abundance and high domoic acid concentrations in surface waters south and east of Pt. Conception. The first study employed stepwise multiple linear regression to

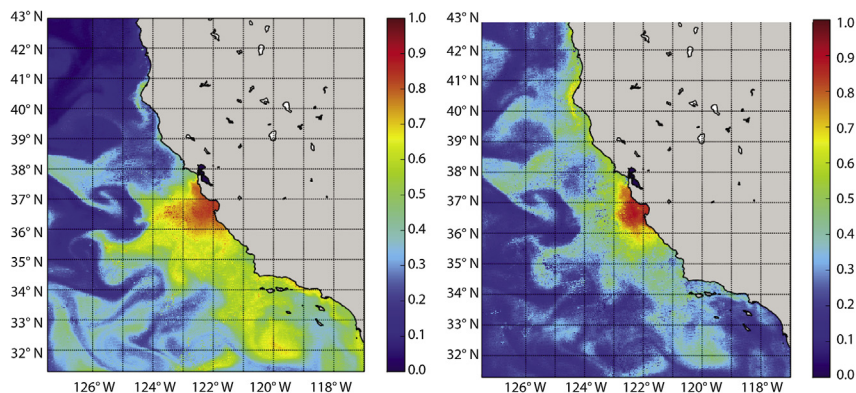


FIGURE 5

Probability of particulate domoic acid (left) and cellular domoic acid (right) for March 26, 2014, from the coupled modeling approach employed by CeNCOOS. Further details are available at <http://www.cencoos.org/sections/conditions/blooms/habforecast/>.

correlate hydrographic and chemical shipboard data with a broad range of *Pseudo-nitzschia* cell densities and domoic acid loads from inshore and offshore sites within the SBC from 2004–2006.³¹ In the follow-on study, Anderson et al.³² created similar models to predict *Pseudo-nitzschia* spp. cell abundance, particulate domoic acid, and cellular domoic acid from a longer HAB dataset that included new observations from 2009 to 2010 and used the more flexible generalized linear model (GLM) method in place of the optimal least squares approach.^{33,34} The significant predictor variables in the new GLMs agree well with previous models,³² indicating a consistent set of environmental controls on HABs over time, e.g., chlorophyll-a, macronutrient availability (reduced ratios of Si:N and Si:P), and upwelling (negative relationship with temperature and positive relationship with salinity).

Whereas statistical models such as these can be criticized because they are not based on ecological understanding of bloom dynamics and are highly dependent on the training data, a recent analysis demonstrates that similar models³⁴ developed for the Monterey Bay successfully captured subsequent (2008–2009) bloom events, including an unusual early winter event. The model successfully predicted a mandated shellfish closure (outside the normal time period when the California Department of Public Health recommends not harvesting shellfish) and also captured the physical forcing presumably leading to this anomalous bloom—early and heavy rains leading to enhanced river flow coupled with weak upwelling. Though these results are not a predictor of future model performance, they highlight that these models can successfully capture changes (such as those due to basin-scale or global trends in climate forcing) that may lead to changing phenology of HAB events.

The statistical modeling approach can also successfully identify underlying predictive patterns without requiring absolute fidelity between the model output

and reality (required if an assimilative model is used). For example, the Navy Coastal Ocean Model (NCOM³⁵) was able to reproduce many observed circulation features of upwelling and relaxation in Central California, and when coupled to a biochemical submodel, outputs were used to drive statistical HAB predictions for Monterey Bay.³⁴ Initial results using this coupled modeling approach failed completely, with worse predictions than random chance, in part because of subtle problems with the biological parameters (chlorophyll and nutrient fields) from the models. When the statistical models were “re-tuned” to only use the numerical model data, statistical HAB model results improved dramatically, demonstrating that the model had skill but also exhibited significant biases when compared to reality (as determined by comparison of model versus measured fields). This approach takes advantage of this fact, using the models to guide development of statistical relationships while remaining relatively insensitive to errors in the model results.

A long-term goal is to merge this statistical approach with fully coupled physical–biological numerical models to develop short-term (days) forecasts of bloom probabilities and spatial trajectories (Figure 6). However, most existing numerical models are simply not advanced enough (particularly the biology) to predict coastal phytoplankton dynamics at the level of specificity required, and they are often too

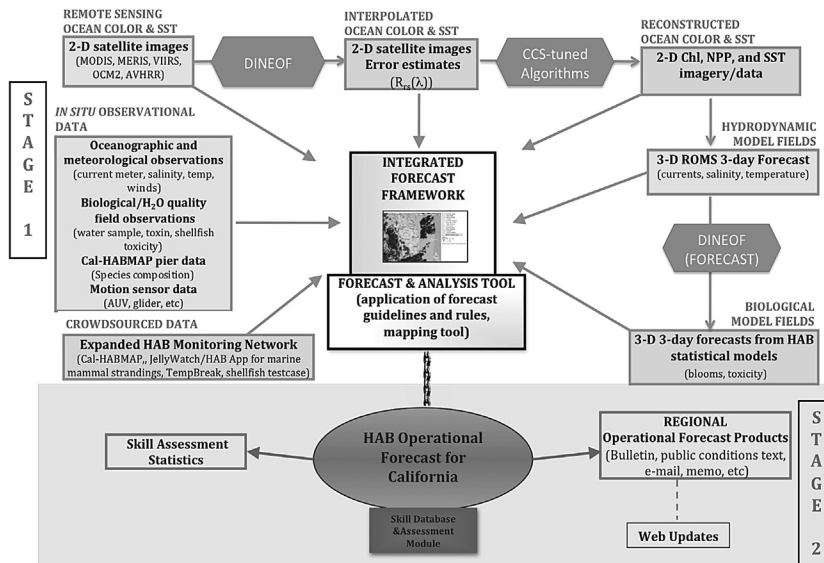


FIGURE 6

Flowchart showing the planned implementation of an operational HAB forecast for California. The effort is currently at Stage 1 (with NASA Applied Sciences Program funding). Partnerships with CeNCOOS and NOAA will transition the effort to Stage 2.

complex and expensive (in terms of development time, computational effort, and operational costs) to maintain indefinitely. In the short term, bio-optical statistical models are being used to create routine HAB forecasts by merging ocean color satellite (MODIS-Aqua) and 3-km resolution Regional Ocean Modeling System (ROMS) model output. Routine forecasts are being run in partnership with the National Ocean Service (NOS) as a testbed for collaboration toward transitioning research results to an operational center, ensuring that a dialogue is established between all stakeholders and that resources are targeted toward sustained operations and maintenance. As coupled physical–biological models improve, so too will the HAB forecasts; this steady progression will ultimately allow for inclusion of other HAB organisms using the same coupled modeling framework.

These forecast efforts highlight the need for and utility of the CalHABMAP framework. The models are integrating across both IOOS regions and utilizing field data provided by the CalHABMAP network. Marine mammal strandings and crowd-sourced data (via Jellywatch) are being used to validate and refine the models. Data are disseminated via CalHABMAP, as well as through partnership with CeNCOOS. And as noted by Frolov et al.,²³ the combination of observations, satellite remote sensing, and integrative modeling provide the only realistic framework for identifying the majority of blooms, including those that may affect offshore development and transport.

4. TOXIN AND SPECIES METHODS INTERCOMPARISON

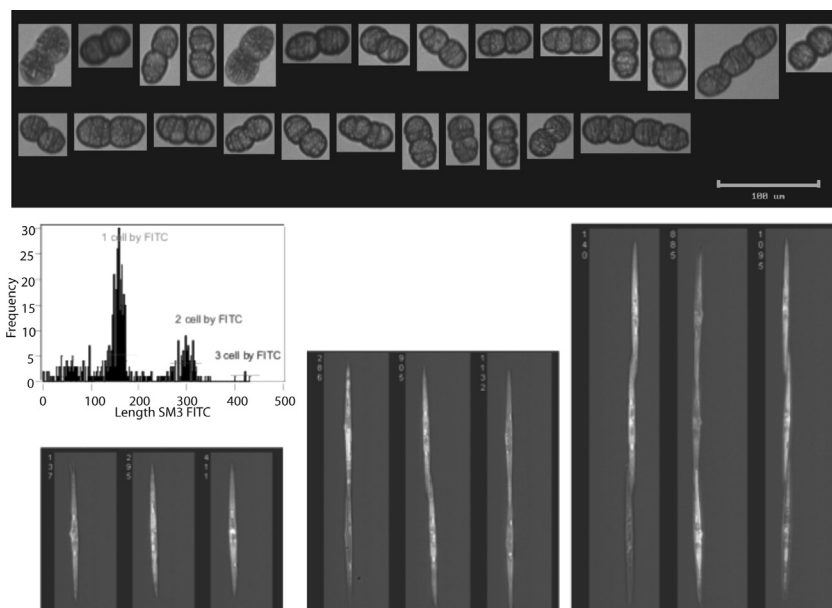
Regulatory agencies, private, state, and federal wildlife stranding networks, and scientific researchers screen environmental samples to determine the presence of toxins. It is common for small subsets of samples to be screened using one of the less expensive assay methods, with the remaining samples analyzed using more costly analytical methods prior to decision-making for closure of operations or publication of scientific results. This process reduces the cost of regulatory analysis and allows processing of a large number of samples from a spatially extensive area to provide information to rescue centers that respond to HAB events. As part of the initial HABMAP workshop, participants determined that the methodological differences were not of concern for the screening application, as most of the positive samples are analyzed using multiple methods to confirm the presence of toxins. Workshop participants agreed, however, that methodological differences were of substantial concern for the shellfish closure applications, spatial comparisons, and trend assessments. Additionally, the recent emergence of HAB species and toxins not traditionally monitored in California has highlighted the need for further standardization. Outside of the formal international certification process led by AOAC International, there have been limited intercalibration studies to assess methodological differences as well as differences among investigators applying the same methods amongst CalHABMAP collaborators.

Participants concluded that the best way to resolve concerns about method differences affecting these applications was to conduct an interlaboratory intercalibration study. This study would determine the precision of these methods and compatibility among datasets in order to ultimately synchronize and combine data. The interlaboratory intercalibration study would assess the need for standardization to a smaller set of methods in establishing a statewide network and would allow development of a Quality Assurance/Quality Control Plan template to guide any laboratory in minimum acceptable practices to ensure data validity and compatibility.

Workshop participants also agreed that trend analysis and forecasts require improvements in accuracy, consistency, and coordination among phytoplankton species identification methods. Four main identification classes employed within the state were identified (Table 1): microscopy, molecular methods, flow cytometry (including FlowCAM (Figure 7) and Imaging Flow CytoBot), and finally, biomass indicators such as HPLC pigments, chlorophyll detection, optical measurements, and remote sensing. Similar to toxins, a need was identified for an interlaboratory

Table 1 Methods Commonly Used by California Researchers and Agencies for Species Identification, Cell Abundance, and Biomass Detection Identified at the 2008 HABMAP Workshop

Method Class	Information Type
Microscopy	
Traditional microscopy	Qualitative and quantitative; absence/presence, percent composition, cells per unit volume
Electron microscopy	Absence/presence; percent composition
Molecular	
Whole cell (fluorescence in situ hybridization)	Quantitative, absence/presence
Homogenate (sandwich hybridization, quantitative polymerase chain reaction)	Quantitative, absence/presence
Flow cytometry	
FlowCAM	Quantitative
Imaging flow CytoBot	Quantitative
Biomass	
High-performance liquid chromatography	Phytoplankton class
Chlorophyll detection	Biomass indication
Optical measurements	Biomass indication
Remote sensing	Biomass indication, spatial extent

**FIGURE 7**

Two examples of imaging technologies employed for HAB enumeration. Images collected from FlowCAM analysis (top) of unpreserved seawater from Southern California, November 2012. The FlowCAM's automated image analysis can readily detect/identify *Cocchlostinum* cells, whereas traditional microscopy using preserved samples often fails due to cell swelling and bursting. FlowCAM images courtesy of Dave Caron, University of Southern California. A culture of *Pseudo-nitzschia australis* (bottom) was probed with FITC and analyzed on an Amnis ImageStream, with automated detection of chain length (histogram). The ImageStream is capable of handling very long chains without clogging as long as the chain width is less than 250 μm .

intercalibration study to determine data compatibility. This calibration is needed across the four different classes of methods, particularly among molecular methods.

As a grassroots organization, CalHABMAP has limited capabilities and even less funding to implement these comprehensive intercalibration exercises. Instead, endorsing the community participation model, this need was highlighted and CalHABMAP members were asked to consider taking on the task by leveraging other funding opportunities and efforts. This was generally very successful. The same year that CalHABMAP made these recommendations, the NOAA Alliance for Coastal Technologies convened a workshop on "Technologies and Methodologies for Detection of Harmful Algae and Their Toxins."³⁶ Peer-reviewed publications comparing various toxin detection methods were also generated,^{37,38} while many participants conducted informal intercalibration efforts between laboratories.

Based on the CalHABMAP recommendations, SCCOOS also centralized toxin detection to ensure consistent data reporting. Though much work remains to be done, particularly more systematic comparisons and intercalibrations for both species and toxin detection, CalHABMAP members have made progress toward consistent measurements, which will ultimately lead to improved trend analysis and forecasts based on accurate, consistent, and coordinated measurements of species and toxins.

5. ECONOMIC ANALYSIS

The final component proposed by CalHABMAP was to develop an economic assessment of the full cost of HABs to the State of California. There is currently no comprehensive global assessment of economic loss due to marine HABs, but it can be conservatively estimated at several billion US\$ annually.³⁹ Using a typical value of information (VOI) estimate of 1% of the “resource” (in this case HAB-related losses),⁴⁰ a comprehensive global HAB observing and forecasting information system would represent a value of \pm \$100 million annually.³⁹ Down-scaling from this global view, marine HAB-related losses in the US are conservatively estimated at \pm \$95 million annually, adjusted for inflation.⁴¹ In freshwater systems, potential eutrophication-related losses in the United States, primarily due to cyanobacterial blooms, are estimated at up to \$4.6 billion annually.⁴² In California, the shellfish industry alone was valued at \$16.4 million in 2008,⁴³ representing a large potential economic loss to HAB events.

Despite the frequent request for a comprehensive and up-to-date economic assessment of the true cost of HABs,^{22,43,44} little new information has been gained. This is the one outstanding objective for CalHABMAP that has yet to be achieved, and it remains a high priority. The economic value of a truly comprehensive HAB monitoring and forecasting system would increase when the value of long-term monitoring of HAB events and associated environmental drivers is included, vis-à-vis trends in HABs with potential global climate change and increasing anthropogenic pressure on coastal ecosystems.³⁹

6. SUMMARY AND RECOMMENDATIONS

In 2008, the newly formed CalHABMAP group set forth an ambitious agenda to establish a coordinated network for harmful algal blooms for the entirety of the State of California. In just a few short years, many of the objectives have been reached, while others remain high-priority items. Concurrently, a state-mandated effort⁴³ identified a similar set of goals, including the following:

- Assess economic and technical feasibility of a statewide HAB observing system.
- Support technology development by coordinating efforts to improve in situ, real-time detection of algae and toxins and by partnering with the Alliance for Coastal Technologies to evaluate new technology.

- Work toward a statewide HABs observing system by building on the existing observation network, e.g., by expanding pier monitoring in the CeNCOOS region, adding HAB sensors to other monitoring networks, and adding sites in the nearshore zone.
- Develop operational HAB forecasting models based on linking ROMS circulation and nutrient, phytoplankton, zooplankton (NPZ) ecosystem models, building on current pilot projects in Monterey Bay and SBC.
- Build an HAB early warning system by expanding the existing HABMAP system to add participants and information products.
- Improve data management capabilities by adding data sources to the California ocean observing systems' HAB Info System and integrating this system with other state data management initiatives.
- Support core research on effects of nutrient loading from anthropogenic and upwelling sources, focusing primarily on the Southern California Bight.
- Designate a lead entity to coordinate efforts associated with the full range of potential impacts. Plan for the transition from research methods to routinely deployed operational tools.

Not surprisingly, many of the CalHABMAP objectives are mirrored by the California Ocean Protection Council report. It is a testament to the power of a grass-roots effort, supported by state and federal programmatic elements, that nearly all of these objectives have been met or are underway. We identify three key challenges that need to be addressed moving forward. First, despite the repeated recommendation for a comprehensive economic assessment of the impact of HABs on the State of California, no such assessment exists or is planned at this time. Second, there is a clear need for continued integration and support of the nascent CalHABMAP network and potential expansion to include other states. Much of the work done so far has been funded by short-term (a few years) research grants. To capitalize on the successes of CalHABMAP, the monitoring and forecasting efforts must be institutionalized at the regional, state, and federal levels. CalHABMAP should, to the extent possible, champion the integration of the various data sets and data portals (such as the new Marine Mammal Health Map) to achieve the goal of a coordinated, statewide network. Third, there is increasing interest in coordinating the marine HABMAP effort with a complementary freshwater program through development of the California Cyanobacterial Harmful Algal Bloom network (CCHAB). This will require careful consideration about how best to integrate freshwater and marine HAB research, monitoring, and forecasting, as well as how best to coordinate the numerous private, state, and federal groups and agencies who are stakeholders in the process. A similar conversation is taking place in other states, as well as federally, and internationally.⁴⁵ It is our hope that CalHABMAP can provide a successful example of how best to implement these strategies.

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