Detection of *Alexandrium fundyense* Bloom Initiation and Transport in the Western Gulf of Maine, USA, Using Mussels (*Mytilus edulis*) on Offshore Hydrographic Moorings

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Abstract

Shellfish toxins that cause Paralytic Shellfish Poisoning (PSP) are seasonally detected in the blue mussel (*Mytilus edulis*) along the western Gulf of Maine (GOM) shoreline, most notably in Casco Bay, Maine. As part of the ECOHAB-GOM field program, mussels were placed in nylon mesh bags and attached to hydrographic moorings deployed both inshore and offshore of Casco Bay. In 1998, toxicity was first detected in the mussels at the most offshore mooring when *Alexandrium fundyense* concentrations reached ca. 200 cells L^{-1}, two weeks prior to detection at the inshore monitoring sites. In contrast, the first toxin detection of year 2000 occurred at an inshore monitoring site in Casco Bay, suggesting local initiation. In both years, however, high levels of toxicity (above quarantine) within Casco Bay were likely the result of delivery and accumulation of *A. fundyense* populations within the Bay from the offshore waters due to both alongshore and onshore transport associated with downwelling-favorable winds. Therefore, monitoring mussels attached to offshore buoys or at offshore islands can complement inshore monitoring programs in regions where large-scale hydrographic processes are responsible for harmful algal blooms (HABs).

Introduction

In the Gulf of Maine (GOM), toxic blooms of *Alexandrium fundyense* occur nearly every year during the spring and summer months, affecting shellfish resources along large stretches of the New England coastline (Anderson, 1997). Several studies have demonstrated that populations of *A. fundyense* are associated with coastal currents that are part of the general circulation of the GOM. Franks and Anderson (1992) observed cells in low-salinity coastal waters and suggested that blooms in the western GOM may originate near the mouth of the Kennebec River. Indeed, higher abundances of *A. fundyense* have been observed early in the bloom season near the frontal boundary of the Kennebec plume as it enters the coastal ocean (Anderson and Keafer, 1993; Anderson *et al.,* submitted). More recently, Townsend *et al.* (2001) demonstrated that offshore *A. fundyense* blooms were associated with the cold, nutrient-rich, tidally well-mixed waters of the Eastern Maine Coastal Current (EMCC) which often deflects offshore of Penobscot Bay, but sometimes can also branch alongshore to join the Western Maine Coastal Current (WMCC; see Fig. 1).

The first detection of shellfish toxicity along the Maine coastline during the spring commonly occurs in Casco Bay, near the Kennebec River mouth. Toxicity usually reaches higher levels and often persists longer than in other areas along the western GOM coast. These observations suggest that Casco Bay is a site for initiation of local blooms or at least an area favorable for accumulation and growth of advected populations, but very little shellfish toxicity data is available from the adjacent offshore waters where *A. fundyense* is known to occur. The objective of this study was to use mussels (*Mytilus edulis*) as biosensors at offshore hydrographic mooring sites to determine if the timing and magnitude of toxicity at the offshore sites could provide evidence of offshore bloom initiation and alongshore and cross-shore transport processes in the Casco Bay region.

Materials and Methods

Hydrographic moorings were deployed both within and offshore of Casco Bay as part of the ECOHAB-Gulf of Maine field program and provided the surface buoys from which to hang mussels (Fig. 1). These moorings provided continuous measurement of temperature (T), salinity (S) and current velocity/direction at 5 m. Three moorings were deployed near Casco Bay in 1998 (M1, M2, and M3). In year

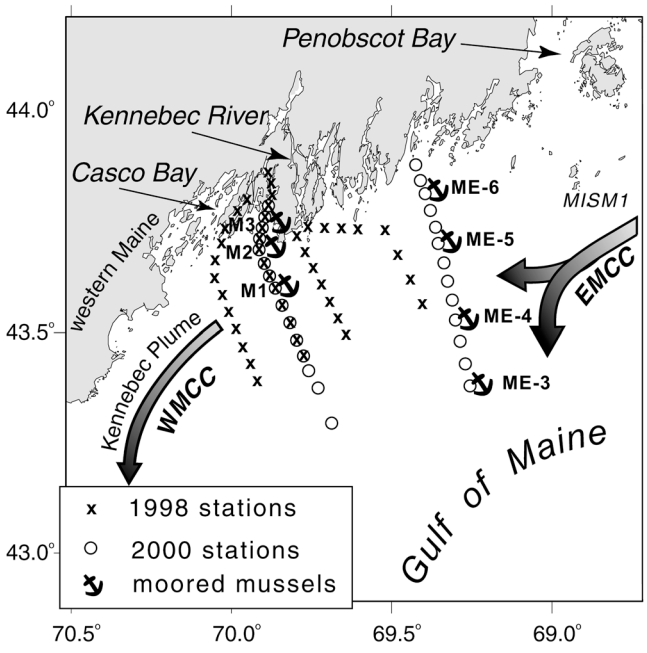

Figure 1 Map of the study area showing the major coastal currents, the EMCC and the WMCC, influencing the western GOM coastline. Hydrographic stations and mussel locations at hydrographic moorings for each study year are indicated.

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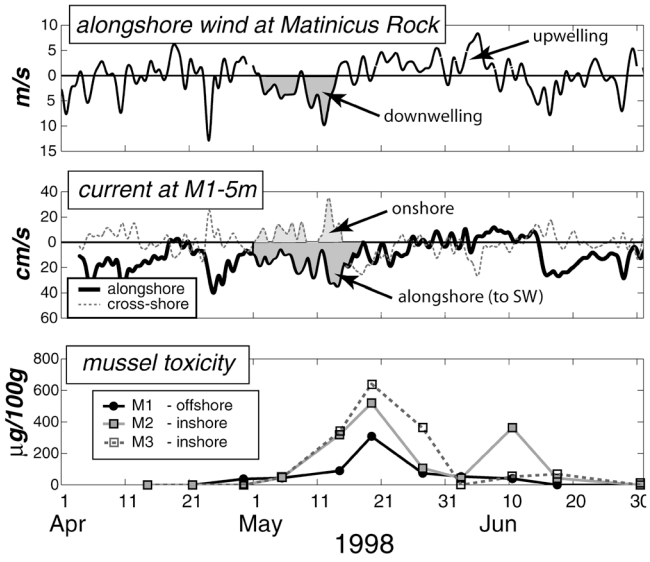

Figure 2 Time series of alongshore wind, alongshore and cross-shore current at M1 mooring, and mussel toxicity (STX eq.) at selected stations in year 1998. The initial outbreak was associated with downwelling-favorable conditions and current flow along and onto the coast.

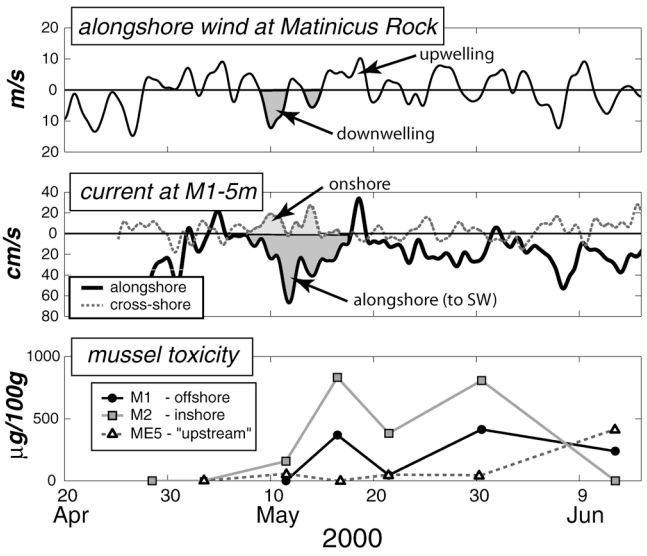

Figure 3 Time series of alongshore wind, alongshore and cross-shore current at M1 mooring, and mussel toxicity (STX eq.) at selected stations in year 2000. As in 1998, toxicity increased with downwelling winds. It persisted with the alongshore and onshore current flow.

2000, additional mussel moorings were established "upstream," out of the influence of the Kennebec River plume (ME-3, ME-4, ME-5, and ME6). Continuous winds were recorded at Matinicus Rock (NOAA # MISM1).

Prior to the bloom season, wild mussels free of PSP toxins were placed in nylon-mesh bait bags and deployed on each buoy at a depth of about 1 m. Each week, snorkelers harvested a mussel bag and attached a replacement (free from toxin) bag. In addition, a bag that was never deployed in the survey region was used as a control. All mussels were assayed for PSP toxins using the standard mouse bioassay (AOAC, 1984).

During the weekly surveys, a CTD/rosette profiler provided T, S measurements and water samples to determine *A. fundyense* cell abundance. Water samples were concentrated with 20 µm sieves and preserved with 5% formalin. *A. fundyense* cells were counted using an immunofluorescent protocol.

Results and Discussion

In 1998, shellfish toxicity was first detected during late April at the most offshore site, M1, followed 1 week later by detection at two moorings, M2 and M3, within Casco Bay. Toxicity at the intertidal monitoring sites in Casco Bay and along the western Maine coast was not detected until two weeks after the offshore levels increased. Although toxic cells were observed within Casco Bay prior to toxin detection in mussels, the highest cell abundance was observed in the offshore waters near the frontal boundary of the Kennebec River plume. The progression of toxicity from offshore to onshore was associated with downwelling-favorable wind conditions that transported the offshore *A. fundyense* population (ca. 200–500 cells L^{-1}) into Casco Bay as indicated by the alongshore and onshore components of the current velocity at M1 (Fig. 2). The results are consistent with a possible offshore source for blooms within Casco Bay.

In contrast, in 2000, shellfish toxicity was first detected at the intertidal monitoring sites within Casco Bay even with the expansion of offshore mussel sites. This observation indicated that a local source of *A. fundyense* cells within Casco Bay might also exist. However, the evidence suggests that the contribution from the offshore waters was more important. First, a denser offshore population (300–500 cells L^{-1}; two- to threefold greater than inshore) existed near the outer Kennebec plume front, similar to 1998, but that population was seaward of the M1 mooring site and therefore was not detected early by the offshore mussels at that mooring. Second, an "upstream" population was present early near mussel sites ME4 and ME5, but it was near the lower limit of cell concentrations that can be detected by the mussels (ca. 200 cells L^{-1}). As toxicity rose rapidly inshore within Casco Bay, toxicity was detected at the same time at two upstream mussel sites (ME4 and ME5), suggestive of an offshore and upstream source. Finally, the rise in toxicity within Casco Bay was associated with downwelling-favorable conditions and transport of surface waters onshore and alongshore at the M1 mooring, comparable to 1998 (Fig. 3). Either the local Bay population grew very rapidly or the offshore population was advected and accumulated within Casco Bay. The rapid rise in both toxicity (from 40 µg 100 g^{-1} to >2000 µg 100 g^{-1}) and cell abundance (from ca 200 cells L^{-1} to >2000 cells L^{-1}) in less than a week, and the association of this rise with downwelling-favorable conditions in both 1998 and 2000, favors the latter inter-

pretation. Transport and accumulation likely dominated local growth processes over these short time scales. Thus, despite the detection of an early season inshore population by the mussel bags in year 2000, significant populations existed <10–20 km offshore. These populations could easily be pulsed into the inshore embayments with wind events and replenished with the flow from the upstream waters. When the flow reversed and moved offshore during strong upwelling, the source population was presumably cut-off from the inshore areas and shellfish toxicity generally declined (*e.g.,* Fig. 2, saxitoxin equivalents).

The westernmost extension of an upstream population of *A. fundyense* associated with the EMCC is thus the most likely source population for PSP outbreaks along the western Maine coastline. This current provides a nutrient-rich environment for growth of *Alexandrium* sp. and other phytoplankton in the GOM (Townsend *et al.,* 2001). The growing population is transported into the western GOM in the spring, facilitated by downwelling-favorable conditions, but toxicity is not detected until the population reaches about 200 cells L^{-1}, which may occur first either offshore (*e.g.,* 1998) or inshore (*e.g.,* 2000). The confluence of the western branch of the EMCC and the river plumes that contribute to the WMCC create an environment where cells can accumulate at frontal boundaries and/or be entrained in the buoyant plume waters. Once in the plume, toxic cells can be delivered into Casco Bay and other embayments along the western GOM coastline with transport strongly influenced by the wind, causing shellfish closures as far south as Massachusetts Bay (Anderson *et al.,* submitted).

This study demonstrated that offshore-moored mussels can serve as useful indicators of impending PSP outbreaks from adjacent offshore waters in the GOM. To be most beneficial, mussels must be deployed at both inshore and offshore sites located based on an understanding of the local and regional circulation patterns. The results must be interpreted with caution, however, due to plankton patchiness and the fact that offshore populations can rapidly develop into inshore blooms during downwelling-favorable conditions. Therefore, wind events and their influence on the behavior of the EMCC and WMCC are critical for prediction of PSP events along the western GOM coastline. These mussel bag data will eventually be used to develop a shellfish toxicity submodel that will be incorporated into bio-physical models currently under development for the prediction of PSP in the GOM (*e.g.,* McGillicuddy *et al.,* 2003). Meanwhile, the state of Maine has expanded their monitoring program to include offshore islands and the deployment of mussels in the offshore waters adjacent to the well-established inshore monitoring sites to improve seafood safety in the region.

Acknowledgements

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