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Insights into the dynamics of harmful algal blooms in a tropical estuary through an integrated hydrodynamic-*Pyrodinium*-shellfish model

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ABSTRACT

In contrast to temperate Harmful Algal Blooms (HABs), knowledge on the mechanisms driving tropical HABs are less well studied. The interaction of a seasonal temperature window, cysts (for certain species) and large-scale transport are some of the key processes in temperate HABs. In the Philippines, HABs occur not along long open coastlines, but in embayments that are highly influenced by run-off and stratification. These embayments are typically also the sites of cultured or wild harvest shellfish and other aquaculture activities. Sorsogon Bay in the northeastern Philippines has experienced prolonged shellfish-harvesting bans due to blooms by *Pyrodinium bahamense* var. *compressum* severely affecting the fisheries industry in this area, as well as leading to Paralytic Shellfish Poisoning illnesses and fatalities. A novel integrated model was developed that mechanistically captures the interactions between hydrodynamic conditions, nutrients, the life history (cells and cysts) of *Pyrodinium*, as well as the cultured shellfish within the bay and their ensuing toxicities due to ingestion of toxic *Pyrodinium* cells and cysts. This is the second model developed for HABs in the Philippines, and the first to integrate different components of *Pyrodinium* bloom dynamics. The model is modularly composed of a watershed nutrient and diffusion model, a 3D hydrodynamic model, a *Pyrodinium* population model and a shellfish toxin model. It was able to capture the observed temporal variations of *Pyrodinium* and shellfish toxicity. It was also able to represent some aspects of the spatial distribution in Sorsogon Bay though there were discrepancies. To explore the dynamics of blooms, the linkages between the bloom and decline of the *Pyrodinium* population with shellfish toxicity as affected by temperature, salinity and nutrients were investigated. Comparisons with field results showed the seasonality of blooms in Sorsogon Bay is driven by increased rainfall. The timing of these conditions is important in facilitating *Pyrodinium* excystment and reproduction. Model results showed as well the potential significance of shellfish grazing and dinoflagellate cell mortality in influencing the decline of the bloom, and toxicity levels. This approach is promising in helping to understand mechanisms for HABs more holistically, and the model can be further improved to provide more precise quantitative information.

1. Introduction

The Philippines is an archipelagic country characterized by complex coastlines and numerous embayments. Some of these embayments are sites of recurrent, expensive harmful algal blooms of human health significance. The dinoflagellate, *Pyrodinium bahamense* var. *compressum* (*Pyrodinium*), is the primary toxic algal bloom species (Azanza and Taylor, 2001) that causes Paralytic Shellfish Poisoning (PSP) and forms cysts which is likely an agent in the recurrence of its blooms in affected areas.

The cyst-forming toxic dinoflagellate *Alexandrium fundyense* has been extensively studied along the long coastline and large areas of the Gulf of Maine which is part of the continental shelf of the northeast U.S.A. Blooms of *A. fundyense* have been found to be dependent on the germination of resting cysts from two identified cyst beds (Anderson et al., 2005, 2014) and the growth of these cells during appropriate conditions (particularly temperature and light) in spring time (Stock et al., 2005). These cells are then transported by prevailing currents to

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various parts of the Gulf of Maine.

Out of the approximately 30 embayments around the country that have been affected by *Pyrodinium*, only one, Manila Bay, has been studied intensively to yield information on the key factors and mechanisms influencing blooms. Manila Bay is situated in the western part of Luzon opening up to the West Philippine Sea and has a width ranging from 22 to 60 km (Jacinto et al., 2006). Studies on *Pyrodinium* in this bay (Corrales and Crisostomo, 1996; Azanza et al., 2004; Villanoy et al., 2006; Siringan et al., 2008) have shown that cysts also play a critical role in blooms. Villanoy et al. (2006) highlighted the interaction of cyst re-suspension and germination with the onset of the southwest monsoon when freshwater flux and warm water temperatures resulted in strong water column stratification. They used a Lagrangian model with minimal biological representation to illustrate how *Pyrodinium* germinated from two separate cyst beds were transported around the bay by currents in two distinct gyres: one northeast and the other northwest in direction.

Plankton ecosystem models are being used extensively to increase understanding of algal blooms as well as for forecasting the blooms. Nutrient-Phytoplankton-Zooplankton (NPZ) models and various derivatives are typically coupled to hydrodynamic models to capture bloom dynamics in space and time (e.g., McGillicuddy Jr. et al., 1995; Franks and Chen, 2001; Sunda and Shertzer, 2012). In the Gulf of Maine, McGillicuddy et al. (2005), captured *A. fundyense* population densities using empirically derived functions coupled to a hydrodynamic model. The focal point of most models on HABs is the HAB causative organism and its population dynamics. There are limited, if any, models that integrate the hydrodynamics, the HAB species life cycle and toxicity, and the eventual shellfish toxicity. Shellfish toxin dynamics have usually been modeled separately and have focused on the physiological aspects of toxin accumulation and depuration in different body parts (e.g., Silvert and Subba Rao, 1992; Blanco et al., 1997; Li et al., 2005; Yu et al., 2005; Kwong et al., 2006). The closest study the authors have found that has incorporated the spatially-explicit variation in the densities of toxic algae in shellfish is Ibarra et al.'s (2014) work integrating a Eulerian biophysical model with an individual-based shellfish ecophysiological model. This is a gap particularly in relation to efforts towards HAB mitigation since at the management level shellfish toxicity is the ultimate practical concern. This study addresses this gap by linking the population dynamics of the toxic bloom species and the ensuing shellfish toxicity in an ecosystem model.

The aim of this study is two-fold: 1) develop a model which integrates hydrodynamic information, a HAB species (*Pyrodinium bahamense)* population model and shellfish toxicity; and, 2) investigate the factors and mechanisms involved in bloom formation and decline of *Pyrodinium* in a tropical estuary; contributing to the limited information of HABs in such a setting (Usup et al., 2012), and particularly in the Philippines.

2. Materials and methods

2.1. Study site

This study used data primarily from Sorsogon Bay (Fig. 1), situated northeast of the Philippines, which is one of the many bays that has experienced prolonged shellfish-harvesting bans due to blooms of *Pyrodinium* (Fig. 2). The first ban began in February 1998 and lasted over a year with a few months respite in the middle. After an isolated ban period in 2003, a shellfish-harvesting ban was in effect almost continuously for several years beginning late 2005 through to 2011 in the bay. These bans have severely impacted the shellfish industry and local livelihood.

Sorsogon Bay is much smaller than Manila Bay with a length and width of about 20 km and 10 km, respectively. It exhibits a shallow bathymetry with a maximum of only 9 m, while the narrow mouth of the bay opens up to depths of 24 m. This bathymetric configuration, along with its narrow mouth means a relatively weak exchange occurs with seawater outside the bay. The average residence times in the bay is estimated to be about three months (Villanoy et al., 2008, unpublished report), similar to Manila Bay (Jacinto et al., 2006). The area experiences higher rainfall from August to February in contrast with Manila Bay, in which the rainy season falls from June to September. Similar bloom processes observed in Manila Bay might be driving the *Pyrodinium* blooms in Sorsogon Bay, however, there are also differences in their configurations and environmental conditions that can lead to variations in bloom dynamics.

2.2. Model description

2.2.1. Modeling nutrient load and river discharge

Due to the dearth of in situ nutrient concentrations and in order to investigate the role of nutrient inputs on *Pyrodinium* blooms, nutrient load, specifically nitrogen, and river discharge values were estimated using a watershed model. Nutrient delivery to the bay, as well as river discharge, was estimated using a raster-based pollutant and sediment yield model called Nonpoint-Source Pollution and Erosion Comparison Tool (N-SPECT), developed by the US NOAA Coastal Services Center. N-SPECT models the basic hydrologic processes, which include overland flow, erosion, and nonpoint-source pollution for watersheds utilizing the Universal Soil Loss Equation. The model runs in a geographic information system (GIS) environment and is available at http://www.csc.noaa.gov/digitalcoast/tools/nspect/. This model has been applied in the US particularly in Hawaii (see N-SPECT manuals) and in the Mesoamerican region (Burke and Sugg, 2006).

N-SPECT requires a number of map layers as model input such as elevation, soil, land cover, rainfall, and other derived grids. A soil map obtained from the Bureau of Soils and Water Management was manually digitized for this purpose. Together with this data, a land cover map from Conservation International (1999) was also updated and utilized. Aside from the various map layers, the model also requires curve numbers, cover factor, and pollutant coefficients. Due to the lack of in situ information, default values were used in this study.

The amount of nitrogen (N) and river discharge at the river mouths were calculated for 2009 using monthly TRMM data (disc2.nascom.nasa.gov/Giovanni/tovas) as rainfall input. A rainfall-runoff model based on Fraedrich (2010) and adapted for the region by David and Peñaflor (2000) was used to derive run-off. River discharge values were derived from elevation, watershed area and rainfall. This data was then scaled according to actual 2009 discharge values available from the Department of Public Works and Highways–Bureau of Research and Standards (DPWH-BRS). Only ten major rivers were used for the analysis (Fig. 1B). The river discharge and nutrient load estimates were used as input to the hydrodynamic model and used as the initial values for diffusion throughout the bay, respectively.

2.2.2. Hydrodynamic model (circulation, temperature and salinity)

A hydrodynamic model of Sorsogon Bay for 2009 which simulates the three-dimensional circulation, as well as temperature and salinity changes through time across depth was developed using Delft3D FLOW. Delft3D Flow is the hydrodynamic module of the DELFT3D software which has a suite of applications for modelling phenomena in various water bodies (shallow seas, coastal areas, etc.). Specifically, Delft3D Flow is capable of simulating two to three–dimensional unsteady flow and transport from tidal and/or meteorological forcing, as well as density–driven flow resulting from non–uniform temperature and salinity distributions (Deltares, 2011). The resulting velocities, as well as hourly temperature and salinity values from this initial model were used as hydrodynamic forcing for the biological model.

The model domain covered the entire bay area with a grid resolution of 300 m × 300 m. A sigma coordinate system with 5 vertical layers was used. The percentage of the water column represented per layer are as follows: Layer 1 is 5%; Layer 2 is 10%; Layer 3 is 25%;