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Environmental links to interannual variability in shellfish toxicity in Cobscook Bay and eastern Maine, a strongly tidally mixed coastal region

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ABSTRACT

The Gulf of Maine experiences annual closures of shellfish harvesting due to the accumulation of toxins produced by dinoflagellates of the genus *Alexandrium*. Factors controlling the timing, location, and magnitude of these events in eastern Maine remain poorly understood. Previous work identified possible linkages between interannual variability of oceanographic variables and shellfish toxicity along the western Maine coastline but no such linkages were evident along the eastern Maine coast in the vicinity of Cobscook Bay, where strong tidal mixing tends to reduce seasonal variability in oceanographic properties. Using 21 years (1985–2005) of shellfish toxicity data, interannual variability in two metrics of annual toxicity, maximum magnitude and total annual toxicity, from stations in the Cobscook Bay region are examined for relationships to a suite of available environmental variables. Consistent with earlier work, no (or only weak) correlations were found between toxicity and oceanographic variables, even those very proximate to the stations such as local sea surface temperature. Similarly no correlations were evident between toxicity and air temperature, precipitation or relative humidity. The data suggest possible connections to local river discharge, but plausible mechanisms are not obvious. Correlations between toxicity and two variables indicative of local meteorological conditions, dew point and atmospheric pressure, both suggest a link between increased toxicity in these eastern Maine stations and weather conditions characterized by clearer skies/drier air (or less stormy/humid conditions). As no correlation of opposite sign was evident between toxicity and local precipitation, one plausible link is through light availability and its positive impact on phytoplankton production in this persistently foggy section of coast. These preliminary findings point to both the value of maintaining long-term shellfish toxicity sampling and a need for inclusion of weather variability in future modeling studies aimed at development of a more mechanistic understanding of factors controlling interannual differences in eastern Gulf of Maine shellfish toxicity.

1. Introduction

Harmful algal blooms (HABs) caused by dinoflagellates of the genus *Alexandrium* spp. necessitate annual shellfish bed closures along coastlines of the Gulf of Maine. *Alexandrium* spp. produce a number of toxins that are often referred to as saxitoxin equivalents (Anderson et al., 1994). Among these toxins are neurotoxins that if ingested in a large enough quantity can cause paralytic shellfish poisoning (PSP) in vertebrate consumers, including humans. Closures of shellfish beds due to PSP toxicity in Maine are patchy in both space and time throughout the spring, summer, and fall (Anderson, 1997). To protect human health, the Maine Department of Marine Resources (DMR) monitors shellfish each season throughout the Maine coast for toxicity levels (Bean et al., 2005). Samples are collected roughly weekly at approximately 100 stations along the coast, with expanded sampling efforts used to isolate events in time and space. Samples are processed using Association of Official Analytical Chemists procedures (AOAC) for mouse bioassay that determine a toxicity score (Hallegraeff et al., 1995). Scores approaching 80 μg STX equivalents 100 g^{-1} tissue, the quarantine toxicity level set by the World Health Organization, result in shellfish bed harvesting closures. Economic losses due to closures can be substantial, totaling ~$5 M in lost revenue for Maine businesses and $18 M in Massachusetts in 2005 alone (Jin et al., 2008).

Links between the space and time variability of *Alexandrium* cell distributions in the Gulf of Maine, environmental variability and coastal shellfish toxicity levels are the subject of ongoing research (Anderson, 1997; Anderson et al., 2005). Townsend et al. (2001, 2005) show that offshore cell distributions in the open Gulf of Maine have links to increased nutrient concentrations and light availability imposed by stratification, both modulated by overall

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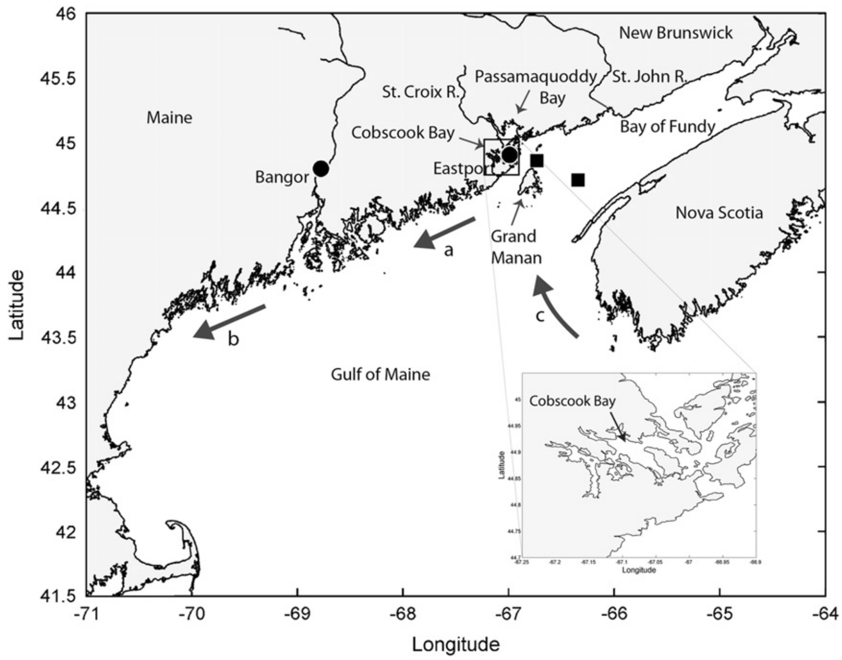

Fig. 1. The Gulf of Maine showing the location of Cobscook Bay, the St. Croix and St. John Rivers, other relevant geographic sites, the locations where surface temperature records (black squares) and meteorological records (black circles) are measured, and the direction of residual surface circulation in the coastal Gulf of Maine (a, Eastern Maine Coastal Current, b, Western Maine Coastal Current, and c, flow on the southern Scotian shelf). Inset shows detail of Cobscook Bay region. We subjectively identify regions in the vicinity of a, as eastern Maine and those in the vicinity of b, as western Maine.

circulation patterns. Overall cell distributions near shore appear to be strongly controlled by the Maine coastal currents (Keafer et al., 2005). Concentrations develop earliest in the season in warmer western portions of the Gulf and later in the east, with the possibility that surface distributions are initially fed by a series of cyst beds along the coast (McGillicuddy et al., 2005a) and then modulated by the hydrographic conditions of that year (McGillicuddy et al., 2011). Establishing links between interannual environmental variability and *Alexandrium* cell numbers/distribution is difficult due to the complex physical–biological interactions regulating these blooms and the relatively few large-scale surveys of cell counts. Furthermore, McGillicuddy et al. (2005b) show that overall offshore populations were relatively stable from year to year over the six years they examined (between 1993 and 2002), suggesting that interannual variability in coastal shellfish toxicity might largely be regulated by transport processes and/or local processes close to shore. Here we make use of over two decades of shellfish toxicity records at multiple coastal sites to investigate possible links between toxicity and environmental variability focusing on a region within which no previous links have been found.

Previous work shows strong ecological heterogeneity along the coast of Maine (Fig. 1) among a wide assortment of benthic marine distributions and processes (e.g. Hale, 2010) as well as HAB impacts (Hurst and Yentsch, 1981; Bean et al., 2005; Thomas et al., 2010), most likely linked to strong gradients in oceanographic conditions along the coast (e.g. Brooks, 1985; Pettigrew et al., 2005; Townsend et al., 2005). Superimposed on the residual cyclonic circulation of the gulf that creates southwestward flow along the Maine coast is tidal forcing that increases from the southwest to the northeast. Southwestern portions of the coast (Fig. 1) are therefore downstream of our study area, experience reduced tidal mixing and strong seasonal surface temperature cycles, with warm, stratified, nutrient deplete conditions and relatively weak flow of the Western Maine Coastal Current prevailing at the surface throughout the summer. Eastern portions of the coast are upstream, experience some of the strongest tidal mixing in the world, are subjected to relatively strong advective alongshore flow of the cold, well-mixed Eastern Maine Coastal Current (Fig. 1), and have a reduced surface seasonal temperature cycle, remaining relatively cold, nutrient replete, and well mixed throughout the year (Townsend et al., 2006).

Cobscook Bay is a highly denticulated inlet lying near the Canadian border at the eastern end of the Maine coast near the mouth of the Bay of Fundy (Fig. 1). With a mean tidal range of 5.7 m, tidal forcing is extremely strong in this region. Cobscook Bay has an average flushing time of about two days and all water entering the bay flows through a complex island archipelago and a narrow entrance channel and is therefore strongly mixed (Brooks et al., 1999). Water entering the bay is potentially influenced by a number of sources. Freshwater influences include drainage into Cobscook Bay itself which is relatively minor, discharge from the St. Croix River at the head of Passamaquoddy Bay (Fig. 1) and influences from the St. John River, located upstream of the region, the largest direct riverine freshwater input into the Gulf of Maine (Fig. 1). Oceanic water influencing Cobscook Bay and the nearby coast arrives from the mouth of the Bay of Fundy. These waters originate from the well-mixed southern Scotian Shelf (Fig. 1) and waters within the Bay of Fundy, and are influenced by Gulf of Maine water at the upstream portion of the Eastern Maine Coastal Current.

Toxicity levels in shellfish along the Maine coast are strongly seasonal, peaking in summer (Shumway et al., 1988) and not present (or minimal) in winter. Early work suggested the influence of oceanographic variables controlling coastal toxicity variability in western Gulf of Maine regions, including the hypothesis that coastal freshwater advection modulated by wind forcing might be related to toxicity along the western coast of Maine (Franks and Anderson, 1992a,b). Luerssen et al. (2005) suggested that alongshore flow structure evident in surface temperature patterns was linked to western coastal toxicity. A survey of 21 years of interannual variability of shellfish toxicity along the whole Maine coast (Thomas et al., 2010) showed strong and coherent geographic pattern among stations with similar interannual variability. Stations