Environmental Factors Linked to Harmful Algal Bloom Induced Shellfish Toxicity in Cobscook Bay, Maine

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ENVIRONMENTAL FACTORS LINKED TO HARMFUL ALGAL BLOOM INDUCED SHELLFISH TOXICITY IN COBSCOOK BAY, MAINE.

by

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A Thesis Submitted in Partial Fulfillment
of the Requirements for a Degree with Honors
(Marine Science)

The Honors College

University of Maine

May 2012

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Abstract

The Gulf of Maine experiences annual closures of shellfish harvesting due to the accumulation of toxins resulting from harmful algal blooms of the dinoflagellate *Alexandrium* spp. If ingested by humans, these toxins can cause paralytic shellfish poisoning. The factors affecting the timing, location, and magnitude of these events remain poorly understood. Previous work found no obvious correlations between Gulf of Maine oceanographic variability and interannual variability in toxicity in the strongly tidally mixed eastern Maine coastal region in the vicinity of Cobscook Bay. Using 21 years (1985-2005) of Maine Department of Marine Resources shellfish toxicity data, interannual variability in two metrics of annual toxicity, maximum magnitude and integrated total annual toxicity, are examined for relationships to a suite of environmental variables. Consistent with earlier work, no correlation was found between toxicity and oceanographic variables, even when individual station toxicity was compared to very proximate variables such as local sea surface temperature and river discharge. However, correlations between toxicity and two variables indicative of local weather, dew point and atmospheric pressure, both suggest a link between increased toxicity and clearer skies/ drier air. As no correlation was evident between toxicity and local precipitation, we hypothesize that the link is through light availability in this persistently foggy section of coast.

Acknowledgements

I thank Maine Department of Marine Resources for access to the 21 years of shellfish toxicity data. I thank the Satellite Oceanography laboratory at the University of Maine for the sea surface temperature images and the United States Geological Survey for river discharge data. I thank Bangor and Eastport Airports for the collection of 21 years of numerous atmospheric parameters. This research was performed with funding from the University of Maine. A special thank you to my thesis committee for support and assistance, to Ryan Weatherbee for lessons on programming software, and to my advisor Dr. Andrew Thomas for guidance and support through this process.

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1. Introduction

Harmful algal blooms (HABs) caused by the dinoflagellate *Alexandrium* spp. necessitate shellfish bed closures in the Gulf of Maine. These dinoflagellates produce compounds called saxitoxins, (Anderson et al., 1994) neurotoxins that if ingested in a large enough quantity, can cause paralytic shellfish poisoning (PSP). Saxitoxins affect neuroreceptors in the brain causing paralysis, eventually shutting down the body if left untreated. Marine shellfish become toxic to humans when they ingest the algae from these HABs through filter feeding. Shellfish bed closures in Maine occur episodically throughout the spring, summer, and fall most commonly in early summer and in the fall, the latter usually being smaller in magnitude (Anderson, 1997).

To protect human health, since 1958 the Maine Department of Marine Resources (DMR) has monitored Maine shellfish for toxicity levels throughout each season (Bean et al., 2005). Samples are collected approximately weekly at about 100 stations along the coast and a mouse bioassay is used to determine a toxicity score. Scores approaching 80 μg/ 100g tissue, the quarantine toxicity level set by the United States Food and Drug Administration, result in shellfish bed closures. Economic losses due to closures can be substantial, totaling $14.8 million in lost output for Maine businesses in 2005 (Athearn, 2005). However, links between the space and time variability of shellfish toxicity levels and environmental variability remain poorly understood. Furthermore, environmental processes controlling *Alexandrium* spp. dynamics in the Gulf of Maine remain the subject of ongoing research.

Previous work shows strong ecological heterogeneity along the coast of Maine among a wide assortment of marine distributions and processes (Hale, 2010) including

HAB impacts (Thomas et al., 2010; Bean, 2005), most likely linked to strong gradients in oceanographic conditions influencing the coast (Anderson, 1997; 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, tidal forcing increases from the southwest to the northeast. Southwestern portions of the coast are therefore downstream, experience reduced tidal mixing and strong seasonal surface temperature cycles. Warm, stratified, nutrient deplete conditions prevail during the summer. Eastern portions are upstream and experience some of the strongest tidal mixing in the world. These portions are subjected to relatively strong advective alongshore flow of the cold Eastern Maine Coastal Current, and have a reduced seasonal temperature cycle, remaining relatively cold, nutrient replete, and well mixed throughout the year.

Cobscook Bay is a strongly denticulated inlet lying near the Canadian border at the northeastern end of the Maine coast near the mouth of the Bay of Fundy (Figures 1 and 2). With a mean tidal range of 5.7 meters, tidal forcing is extremely strong in this region resulting in an average flushing time of about two days for Cobscook Bay (Brooks et al., 1999). All water entering the bay flows through a complex island archipelago and a narrow, relatively shallow, entrance channel and is therefore strongly mixed. 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 Saint Croix River at the head of Passamaquoddy Bay (Figure 1) and influences from the Saint John River, located upstream of the region, the largest riverine freshwater input into the Gulf of Maine (Figure 1). Oceanic water influencing Cobscook Bay arrives from the eastern portion of the entrance to the Bay of Fundy. These waters originate from the

Nova Scotia Current that travels around the Nova Scotia peninsula and into the Bay of Fundy, where it is influenced by Gulf of Maine water at the upstream portion of the Eastern Maine Coastal Current.

Environmental factors influencing the timing and distribution of *Alexandrium* spp. populations in the Gulf of Maine are the subject of ongoing research. The populations begin each spring in two major *Alexandrium* cyst beds (Libby and Anderson, 2010) and spread through the Gulf of Maine by the Maine coastal currents. Previous work suggests that there are discrete regions of *Alexandrium* populations that are controlled by unique factors, both oceanographic and environmental. Toxins within these dinoflagellates vary with region, generally becoming less toxic the further south the population (Anderson, 1997; Etheridge and Roesler, 2005). Nutrient and light availability also regulate offshore bloom dynamics (Townsend et al., 2001) with larger densities of *Alexandrium* present in regions of higher surface light and nutrient availability.

Early work suggested that wind-driven upwelling and coastal freshwater advection might be related to toxicity along the southern coast of Maine (Franks and Anderson, 1992 (a) and 1992 (b)). A broad survey of 21 years of interannual variability of shellfish toxicity along the Gulf of Maine coast (Thomas et al., 2010) found strong oceanographic links to sea surface temperature patterns and surface Ekman transport driven by wind stress along the southwestern, downstream portion of the Maine coast. However, this work could not identify oceanographic factors linked to coastal toxicity variability in regions along the colder upstream eastern Maine coast, including stations in Cobscook Bay. Here I expand on this earlier work in three ways. The focus is specifically on far eastern regions of the Gulf of Maine. I analyze interannual toxicity variability at individual stations rather than statistically clustered groups of stations. Lastly, I compare these to an expanded list of oceanographic and atmospheric factors more local to the toxicity sampling sites of this eastern Maine coast.

2. Data and Methods

2.1 Toxicity Data and Metrics

Twenty-one years of shellfish toxicity data from 1985 to 2005 were obtained from the Maine Department of Marine Resources. The original data comprised over 64,000 records, measured in over 10 different species, with approximately 350 stations sampled at least once between 1985 and 2005. Of these stations, about 100 were sampled ~weekly each year along the Gulf of Maine providing a clear picture of seasonal patterns within each year. I use only those stations sampled multiple times each year. Nine stations are in the Cobscook Bay area (Figure 2) with the others spread along the rest of the Maine coast. Toxicity records are collected between March 1 and November 1 of each year. To avoid biases based on species-specific rates of toxin uptake and depuration, this study focuses on toxicity records only from the genus *Mytilus* that account for approximately 58 percent of records.

Following protocols outlined in Thomas et al. (2010) the toxicity time series at each station, in each year, was reduced to two metrics of interannual variability; Magnitude of Toxicity and Integrated Annual Toxicity. To reduce bias by single measurements, Magnitude of Toxicity is calculated as the mean of the three highest toxicity measurements at a station for a given year. This was calculated only for stations and years with at least 10 valid toxicity measurements. Integrated Annual Toxicity is calculated as the mean of all toxic values in a year greater than zero performed for stations and years with at least five toxicity values of zero or above. These metrics provide related, but slightly differing views of how toxic a station was in each year.

2.2 Environmental Data

Mean daily river discharge data from the Saint John (site 1014000) and Saint Croix (site 1021000) rivers (Figure 1) are available from the United States Geological Survey for the period 1985-2005. From these I calculated mean monthly discharge in each calendar month in each study year for each river.

Multiple daily satellite-measured sea surface temperature records of the Gulf of Maine are collected by the Satellite Oceanography Laboratory at the University of Maine and produced into monthly mean images. Monthly data spanning the period 1985-2005 were subsampled at two stations located near the northern end of Grand Manan Island and over Manan Basin (Figure 1) to create interannual time series of surface ocean temperature in the vicinity of Cobscook Bay.

Air temperature and precipitation records are from the Eastport International Airport (Figure 1). Precipitation data are received as monthly total precipitation over the study period and air temperatures are monthly means.

Relative humidity, atmospheric pressure, and dew point are available from the Bangor International Airport (Figure 1). All were received as daily averages over the study period. I calculated mean monthly values for each data set for comparison with the toxicity metrics.

2.3 Analysis

The nonparametric Spearman Rank correlation is used to quantify the relationships between concurrent interannual variability of the two toxicity metrics and the suite of environmental metrics over the 21 year study period. I use nonparametric statistics because tests of the underlying distribution of the toxicity data suggested non normal distributions.

3. Results and Discussion

Neither of the sea surface temperature time series nor river discharge from either the Saint John or the Saint Croix rivers was found to have a strong relationship with either metric of interannual toxicity pattern (Tables 1 and 2). A few stations show significant correlations in some months, but here we seek persistent correlations across many stations. This lack of relationship is consistent with the results of Thomas et al. (2010) who found no relationship between interannual variability in the toxicity of eastern Maine station groups and Gulf of Maine sea surface temperature or Penobscot River discharge. Here I show similar results but tested against rivers and sea surface temperature locations more proximate to the eastern stations and applied to individual stations. One possible mechanism explaining this lack of interaction is the strong tidal mixing.

As phytoplankton, *Alexandrium* require both light and nutrients, and previous work suggests that cell distribution patterns in the open Gulf of Maine are linked to circulation and hydrographic characteristics (Townsend et al., 2001, 2005). Along the eastern Maine coast and in Cobscook Bay, however, the strong tidal mixing may be sufficient to remove the effects of interannual variability in nutrient availability imposed by varying river discharge or sea surface temperature. Our results also imply that interannual variability in any chemical constituents in the local rivers have no measurable link to toxic variability. Correlational analysis of the atmospheric factors air temperature, relative humidity, and precipitation showed no or only weak relationships with the magnitude of annual toxicity and integrated annual toxicity (Tables 1 and 2).

Atmospheric pressure has a positive correlation with toxicity in Cobscook Bay, Maine, (Table 1 and Figures 3 and 4) especially the mean monthly atmospheric pressure in early spring (March). Lower atmospheric pressure generally indicates storms and poor weather conditions while higher atmospheric pressure indicates fewer storms and less cloudy skies. The positive correlation indicates that increased atmospheric pressure is associated with increased toxicity suggesting higher toxicity reading during years with less stormy weather.

Mean early summer (June) dew point has a negative correlation with toxicity in Cobscook Bay, Maine (Table 1 and Figures 5 and 6). Higher dew point indicates unstable, moist air which causes cloudy weather and storms. Lower dew point indicates stable, dry air of poor cloud-forming potential. The negative correlation indicates that on interannual scales, increased dew point is associated with decreased toxicity, meaning that years with less air moisture and fewer storms generally have higher toxicity values. This is consistent with the relationship observed for atmospheric pressure.

Analysis of the relationships between these two atmospheric factors and toxicity metrics at all stations along the Maine coast shows correlations strongest north of Penobscot Bay, especially in Cobscook Bay (Figures 7 and 8). These results show a similar disconnect of the Cobscook Bay *Alexandrium* population from those along the western Maine coast as was seen in Thomas et al. (2010). Isolation of this population and the resulting difference in environmental linkages may be related to the secluded nature of the bay or the different hydrographic conditions due to regional tidal mixing.

Two atmospheric factors with strong correlations in Cobscook Bay suggest increased atmospheric water content and cloudy weather results in a decrease in toxicity. Our data is not capable of inferring causality but plausible mechanisms can be suggested. During years with reduced storms, more sunlight would reach phytoplankton possibly increasing coastal ocean productivity. Increased phytoplankton productivity would include an increased growth and reproduction rate of *Alexandrium* providing increased HAB concentration to the mussels.

Another possible mechanism suggested by the observed relationships is that increased sunlight may affect the toxicity of individual cells. Toxin concentrations within *Alexandrium* cells vary among species and physiological conditions causing some to be more toxic than others (Anderson et al., 1994). Environmental conditions may allow for variability of dominant species within *Alexandrium* populations affecting the toxicity readings. Previous studies have also shown that the toxicity of *Alexandrium* cells is affected by environmental factors such as temperature and irradiance which may also contribute to interannual variability (Etheridge and Roesler, 2005).

Another mechanism resulting in interannual variability of shellfish toxicity is variable filtering rates of the organisms. Studies show variability of feeding rates of *Mytilus edulis* due to many environmental factors including cell vertical particle flux, temperature, and seston abundance and composition, many of which were not evaluated in this study (Cranford and Hill, 1999). Also, studies of the bivalve *Mya arenaria* found that a natural genetic mutation, usually found in organisms with repeated exposure to HABs, increases their resistance to toxins allowing them to more quickly accumulate toxins than those without the mutation (Bricelj et al., 2010 and Connell et al., 2007). It is unknown whether other shellfish species undergo similar mutations, but these changing conditions could contribute to interannual variation in toxicity levels not only in the present, but as a long term effect.

4. Conclusions

Previous work examining links between interannual variability in Maine coastal shellfish toxicity and environmental variability found no relationships between regionally averaged Cobscook Bay area measurements and Gulf of Maine oceanographic metrics. Our results confirm these findings, even after treating individual site locations within the Cobscook Bay area and examining very local oceanographic measurements. However, I show that two locally varying environmental metrics indicative of weather conditions are correlated with 21 years of shellfish toxicity in Cobscook Bay at a number of sampling sites. Correlations between toxicity and atmospheric pressure and dew point both indicate that sunnier and drier weather is associated with higher toxicity levels. Such correlations were evident at only a few scattered stations further west along the Maine coast where previous work has shown toxicity interannual variability has closer links to oceanographic factors. It is possible that the extremely strong tidal mixing in the Cobscook Bay region reduces interannual variability of most oceanographic signals. While our data are incapable of addressing causality or examining mechanisms, our results found no parallel correlations between shellfish toxicity and local precipitation, river discharge or air temperatures, suggesting that any interaction with weather may be through light availability. This region is characterized by recurrent strong spring/summer fog, a phenomena that would be reduced in years of higher atmospheric pressure and lower atmospheric water content. The mechanisms of interaction are beyond the scope of the present work, but increased light availability may lead to increased Alexandrium cell densities, changes in cell toxin content, or differences in shellfish filtering/depuration rates. Results reported here support the continued intensive monitoring and archiving of shellfish toxicity scores from a wide diversity of regions along the Maine coast. It is evident that strong geographic differences in both oceanographic interannual variability and the interaction of Alexandrium-induced shellfish toxicity with environmental conditions make the application of models developed in only one region, or region-specific models unlikely to be applicable to such a heterogeneous coastline. More importantly, factors beyond variability in ocean conditions, such as local weather, need to be taken into account in future studies focused on assisting management forecasts.

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Table 1. Correlation (r) between monthly environmental metrics and Integrated Annual Toxicity. Significance levels: **95%**, 90%, and " - " indicates no significant correlation.

Environmental Metric	Station	Month					
		March	April	May	June	July	August
Air Temperature	**320**	-	-	-	-	-	-
	321	-0.39	**-0.47**	-	-	-	-
	333	-	-0.40	-	-	-	-
	336	-	-	-	-	-	-
	338	-0.41	-	-	-	-	-
	343	-	-	-	-	-	-
	346	-	-	-	-0.40	-	-0.42
	351	-	-	-	-	-	**-0.62**
	353	-	-	-	-0.41	-	**-0.47**
Relative Humidity	**320**	-	-	-	-	-	-
	321	-	-	-	-	-	-
	333	-	-	-	-0.38	-	-
	336	-	-	-	-	-	-0.41
	338	-	-	-	-	-	-
	343	-	-	-	-	-	-
	346	-	-	-	-	-	-
	351	-	-	-	-	-	-
	353	-	-	-	-	-	-
Precipitation	**320**	-	-	0.39	-	-	-
	321	-	-	0.43	-	-	-
	333	-0.41	-	0.41	-	-	-
	336	-	-	-	-	**0.51**	-
	338	**-0.46**	-	-	-	-	-
	343	-0.41	-	-	-	-	-
	346	-	-	-	-	**0.44**	-
	351	-	-	-	-	-	-
	353	-	-	-	-	-	-
Dew Point	**320**	-	-	-	-	-	-
	321	-	-	-	-	-	-
	333	-	-	-	**-0.53**	-	-
	336	-	-	-	-	-	-
	338	-	-	-	-0.38	-	-
	343	-	-	-	**-0.45**	-	-
	346	-	-	-	**-0.54**	-	-
	351	-	-	-	-	-	-
	353	-	-	-	**-0.47**	-	-

Atmospheric Pressure	**320**	**0.47**	-	-	-	**0.50**	-
	321	**0.48**	-	-	-	-	-
	333	**0.54**	-	-	-	0.41	-
	336	-	-	-	-	-	-
	338	**0.54**	-	-	-	-	-
	343	0.43	-	-	-	-	-
	346	0.40	-	-	-	-	-
	351	-	-	-	-	-	-
	353	-	-	-	-	-	-
St. Croix River Discharge	**320**	-0.42	-	-	-	-	-
	321	**-0.43**	-	-	-	-	-
	333	-	-	-	-	-	-
	336	-	-	-	-	-	-
	338	**-0.47**	-	-	-	-	-
	343	-	-	-	-	-	-
	346	-	-	-	-	-	-
	351	-	-	-	-	-	-
	353	**-0.47**	-	-	-	-	-
St. John River Discharge	**320**	-	-	-	-	-0.41	-
	321	-	-	-	-	-	-
	333	-	-	-	-	-	**0.47**
	336	-	-	-	-	-	0.40
	338	-	-	-	-	-	-
	343	-	-	-	-	-	-
	346	-	-	-	-	-	**0.76**
	351	-	-	-	-	-	0.38
	353	-0.38	-	-	-	-	**0.68**
Sea Surface Temperature Manan Basin	**320**	**0.49**	-	-	-	-	-
	321	-	-	-	-	-	-
	333	-	-	-	-	-	-
	336	0.38	-	-	-	-	-
	338	-	-	-	-	-	-
	343	-	-	-	-	-	-
	346	-	-	-	-	-	-
	351	-	-	-	-	-	-
	353	-	-	-	-	-	-

Sea Surface Temperature	**320**	-	-	-	-	-	-
North of Grand Manan	**321**	-	-	-	-	-	-
	333	-	-	-	-	-	-
	336	-	-	-	-	-	-
	338	-	-	-	-	-	-
	343	-	-	-	-	-	-
	346	-	-	-	-	-	-
	351	-	-	-	-	-	-
	353	-	-	-	-	-	-

Table 2. Correlation (r) between monthly environmental metrics and Magnitude of Annual Toxicity. Significance levels: **95%**, 90%, and " - " indicates no significant correlation.

Environmental Metric	**Station**	**Month**					
		March	**April**	**May**	**June**	**July**	**August**
Air Temperature	**321**	-0.37	**-0.47**	-	-	-	-
	333	-	-	-	-	-	-
	336	-	-	-0.41	-	-	-
	338	-0.38	-	-	-	-	-
	343	-	-	-	-	-	-
	351	-	-	-	-	-	**-0.56**
	353	-	-	-	-0.42	-	-0.40
Relative Humidity	**321**	-	-	-	-	-	-
	333	-	-	-	-	-	-
	336	-	-	-	-	-	-0.41
	338	-	-	-	-	-	-
	343	-	-	-	-	-	-
	351	-	-	-	-	-	-
	353	-	-	-	-	-	-
Precipitation	**321**	-	-	**0.44**	-	-	-
	333	-0.41	-	0.42	-	-	-
	336	-	-	-	-	**0.49**	-
	338	**-0.44**	-	-	-	-	-
	343	-0.39	-	-	-	-	-
	351	-	-	-	-	-	-
	353	-	-	-	-	-	-

Dew Point	**321**	-	-	-	-	-	-
	333	-	-	-	**-0.51**	-	-
	336	-	-	-	-	-	-
	338	-	-	-	-0.40	-	-
	343	-	-	-	-0.42	-	-
	351	-	-	-	-	-	-
	353	-	-	-	**-0.50**	-	-
Atmospheric Pressure	**321**	**0.49**	-	-	-	-	-
	333	**0.52**	-	-	-	0.42	-
	336	-	-	-	-	-	-
	338	**0.54**	-	-	-	-	-
	343	0.38	-	-	-	-	-
	351	-	-	-	-	-	-
	353	-	-	-	-	-	-
St. Croix River Discharge	**321**	-0.43	-	0.37	-	-	-
	333	-	-	-	-	-	-
	336	-	-	-	-	-	-
	338	**-0.43**	-	-	-	-	-
	343	-	-	-	-	-	-
	351	-	-0.41	-	-	-	-
	353	**-0.47**	-	-	-	-	-
St. John River Discharge	**321**	-	-	-	-	-	-
	333	-	-	-	-	-	**0.48**
	336	-	-	-	-	-	-
	338	-	-	-	-	-	-
	343	-	-	-	-	-	-
	351	-	-	-	-	-	0.38
	353	-0.40	-	-	-	-	**0.69**
Sea Surface Temperature Manan Basin	**321**	-	-	-	-	-	-
	333	-	-	-	-	-	-
	336	0.41	-	-	-	-	0.42
	338	-	-	-	-	-	-
	343	-	-	-	-	-	-
	351	-	-	-	-	-	-
	353	-	-	-	-	-	-
Sea Surface	**321**	-	-	-	-	-	-

Temperature North of Grand Manan	**333**	-	-	-	-	-	-
	336	-	-	-	-	-	-
	338	-	-	-	-	-	-
	343	-	-	-	-	-	-
	351	-	-	-	-	-	-
	353	-	-	-	-	-	-

Figures

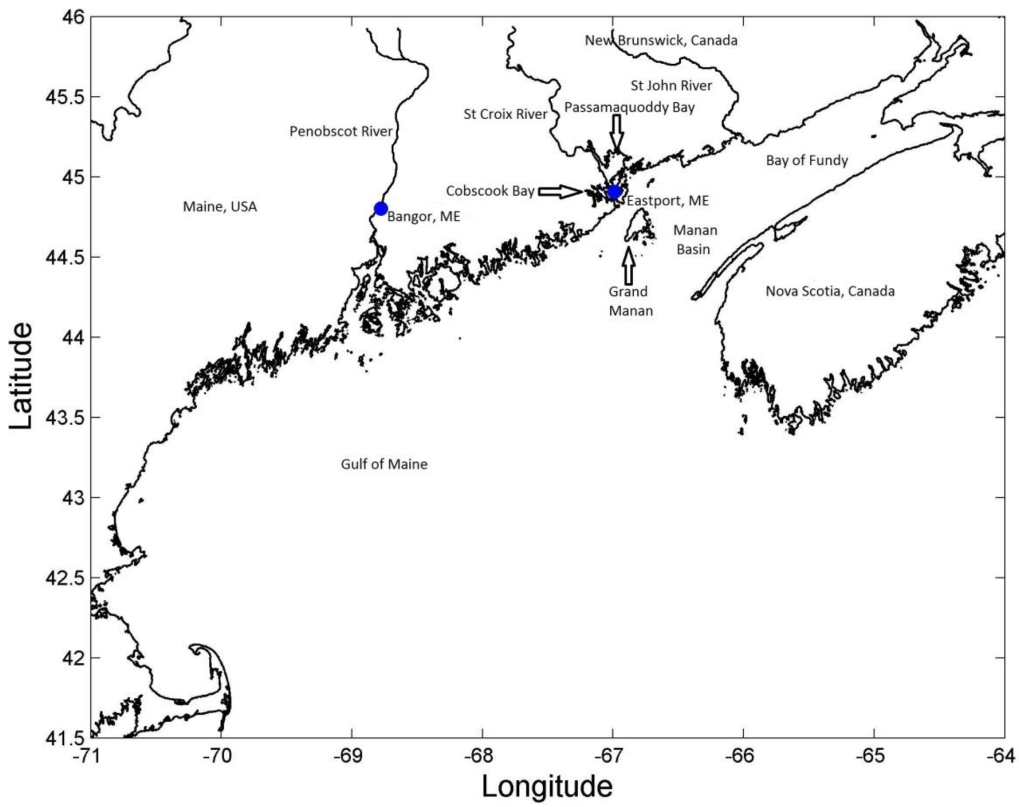

Figure 1. The Gulf of Maine study area showing data sources (blue dots), Saint Croix River, Saint John River, and other important landmarks.

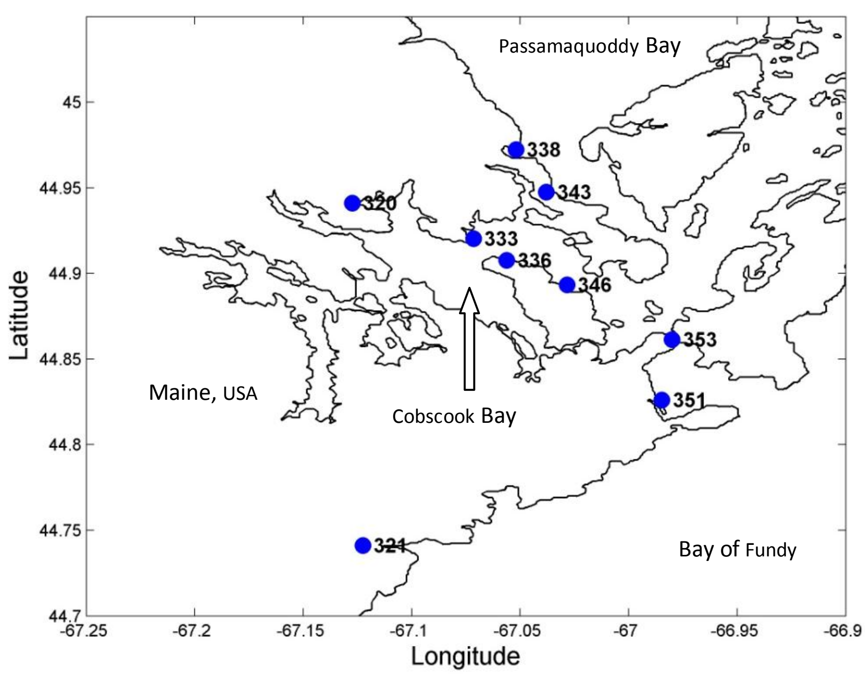

Figure 2. Cobscook Bay study area showing station locations and important landmarks.

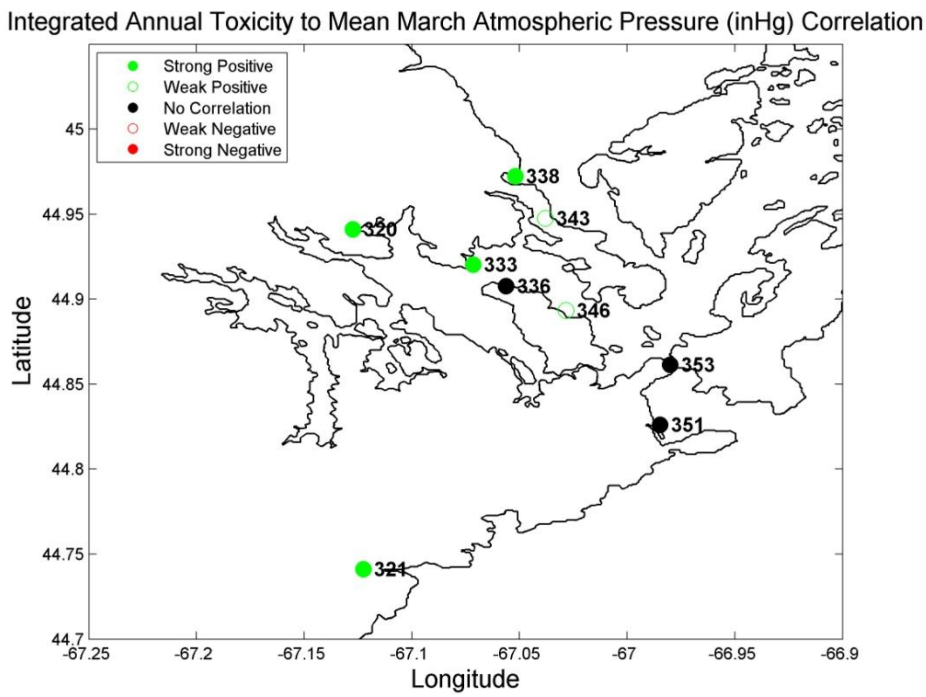

Figure 3. Cobscook Bay showing station-specific correlation significance between Integrated Annual Toxicity and mean March atmospheric pressure. Strong correlation 95% significance and weak correlation 90% significance.

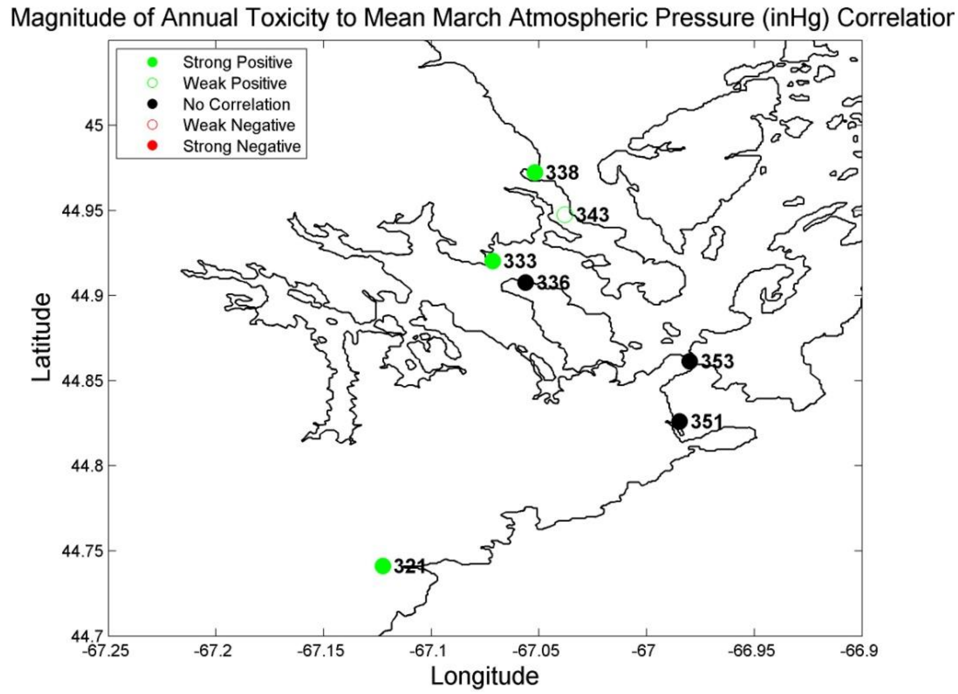

Figure 4. Cobscook Bay showing station-specific correlation significance between Magnitude of Annual Toxicity and mean March atmospheric pressure. Strong correlation 95% significance and weak correlation 90% significance.

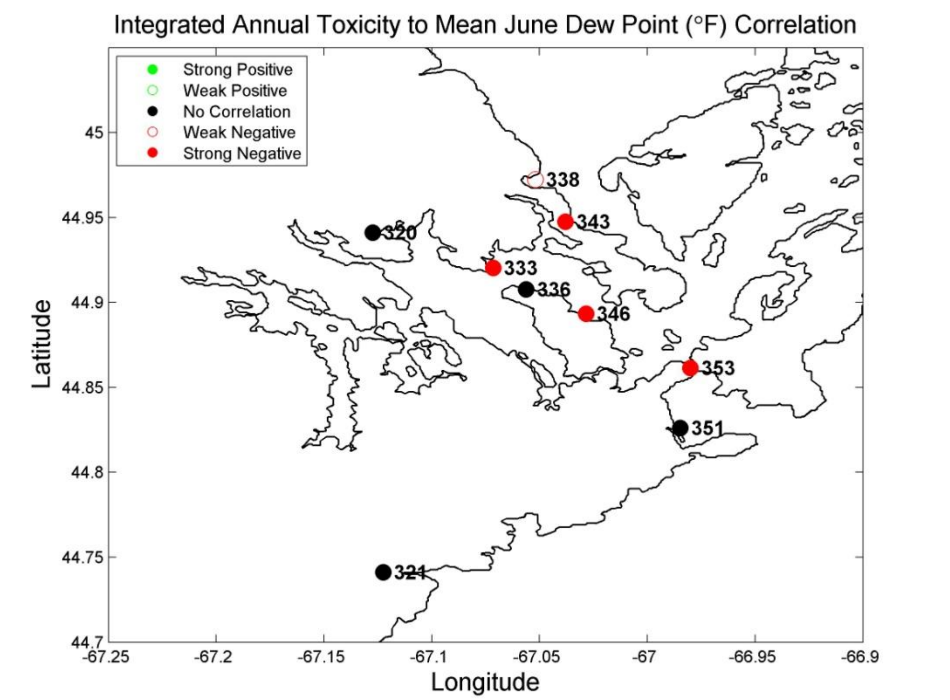

Figure 5. Cobscook Bay showing station-specific correlation significance between Integrated Annual Toxicity and mean June dew point. Strong correlation 95% significance and weak correlation 90% significance.

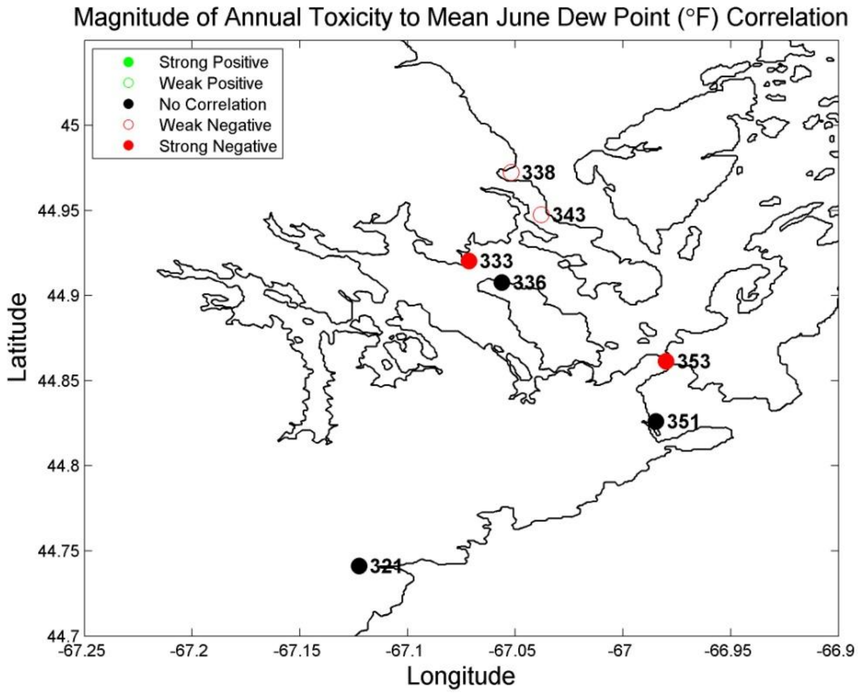

Figure 6. Cobscook Bay showing station-specific correlation significance between Magnitude of Annual Toxicity and mean June dew point. Strong correlation 95% significance and weak correlation 90% significance.

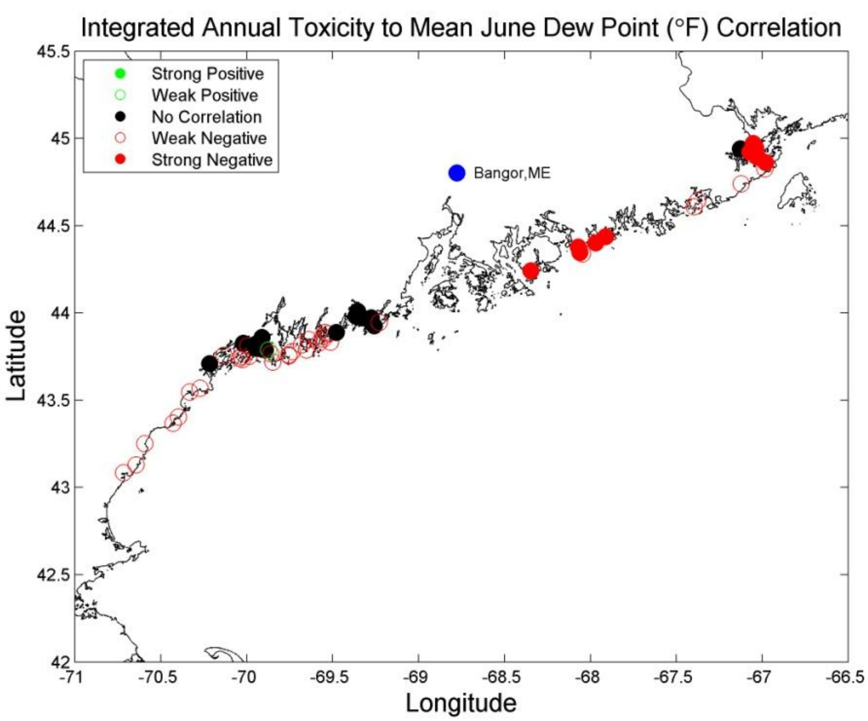

Figure 7. Integrated annual toxicity correlated with June dew point along the whole Gulf of Maine. Strong correlation 95% significance and weak correlation 90% significance.

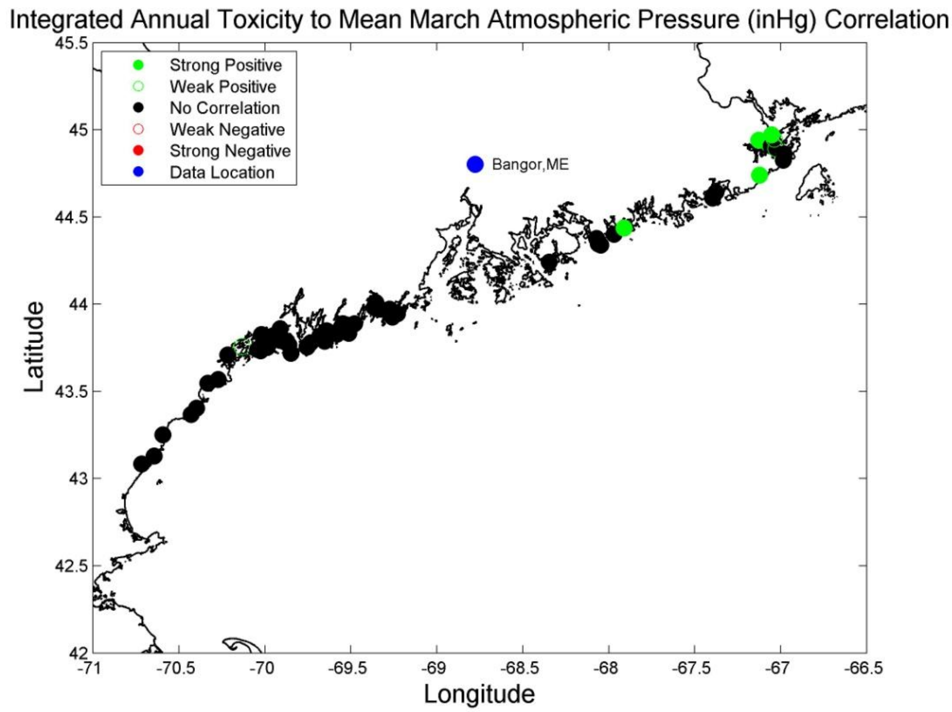

Figure 8. Integrated annual toxicity correlated with March atmospheric pressure along the whole Gulf of Maine. Strong correlation 95% significance and weak correlation 90% significance.

Author's Biography

Hannah M. Horecka was born in Benson, Minnesota on March 23, 1990. There she was raised and graduated from Benson Senior High School in 2008. Majoring in marine science at the University of Maine, Hannah has a concentration in marine biology and a minor in Spanish. She is a member of Kappa Delta Phi National Affiliated Sorority and was active with the University of Maine Women's Ice Hockey Club and Yoga Club.

Upon graduation, Hannah plans to attend a laboratory internship with the Maine Department of Marine Resources Biotoxin Program assisting in the collection of shellfish toxicity data along the northern Maine coast before pursuing a career in public education of the marine sciences.