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Harmful algal blooms and climate change: Learning from the past and present to forecast the future

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ABSTRACT

Climate change pressures will influence marine planktonic systems globally, and it is conceivable that harmful algal blooms may increase in frequency and severity. These pressures will be manifest as alterations in temperature, stratification, light, ocean acidification, precipitation-induced nutrient inputs, and grazing, but absence of fundamental knowledge of the mechanisms driving harmful algal blooms frustrates most hope of forecasting their future prevalence. Summarized here is the consensus of a recent workshop held to address what currently is known and not known about the environmental conditions that favor initiation and maintenance of harmful algal blooms. There is expectation that harmful algal bloom (HAB) geographical domains should expand in some cases, as will seasonal windows of opportunity for harmful algal blooms at higher latitudes. Nonetheless there is only basic information to speculate upon which regions or habitats HAB species may be the most resilient or susceptible. Moreover, current research strategies are not well suited to inform these fundamental linkages. There is a critical absence of tenable hypotheses for how climate pressures mechanistically affect HAB species, and the lack of uniform experimental protocols limits the quantitative cross-investigation comparisons essential to advancement. A HAB "best practices" manual would help foster more uniform research strategies and protocols, and selection of a small target list of model HAB species or isolates for study would greatly promote the accumulation of knowledge. Despite the need to focus on keystone species, more studies need to address strain variability within species, their responses under multifactorial conditions, and the retrospective analyses of long-term plankton and cyst core data; research topics that are departures from the norm. Examples of some fundamental unknowns include how larger and more frequent extreme weather events may break down natural biogeographic barriers, how stratification may enhance or diminish HAB events, how trace nutrients (metals, vitamins) influence cell toxicity, and how grazing pressures may leverage, or mitigate HAB development. There is an absence of high quality time-series data in most regions currently experiencing HAB outbreaks, and little if any data from regions expected to develop HAB events in the future. A subset of observer sites is recommended to help develop stronger linkages among global, national, and regional climate change

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and HAB observation programs, providing fundamental datasets for investigating global changes in the prevalence of harmful algal blooms. Forecasting changes in HAB patterns over the next few decades will depend critically upon considering harmful algal blooms within the competitive context of plankton communities, and linking these insights to ecosystem, oceanographic and climate models. From a broader perspective, the nexus of HAB science and the social sciences of harmful algal blooms is inadequate and prevents quantitative assessment of impacts of future HAB changes on human well-being. These and other fundamental changes in HAB research will be necessary if HAB science is to obtain compelling evidence that climate change has caused alterations in HAB distributions, prevalence or character, and to develop the theoretical, experimental, and empirical evidence explaining the mechanisms underpinning these ecological shifts.

1. Introduction

The warming of the global system is unequivocal and has resulted in unprecedented changes in climate, meaning decadal or longer time scale shifts in overall weather characteristics (Stocker et al., 2013). The proximal changes, manifest primarily in terms of temperature, precipitation, and wind, work interactively with surface water acidification stemming from increased CO_2 emissions to alter mean surface water conditions, and perhaps more importantly their extremes. There is increasing concern that this shifting milieu will cause changes in phytoplankton community structure and composition, including a greater prevalence and geographical spread of harmful algal blooms. But the anticipated linkages between climate change and harmful algal blooms are founded on limited and often conflicting experimental and observational data. Scientists are left mostly to "informed" speculation about whether future climate may enhance or diminish the frequency, intensity, and distribution of HAB outbreaks. A fundamental challenge to HAB scientists is to identify key indicators and demonstrated relationships that reveal solid evidence of climate-induced changes in harmful algal blooms.

The current state of knowledge stems from a rich literature on the taxonomy, growth characteristics, and ecophysiology of freshwater and marine phytoplankton collectively grouped as "harmful algae". This societally defined category includes toxic species that express toxicity to higher trophic levels, largely fish, shellfish, marine mammals, or humans, and include members of the cyanobacteria, dinoflagellates, raphidophytes, haptophytes, and diatoms. Included also under the HAB umbrella are largely human-caused high-biomass events that, while often comprising non-toxic phytoplankton species, still critically alter ecosystems through hypoxia/anoxia, altered food web efficiencies, stimulation of pathogenic bacteria, or other ecological consequences.

Current spatial and temporal ranges of HAB species will most certainly change under future climate scenarios. Spatially, one can expect that the geographic domains of species may expand, contract, or just shift latitudinally. Temporally, the seasonal windows for growth will also contract and expand. Successful "invasions" of new HAB species will depend fundamentally on the species "getting there", through spatial transport, "being there" as indigenous species (hidden flora) that potentially can grow in abundance within the phytoplankton community, and "staying there" by persistence through unfavorable conditions (e.g., high temperature, nutrient depletion, overwintering).

The HAB research community is largely unprepared to address these questions. The central challenge is to achieve consensus about the way forward from both research and management perspectives. This focused community synergy will be critical if the knowledge base is to advance faster than the influence of climate-related changes on harmful algal blooms, and if statistically credible evidence of this change can be provided soon enough to contribute to the societal debate over climate change impacts. These preparations will be particularly critical for high latitude regions where climate change impacts are liable to be most rapid and substantial (Stocker et al., 2013). The foundation of HAB knowledge has accumulated mainly through isolated investigations, as with most environmental sciences, but this piecemeal process does not readily foster as powerful a knowledge structure as can be achieved through synergistic, collective, and collaborative approaches. That is, a collective vision is needed that can identify the "known knowns" and rank the levels of the "known unknowns" if the community is to presage climate change-HAB linkages before they develop.

In working to achieve a higher level of cooperation among HAB and climate scientists, there is some guidance to be gleaned from the ocean acidification field, which used broad collaboration to create the infrastructure and standard methods needed to generate scientific awareness and funding streams that critically address the environmental and biological questions of greatest importance. Moving the understanding of HAB-climate change interactions beyond informed speculation will require rigorous, testable hypotheses to guide scientists, managers and the public on what changes are happening or are projected, estimation of the confidence limits on those projected changes, and establishing the infrastructure and studies needed to capture these necessary data.

As a beginning, there is a strong need to outline clearly what currently is known (and not known) about the environmental conditions that favor initiation and maintenance of different types of HAB events, and how sensitive those key parameters are to changes in the climate system (Fig. 1). As a first step in that process, a four-day workshop was held in Spring 2013 at Friday Harbor Laboratories, University of Washington, comprised of 11 HAB researchers with diverse expertise spanning the ecophysiology and nutrient acquisition of HAB species, their nutritional quality and implications for food web structure and ecosystem health, and observational platforms, time series analyses and prediction. This paper summarizes the discussion at that workshop, illustrated by an overview assessment of how environmental change may affect different HAB types (Fig. 2). This document is not intended to be a comprehensive description of potential linkages between climate change and harmful algal blooms, but rather to: (1) give a sense of near-term research that may hold the greatest promise for knowledge advancement and impact, (2) provide funding agencies, managers, and interested stakeholders an overview assessment of current knowledge and key gaps in this knowledge, (3) assist in leveraging the use of current ocean observing systems to obtain important, HAB-related parameters, and (4) perhaps most importantly, attract the interest of non-HAB researchers who are developing relevant new tools or approaches (molecular, cellular, modeling, sensor) that hold promise for HAB research. A