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Ecological forecasting in Chesapeake Bay: Using a mechanistic–empirical modeling approach

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ABSTRACT

The Chesapeake Bay Ecological Prediction System (CBEPS) automatically generates daily nowcasts and three-day forecasts of several environmental variables, such as sea-surface temperature and salinity, the concentrations of chlorophyll, nitrate, and dissolved oxygen, and the likelihood of encountering several noxious species, including harmful algal blooms and water-borne pathogens, for the purpose of monitoring the Bay's ecosystem. While the physical and biogeochemical variables are forecast mechanistically using the Regional Ocean Modeling System configured for the Chesapeake Bay, the species predictions are generated using a novel mechanistic–empirical approach, whereby real-time output from the coupled physical–biogeochemical model drives multivariate empirical habitat models of the target species. The predictions, in the form of digital images, are available via the World Wide Web to interested groups to guide recreational, management, and research activities. Though full validation of the integrated forecasts for all species is still a work in progress, we argue that the mechanistic–empirical approach can be used to generate a wide variety of short-term ecological forecasts, and that it can be applied in any marine system where sufficient data exist to develop empirical habitat models. This paper provides an overview of this system, its predictions, and the approach taken.

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1. Introduction

The Chesapeake Bay is the largest estuary in North America and represents an extremely valuable regional resource. Recreationally, the sport fishing industry annually yields nearly $300 million, and swimming and boating are supported by numerous beaches and safe harbors. Ecologically, vast wetlands surround the Bay and its tributaries and offer a haven for a rich diversity of wildlife. Economically, the Bay supports several commercial fisheries. The Bay is the largest producer of blue crabs in the world, with yearly harvests of approximately 25 million kg, and the value of the finfish and shellfish harvested annually is approximately $1 billion. These and other ecosystem services rely on the Bay's ecological health. Yet several types of natural and human-induced changes in water quality conditions have degraded the Bay's ecosystem and jeopardized its economic productivity (Kemp et al., 2005).

Furthermore, various organisms also affect Chesapeake Bay ecosystem services. For example, the scyphomedusa *Chrysaora quinquecirrha*, a species of stinging jellyfish locally known as sea nettles, can reach very high concentrations during summer in the Chesapeake Bay (Purcell et al., 1994). The medusae can inflict painful stings and therefore have a significant negative impact on recreational activities. They are also an important predator that control plankton dynamics due to their high trophic position and voracious consumption of zooplankton, including ctenophores and fish larvae (Baird and Ulanowicz, 1989; Purcell, 1992; Purcell and Decker, 2005). Harmful algal bloom (HAB) events and several species of water-borne pathogens also commonly occur in Chesapeake Bay and can adversely affect aquatic animal and human health, and local economies (Colwell et al., 1977; Gallegos and Bergstrom, 2005; Goshorn et al., 2002; Grattan et al., 1998; Marshall and Burchardt, 2005; Tango et al., 2005).

Developing the capability to predict the timing, location, and intensity of these nuisance and often harmful biotic events and the conditions that give rise to them could improve the monitoring capabilities of local, state, and federal agencies and thus their effectiveness in mitigating the deleterious impacts they have on human and ecosystem health. In response to this need, we constructed and

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implemented the Chesapeake Bay Ecological Prediction System (CBEPS) for Chesapeake Bay and its major tributaries. The CBEPS regularly provides short-term predictions of various species and hydrodynamic and biogeochemical variables in Chesapeake Bay for the purpose of monitoring the Bay's ecological health (Table 1, Fig. 1). The system, which is one of only a handful of near-real time coupled physical–biogeochemical implementations, generates daily nowcasts and three-day forecasts of physical variables, such as sea-surface temperature and salinity, and biogeochemical variables, such as nutrient and chlorophyll concentrations, light, and zooplankton biomass, using an estuarine hydrodynamic model with fully mechanistic physical and biogeochemical components. These variables then drive multivariate empirical habitat suitability models that predict the likelihood of encountering or (relative) abundance of several noxious organisms, including the jellyfish *C. quinquecirrha*, three species of HABs and several water-borne pathogens, e.g. *Vibrio vulnificus*, in Chesapeake Bay (Fig. 2). The empirical habitat models, which are developed using historical data, relate ambient environmental conditions to the probability of occurrence or abundance of the target species. This is in contrast to the prevailing approach of forecasting HABs and bacteria in the coastal ocean, at least in the US (Brown et al., 2013), whereby the species, toxin, or an appropriate proxy is detected in observations and then the object is transported forward in time using velocity fields from a numerical hydrodynamic or transport model.

This paper provides the first overview of CBEPS, focusing on the various mechanistic and empirical habitat suitability models it employs for generating the short-term ecological predictions in near-real time. The CBEPS has also been used to generate hindcasts, but we restrict our discussion here to how the model has been implemented to routinely generate nowcasts and three-day forecasts. We also briefly describe how the forecasts, in the form of digital images, are made available via the World Wide Web to individuals and interested agencies to guide recreational, management, and research activities and discuss the strengths and weaknesses of the hybrid mechanistic–empirical approach that is employed to generate them.

2. The Chesapeake Bay Ecological Prediction System components

The CBEPS consists of four major components (Fig. 3): (1) the Ocean Quality Control System (OQCS), which automatically retrieves various hydrodynamic and hydrological measurements, both historical for validation and real-time for model forcing, and performs quality control on these inputs; (2) the Ocean Hydrodynamic Modeling System (OHMS), which contains the coupled hydrodynamic–biogeochemical numerical models that is used to obtain 3D real-time and forecasted evolving states of the Chesapeake Bay's hydrodynamic circulation, temperature, salinity and biogeochemical properties including concentrations of chlorophyll, nitrate, ammonium, dissolved oxygen, and sediment; (3) the Ocean Model Assessment System (OMAS), which assesses the skill of the model predictions by comparing model results with measurements acquired by OQCS using a set of skill metrics; and (4) the Ocean Model Dissemination System (OMDS), which archives data and disseminates forecasts using cutting-edge model interoperability techniques in order to present model results to the end users through an efficient and convenient interface. The empirical habitat models are also contained within the OHMS component. A suite of Linux/Unix Shell scripts, Perl scripts, Fortran and C programs, NCL programs, MATLAB scripts and GIS shape files automatically perform the tasks of obtaining real-time forcing data, generating the model input files, running the model, processing the model output and displaying the graphical products on a dynamic, interactive web site.

The following sections describe the major functional features in the CBEPS.

Table 1
Physical, biogeochemical, and organismal forecasts generated by the Chesapeake Bay Ecological Prediction System.

Physical	Biogeochemical	Organismal
Temperature	Nitrate (NO_3)	*Chrysaora quinquecirrha* (scyphomedusa)
Salinity	Ammonia (NH_4)	*Karlodinium veneficum* (dinoflagellate)
Water density	Dissolved organic nitrogen	*Prorocentrum minimum* (dinoflagellate)
Current velocity (u, v, w)	Chlorophyll	*Microcystis aeruginosa* (cyanobacteria)
Sea surface height (tidal and non-tidal water level)	Inorganic suspended sediments	*Vibrio cholerae* (bacteria)
Turbulent eddy viscosity	Detritus (small and large component)	*Vibrio parahaemolyticus* (bacteria)
Turbulent kinetic energy	Dissolved oxygen	*Vibrio vulnificus* (bacteria)
Diffuse attenuation coefficient	Phytoplankton	Zooplankton

2.1. Chesapeake Bay Regional Ocean Modeling System

The Chesapeake Bay Regional Ocean Modeling System (ChesROMS; Fig. 4) (Xu et al., 2012) is an open source Chesapeake Bay implementation of the Regional Ocean Modeling System (ROMS, see Shchepetkin and McWilliams, 2005; Wilkin et al., 2005). This fully 3-dimensional model simulates the circulation and physical properties (sea surface height, temperature, salinity, density, and velocity) of the estuary and includes biogeochemical and sediment transport sub-models (described later). The physical model is based on finite difference on 2-dimensional horizontally (2DH) orthogonal curvilinear grids (Arakawa C-type staggered grid) and vertical terrain-following sigma coordinates with time integration split into external and internal modes for primitive hydrodynamic variables including surface elevation, velocity and passive tracers (temperature, salinity and the biogeochemical state variables).

The 150×100 horizontal model grid (Fig. 5) with 20 sigma levels results in a relatively coarse horizontal resolution of 0.5 to 5 km and a vertical resolution of 0.2 to 1.5 m. Bathymetry data used for constructing the grid was obtained from the US Coastal Relief Model at the National Oceanic and Atmospheric (NOAA) National Geophysical Data Center (Fig. 5). Lateral forcing of the model consists of real-time freshwater inputs based on United States Geological Survey (USGS) gauged data for the nine major rivers feeding the Bay. A correction factor is applied to the discharge rates of some USGS gauge stations to account for the fact that the injection point in these rivers is located upstream of the model grid and the measured discharge does not include the extra runoff collected from downstream drainage areas. Both tidal and non-tidal influences at the Bay mouth are derived from the Advanced Circulation Model for Coastal Ocean Hydrodynamics (ADCIRC) model tidal constituents, and water level data are extracted from local tide station measurements.

Atmospheric forcing quantities, including 3-hourly winds, net shortwave and downward longwave radiations, air temperature, relative humidity, and pressure, are obtained from the National Center for Environmental Prediction (NCEP) North American Regional Reanalysis (NARR) and North American Mesoscale (NAM) model products. Provisional meteorological predictions from NAM, as well as the assumption of persistence of river discharge and river nutrient loading, and OBC non-tidal water levels, provide forcing input for the three-day forecasts. Vertical profiles of monthly climatological temperature and salinity, and seasonal concentrations of nitrate, oxygen, and chlorophyll (= phytoplankton), from the World Ocean Atlas 2001 (WOA01) database are currently used to set the physical and biogeochemical boundary conditions at the mouth of the Bay for both nowcasts and three-day forecasts. The WOA01 data are based