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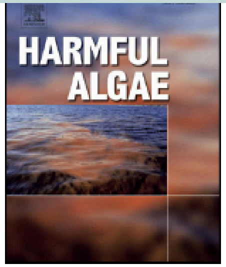

Modeling harmful algal blooms in a changing climate

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ABSTRACT

This review assesses harmful algal bloom (HAB) modeling in the context of climate change, examining modeling methodologies that are currently being used, approaches for representing climate processes, and time scales of HAB model projections. Statistical models are most commonly used for near-term HAB forecasting and resource management, but statistical models are not well suited for longer-term projections as forcing conditions diverge from past observations. Process-based models are more complex, difficult to parameterize, and require extensive calibration, but can mechanistically project HAB response under changing forcing conditions. Nevertheless, process-based models remain prone to failure if key processes emerge with climate change that were not identified in model development based on historical observations. We review recent studies on modeling HABs and their response to climate change, and the various statistical and process-based approaches used to link global climate model projections and potential HAB response. We also make several recommendations for how the field can move forward: 1) use process-based models to explicitly represent key physical and biological factors in HAB development, including evaluating HAB response to climate change in the context of the broader ecosystem; 2) quantify and convey model uncertainty using ensemble approaches and scenario planning; 3) use robust approaches to downscale global climate model results to the coastal regions that are most impacted by HABs; and 4) evaluate HAB models with long-term observations, which are critical for assessing long-term trends associated with climate change and far too limited in extent.

2.1. Statistical models

Statistical models use observations to relate key forcing variables (e.g., a nutrient concentration, temperature, upwelling wind index, or time of year) to relevant measures of HABs (e.g., the timing of HAB events or the abundance, toxicity, and spatial distributions of HAB species). A wide range of forcing variables are typically considered during model development, some of which may be interrelated (e.g., temperature and time of year, salinity and river discharge). While the choice of forcing variables is often guided by our understanding (theoretical or empirical) of the underlying physical and biological processes, statistical models do not attempt to represent those processes directly, only the cumulative effects of them. Statistical models require extensive observations to develop robust relationships between forcing variables and HAB response. As such, some of the most compelling examples come from regions with long records of HAB monitoring and investigation. Examples include *Pseudo-nitzschia* and *Dinophysis* blooms

2.2. Process-based models

Process-based (or mechanistic) models use mathematical equations to explicitly simulate key physical and biological processes that govern HABs and HAB outcomes. Their development requires detailed knowledge of critical life history characteristics and the factors that modulate them as well as transport pathways. As such, they require large amounts data to represent the many processes in the system and can be limited by their parameterizations of rates of growth, mortality, mobility, toxin production, and other key processes that are typically derived from simplified laboratory studies of isolated strains. In situations where observational or laboratory data are limited, process-based models instead may be informed by data on similar organisms or may be limited to focusing on a subset of processes that are particularly important to bloom dynamics. Because process-based models are more comprehensive than statistical models, they take more time and effort to develop and are more computationally expensive to run. Process-based models can be difficult to constrain given the nonlinearity and intermittency of HABs, but they are usually more transferable across regions because of their explicit representation of physical and biological processes.

3. Modeling HABs in a changing climate – what has been done?

Projecting HAB response to climate change involves extending the simulation period of existing HAB models to decades, centuries, or potentially paleo time scales for retrospective climate analyses. Data describing future forcing conditions can be obtained from GCM simulations and used as input variables to HAB models. GCMs forecast ocean circulation and water properties under future climate scenarios informed by various greenhouse gas concentration trajectories. These scenarios describe a range of possible futures based on greenhouse gas emissions, economic development, population growth, and other factors. The output generated by GCMs quantify changes in physical and biogeochemical conditions and can be combined with statistical relationships from past observations to project changes in HABs. Additional model layers to represent climate change effects outside of the ocean, such as watershed hydrology or land use, can also be integrated. This offers a relatively simple approach for examining climate impacts on HABs, but statistical models become increasingly error-prone when projecting into conditions different from the training data set (Flynn and McGillicuddy, 2018). This is because the statistical relationships may represent the cumulative effect of multiple processes or interactions that cannot be extrapolated, and also because thresholds or tipping points that were not identified or characterized by prior observations may be exceeded in the projections. Process-based models are less prone to these potential issues, but they represent only a portion of the physical and biological complexity due to computational constraints and data limitations, and so even process-based models validated under present conditions may not simulate many of the hypothesized responses to climate change. Here we discuss some of the approaches for using statistical and process-based HAB models to project HAB response to climate change. The different approaches vary in complexity in terms of how many forcing variables are considered and how they are derived.

4. Modeling HABs in a changing climate – what should be done?

The fact that relatively few modeling studies quantitatively project how climate change may affect the distribution and abundance of HAB populations or toxicity is symptomatic of the challenges associated with this important task. Challenges associated with understanding the biological response of HABs to climate change, as well as suggestions for best practices that should be employed to address them, are discussed in Wells et al. (2015); however, little attention was given to the modeling infrastructure needed to project HAB response to climate change. Generating useful projections of HAB response to climate change will require engagement with other communities that can help refine the representation of future conditions in HAB models, including climate scientists, marine ecologists, watershed hydrologists, invasive species biologists, and environmental managers and policy makers (Glibert et al., 2010). Here we offer several suggestions to improve modeling of HABs in a changing climate, schematically summarized in Fig. 1.

What should be done?:

1. Use process-based models
   - Better suited for long-term projections
2. Use an ensemble approach
   - Considers multiple model scenarios to quantify how different choices of key input factors affect the uncertainty in model projections
3. Use downscaled climate models
   - Resolving physical and biochemical processes at costal scales to identify local impacts
4. Evaluate models with long-term observations
   - Biases occur and skills vary regionally; long-term observations are critical to evaluate trends

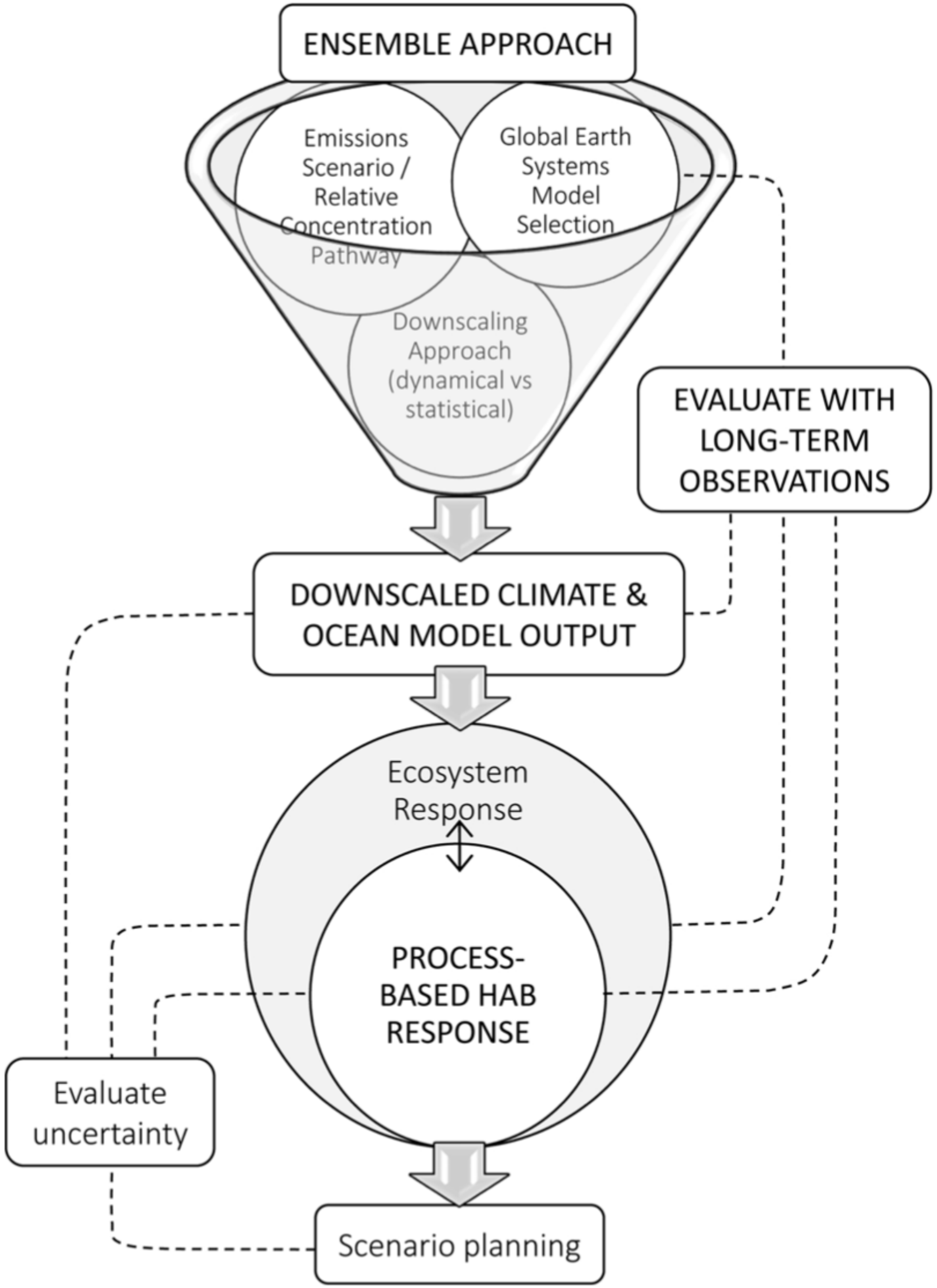

Fig. 1. Schematic diagram summarizing considerations for improving modeling of HAB response to climate change. Multiple global earth systems models, emissions scenarios/relative concentration pathways, and downscaling approaches should be considered in an *ensemble approach* to generate *downscaled climate and ocean model output*. Downscaling is necessary to resolve critical physical and biogeochemical processes for HAB development at coastal scales. These downscaled data should be used to force *process-based models of HAB response* with the results considered in an ecosystem context. Models should be *evaluated with long-term observations*. This step can be informative for selecting global models, identifying biases in downscaled model projections, and validating models of HAB and ecosystem response. An important final step is to identify components of the model system that are key sources of uncertainty in the long-term HAB response (i.e., *evaluate uncertainty*) and to develop scenarios (i.e., *scenario planning*) around those sources of uncertainty in the development of societal response strategies.