Paralytic Shellfish Poisoning on Georges Bank: *in situ* Growth or Advection of Established Dinoflagellate Populations?

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ABSTRACT

Evidence is presented that the alongshore progression of paralytic shellfish poisoning (PSP) in the southern Gulf of Maine in 1990 was due to the southward movement of a buoyant plume of lower salinity water and its associated population of the dinoflagellate *Alexandrium tamarense*, originating in the Androscoggin and Kennebec River outflow. The movement of this plume into and across Massachusetts Bay is documented by hydrographic cruise transects and by moored observations of salinity and temperature. These data are consistent with the hypothesized link between shellfish PSP toxicity in offshore waters of Georges Bank and the long distance transport of the buoyant plume. These results also suggest a pathway by which human contaminants in riverine flows can travel across large distances to impact the rich offshore fisheries of the Gulf of Maine.

Background

Paralytic shellfish poisoning (PSP) outbreaks are caused by "blooms" of the red tide dinoflagellate *Alexandrium tamarense* and other closely related algae. In southern New England, this problem has historically been associated with nearshore or intertidal shellfish resources along the western Gulf of Maine. In recent years, however, high levels of PSP have been detected in shellfish from the offshore waters of Georges Bank and Nantucket Shoals. The source of the toxin in the surf clams and scallops is not known, although it is the same toxin found in the nearshore shellfish. Three alternative hypotheses have been advanced to explain these outbreaks: 1) the dinoflagellate *A. tamarense* grows in the waters on or near Georges Bank, possibly accumulating at frontal features (*in situ* growth); 2) dormant resting cysts of *A. tamarense*, produced by blooms at distant locations, are advected onto Georges Bank where they are consumed by shellfish, which retain the PSP toxins; and 3) large, nearshore blooms of *A. tamarense* in the western Gulf of Maine are advected across Massachusetts Bay and onto Georges Bank.

Here we describe ongoing field investigations of this phenomenon. A more complete data set and analysis will be published elsewhere.

Prior Research

Numerous cruises over three field seasons (1987-89), sampling the nearshore waters north of Cape Ann, Massachusetts, have given us the data needed to formulate a conceptual model of *A. tamarense* bloom development and transport (Franks, 1990; Franks and Anderson, submitted ms.). Critical features of this model, which is appropriate only for waters to the south of Bath, Maine, include:

1. Source: A source population of cells is located to the north of Cape Ann, possibly near the Androscoggin-Kennebec estuary.
2. Transport: Freshwater outflow from the Androscoggin-Kennebec estuary creates a coastally-trapped, buoyant plume. *A. tamarense* cells are associated with this plume and are transported to the south.

3. Dynamics: The alongshore and cross-shore location of the plume, its associated cells, and the resulting PSP toxicity are influenced by the volume of freshwater outflow and the local wind stress.

The behavior of a low salinity, coastally-trapped buoyant plume in response to local wind stress has been extensively modeled by Chao (1987). These modeling results are in excellent agreement with the behavior of a plume investigated during numerous cruise transects offshore from Portsmouth, New Hampshire in 1987-1989 (Franks, 1990). In particular, a down welling favorable wind (from the north) has been shown to extend the plume against the coast and accelerate it alongshore. An upwelling-favorable wind (from the south), reverses the pycnocline slope and moves the plume offshore, creating a thin lens of lower salinity water that is retarded in its movement southward. Concurrent data on the abundance of the toxic *A. tamarense* cells has shown that the dinoflagellate population is located predominantly in the plume, concentrated near the frontal interface between the plume and the offshore waters. Tilting of the pycnocline and movements of the plume due to wind stress are matched by equivalent shifts in the location of the dinoflagellate population.

Ongoing Research

During 1990, three cruises were planned to identify possible source populations of *A. tamarense* within the plume and to track their movement southward along the coast (Figure1). Sampling consisted of CTD profiles at each station and the collection of discrete water samples from three or more depths for the microscopic enumeration of *A. tamarense*.

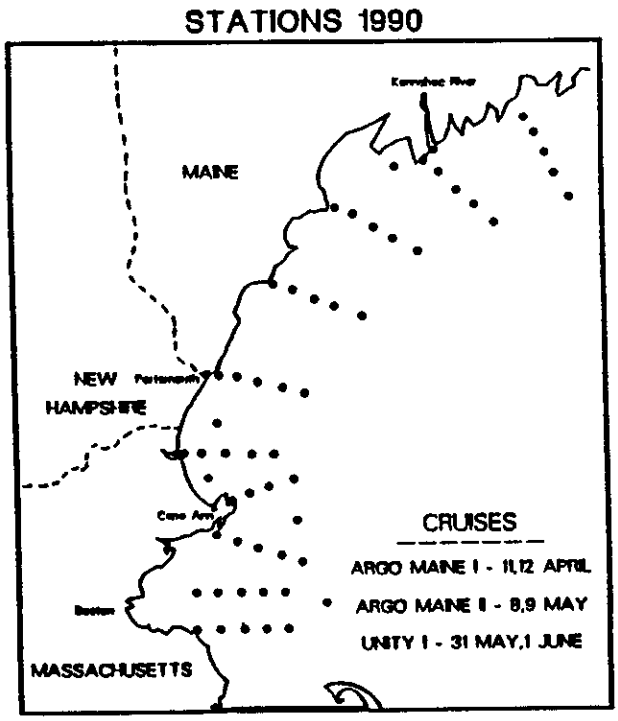

Figure 1. Chart of the study area showing the sampling stations located in the southwestern Gulf of Maine for three cruises in 1990. The five most northerly transects from Monhegan Island, ME south to and including the transect off Portsmouth, NH were initially sampled during the Argo Maine I cruise and repeated during the Argo Maine II cruise approximately 1 month later. The Unity I cruise sampled the six southerly transects from Portsmouth, NH to Cohasset, MA another 3 weeks later.

In April, when coastal water temperatures were approximately 3°C and runoff relatively high, surface salinities revealed the formation of a new water mass from the outflow of the Kennebec and Androscoggin rivers (Figure 2A), consistent with the conceptual model. We did not detect *A. tamarense* directly in the Kennebec estuary, but rather found very low abundances (<20 cells/liter; Figure 2B) associated with the outer boundary of the less-saline plume, possibly at the plume front. This population presumably arose from the late winter, early spring germination of *A. tamarense* cysts which have been previously documented in the nearshore sediments of southern Maine waters (Anderson and Keafer, 1985).

By early May, run-off had temporarily subsided and water temperatures had increased to about 6-7°C. The plume was significantly larger and extended to the south along the coast (Figure 2C). The *A. tamarense* cells were still closely associated with the plume, having increased in number through growth and/or physical accumulation to 200 cells/liter (Figure 2D), an order of magnitude higher than seen in the cruise one month earlier. Toxin was first detected in southern Maine shellfish near this time. Three weeks later in late May toxicity was

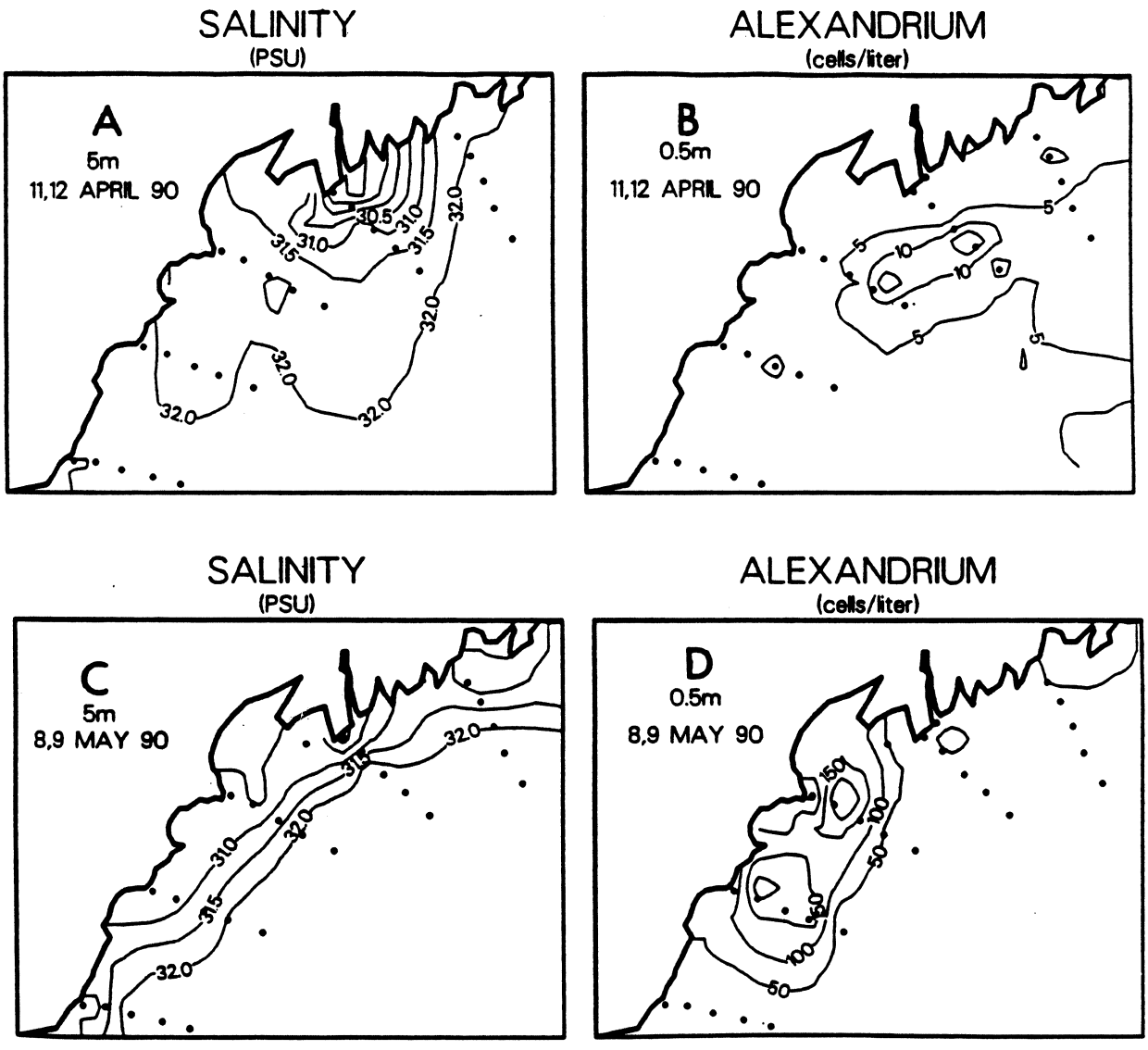

Figure 2. Distribution of salinity (panels A and C) and *A. tamarense* cells (panels B and D) during early April (Argo Maine I; top panels) and early May (Argo Maine II; bottom panels).

first detected on the north shore of Cape Ann, Massachusetts. A cruise on 31 May and 1 June indicated that a large pulse of less saline water (salinity 30–31.5 PSU; Figure 3A) had moved around Cape Ann and into Massachusetts Bay. Although offshore sampling was limited with the outermost station located on Stellwagen Bank, the data suggest that a component of the plume (Figure 3A) traveled further offshore towards Georges Bank and around the tip of Cape Cod (Provincetown) towards Nantucket Shoals. This feature can also be seen in transects across Massachusetts Bay (data not shown) where the plume is confined close to the coast near Cape Ann and broadens further offshore in successive transects from north to south due to the large amounts of fresher water now in Massachusetts Bay. The transects also clearly demonstrate the association of *A. tamarense* with the less-saline waters of the buoyant plume as previously observed by Franks (1990), whereby the cells were predominantly located in the top 15 meters of the surface waters in salinities typically less than 31 PSU. Within the large volume of surface water where salinities were approximately 30.0–30.5 PSU, we have detected another order of magnitude increase in the *A. tamarense* concentration reaching an abundance of greater than 2,000 cells/liter near the south shore of Boston (Figure 3B) at the time when adjacent shellfish beds had just been closed.

Toxicity in shellfish had been detected on the south shore near Cohasset, Massachusetts for the first time approximately 8 days after the first positive reports from the north shore of Cape Ann (21 May), supporting the hypothesis that the cells were transported into Massachusetts Bay by the southward moving plume. Toxicity records from Georges Bank and Nantucket Shoals at this time are ambiguous due to residual wintertime toxicity in surf clams from the year before. There were two separate reports at this time, however, of fishermen on Georges Bank becoming ill due to PSP from eating mussels, *Mytilus edulis* (an early warning indicator species which does not retain toxin from year to year), (Sharifzadeh, 1990).

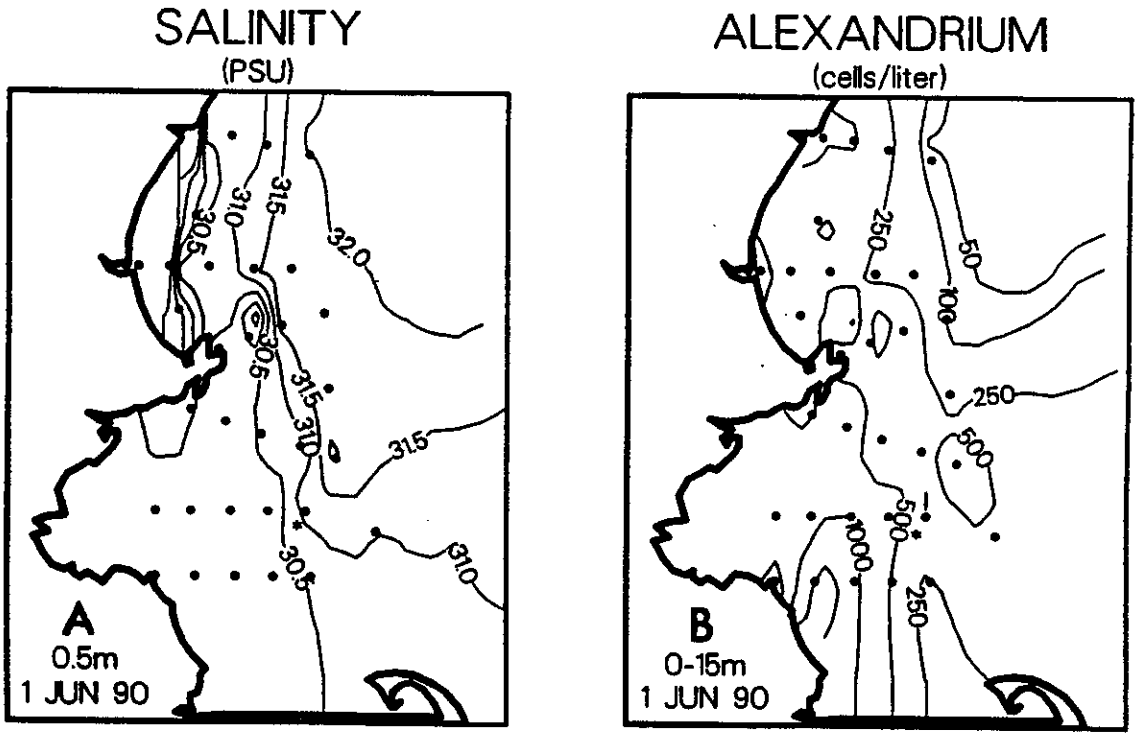

Figure 3. Distribution of salinity (panel A) and *A. tamarense* cells (panel B) during late May, early June (Unity I). UNH mooring is located in Stellwagen Basin denoted by an asterisk (*).

Independent Supporting Evidence

Supporting evidence for the movement of a pulse of less-saline water across Massachusetts Bay and further offshore during this interval has been supplied by Irish and colleagues at the University of New Hampshire (UNH) who maintained a mooring at site U6 in Stellwagen Basin (42° 21.31' North, 70° 24.01' West; Figure 3). The data from the mooring (Figure 4) show that there was a significant decrease in the salinity of the surface waters (2 PSU) beginning on 27-28 May that continued through the early part of June. These dates should be viewed in the context of the onset of PSP toxicity along the coast, first detected on the north shore of Massachusetts on 21 May and then on the south shore at Cohasset on 29 May. At the end of this same interval, we document a significant population of *A. tamarense* in Massachusetts Bay associated with this less-saline water. Therefore, we believe that the coastally-trapped buoyant plume carried the cells from their source in southern Maine, along the north shore of Massachusetts, across Massachusetts Bay, and possibly even to Georges Bank and Nantucket Shoals. The plume originated as the outflow of the Androscoggin/Kennebec Rivers, but was supplemented by the Merrimac River as it traveled south.

The 4 meter temperature signal from the UNH mooring reveals a slight increase in the temperature (1-2°C; data not shown) coincident with the decrease in salinity. It may thus be possible to exploit this water mass characteristic using remote sensing from satellites to visualize the less-saline, warmer plume on larger scales from space. We have obtained several AVHRR images of sea surface temperature from the NOAA 11 satellite during blooms of *A. tamarense* (images not shown). In both 1989 and 1990, the higher temperature signal of the plume was clearly visible in the nearshore waters of the western Gulf of Maine, in excellent agreement with our ship-collected transect hydrography. Also in 1989, Wishner and Schoenherr (this volume) were able to detect a thermal plume in AVHRR images further offshore in the vicinity of the Great South Channel. However, interpretation of the images is much more difficult near Georges Bank due to local surface heating of the deep stratified waters adjacent to the cold, well-mixed shallow waters of the Bank itself. If the plume's higher temperature signal can be resolved from local heating features, near real-time remote sensing could prove very useful for monitoring and possibly prediction of toxic bloom events, especially for vast offshore areas such as Georges Bank which are difficult and expensive to monitor. We are currently exploring this possibility.

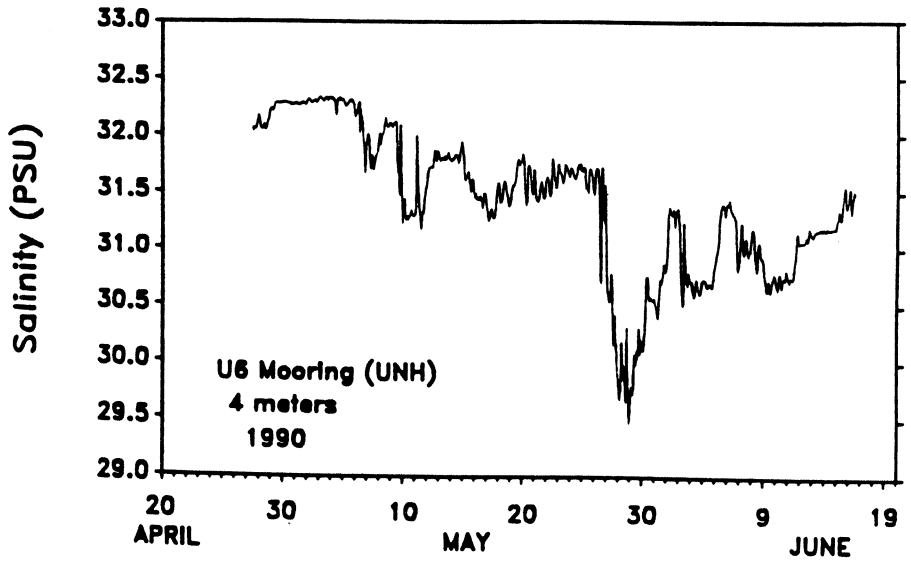

Figure 4. Hourly averages of surface salinity (4 meters depth) during spring, 1990 in Stellwagen Basin at U6 mooring. Data supplied by J. Irish and colleagues at UNH. Used with permission.

Logistical constraints have made it difficult to adequately document the fate of the buoyant plume and its associated toxic dinoflagellate population as they moved out of Massachusetts Bay and into offshore waters, but previous workers (Bigelow, 1927; Bumpus, 1976; Butman et al., 1982) have documented a circulation pattern of net surface water movement around Cape Ann, Cape Cod, and further offshore around Georges Bank which supports our claim. In addition, several recent studies (Chen et al., this volume; Mountain and Manning, this volume) have presented evidence which supports the argument for the movement of less saline water from the nearshore areas of the western Gulf of Maine to offshore areas at similar times and scales as those presented above. Lagrangian pathways are thus reasonably well documented linking nearshore riverine outflow to the distant, offshore waters of Georges Bank. We thus believe that the timing of shellfish toxicity along the coast and the movement of less saline water across Massachusetts Bay are strong supporting evidence for the hypothesis that toxicity on Georges Bank was not due to *in situ* growth of dinoflagellates but rather to the advection of nearshore populations to the offshore waters.

Summary

In summary, we have observed the following: 1) the initiation of a bloom population of *A. tamarense* in southern Maine waters; 2) the development and entrainment of the bloom in a low salinity, coastally-trapped buoyant plume that travelled past Cape Ann, into Massachusetts Bay, and possibly offshore towards Georges Bank; 3) the occurrence of shellfish toxicity along the north and south shores of Massachusetts and on Georges Bank at times coincident with the passage of the buoyant plume; and 4) a low abundance of *A. tamarense* cysts in the Georges Bank region (preliminary data, not shown) suggesting that advected dormant cells are an unlikely source of toxicity. All data collected in 1990 are consistent with the long distance, relatively rapid advection of the nearshore *A. tamarense* bloom population across Massachusetts Bay and onto Georges Bank and Nantucket Shoals, although the hypothesis of an *in situ* localized bloom of *A. tamarense* on or near Georges Bank cannot be evaluated due to lack of data.

Open Questions

Many questions remain unanswered. For example, our results suggest that advection is a possible, if not probable, mechanism for delivery of toxicity to offshore waters, but they do not include the offshore coverage needed to address the existence of an *in situ* bloom of *A. tamarense* on or near Georges Bank. The existence of an offshore bloom may preclude the use of thermal remote sensing information as a monitoring and predictive tool for the onset of toxicity offshore, although it still has great promise with respect to the nearshore pattern of PSP.

A related question concerns the history of PSP toxicity on Georges Bank. The 5 million dollar per year surf clam fishery has been closed to harvesting for the past several years due to high PSP levels, suggesting to some that this offshore toxicity is a recent phenomenon. However, the detection of toxicity coincided with the first attempts to assay toxins in this resource, so it is possible that PSP has long been present in the offshore waters. The few data that are available from prior years indicate that scallops on Georges Bank sampled in 1961–63 and 1980–1981 had low levels of PSP (< 140 µg/100 g digestive tissue; Bourne, 1965; Jamieson and Chandler, 1983). Digestive tissue of scallops from the same locations sampled in 1989 were at least an order of magnitude higher. These limited data suggest that a change may have occurred that has resulted in a significant increase in offshore toxicity over the last decade. If this inference is to be justified, we must look closely at terrestrial runoff and human activities in the context of the persistence and long-distance advection of the coastal plume. The transport of toxic *A. tamarense* cells is an important process in its own right, but it also serves as a model mechanism for the transport of organic contaminants and other pollutants that

enter the Gulf of Maine via river outflow. The results presented here indicate that contaminants released into nearshore waters can have impacts far afield in the rich offshore fisheries of the gulf.

Acknowledgments

We thank J. Irish for the use of unpublished mooring information, personnel from the Massachusetts Division of Marine Fisheries and Massachusetts Department of Public Health for shellfish toxicity data, David Kulis, Raffaella Casoti, and Chris Scholin for technical assistance, and Peter Franks for helpful discussions. Research supported in part by the National Oceanic and Atmospheric Administration, National Sea Grant College Program Office, Department of Commerce under Grant No. NA90-AA-D-SG480, WHOI Project R/B-100, and by the Office of Naval Research through Grant No. N00014-89-J-1111. Contribution No. 7642 from the Woods Hole Oceanographic Institution.

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PROCEEDINGS OF THE GULF OF MAINE SCIENTIFIC WORKSHOP

Woods Hole, Massachusetts
8–10 January 1991

Gulf of Maine Council on the Marine Environment

Edited by Jack Wiggin and
Christopher N.K. Mooers

Published by the Urban Harbors Institute
University of Massachusetts at Boston

December 1992