Post-outfall Surveys of Toxic A*lexandrium fundyense* Populations in Massachusetts Bay, 2001

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Post-outfall Surveys of Toxic *Alexandrium fundyense* Populations in Massachusetts Bay, 2001

by

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Executive Summary

As part of a NOAA Sea Grant project with additional support provided from the Massachusetts Water Resources Authority, 3 hydrographic surveys were conducted in May, 2001 that documented the *Alexandrium fundyense* populations and nutrient conditions off Cape Ann and within Massachusetts Bay near the new sewage outfall site. This report provides the first description of the *A. fundyense* distributions in the Massachusetts Bay region during the spring bloom season following the start of outfall operations in the Fall of 2000. *A. fundyense* cell concentrations were very low during each cruise and never exceeded 10 cells L^{-1}. These abundances were an order of magnitude lower than recorded during previous surveys in 1994, 1995, 1996, 1997, and 1999 and were 2 orders of magnitude lower than recorded during the 1993 outbreak of shellfish toxicity along the south shore of Boston. Extremely low abundances of *A. fundyense* cells (near the detection limit of our methods) were observed in the vicinity or south of the outfall and were always lower than the waters upstream near Cape Ann suggesting that no measurable stimulation of the populations entering Massachusetts Bay waters occurred due to nutrients from the outfall. The low abundances within the region were likely due to the lack of sufficient "upstream" *A. fundyense* cells in the larger Gulf of Maine habitats to the north at that time and the lack of surface nutrients capable of sustaining growth during transport into the Bay.

These surveys provided additional information on the factors regulating the transport of *A. fundyense* populations into the Bay. Analysis of the temperature and salinity properties associated with the *A. fundyense* populations suggested that populations observed near Cape Ann originated from the north and were transported into the region in both the cold, saltier offshore waters of the Eastern Maine Coastal Current (EMCC) and the warmer, less-saline waters of the Western Maine Coastal Current (WMCC). Evidence from satellite-tracked drifter studies and satellite imagery support the hypothesis that *A. fundyense* populations in the Massachusetts Bay region are derived from the north. Most notable were drifter releases near Cape Ann that confirmed previous modeled results which suggested populations will enter the Bay during downwelling-favorable conditions or will pass offshore off Stellwagen Bank during upwelling-favorable conditions.

This study provided valuable input that increased our understanding of *A. fundyense* dynamics in the western Gulf of Maine (GOM), especially at the southern extremity of the transport pathway(s). A conceptual model identifying the source populations in eastern Maine waters and the transport pathways into the western GOM including Massachusetts Bay is presented. This model was derived from the interpretation of the results from this study and the ECOHAB-Gulf of Maine program and is generally being used to identify processes necessary for continued refinement of physical/biological numerical models with the ultimate goal of predicting shellfish toxicity outbreaks due to *A. fundyense* blooms in the GOM region.

Introduction

Toxic or harmful algal blooms, commonly called "red tides", are an economic and public health problem throughout the US and the world. In the New England region, the most serious problem in this context is paralytic shellfish poisoning (PSP), a potentially fatal neurological disorder caused by human ingestion of shellfish that accumulate toxins as they feed on dinoflagellates of the genus *Alexandrium*[1]. These organisms are responsible for human illnesses and occasional death due to PSP, repeated closures of shellfish beds in nearshore and offshore waters, the mortality of larval and juvenile stages of fish and other marine animals (White et al., 1989), and the death of marine mammals such as humpback whales (Geraci et al., 1989). Thirty years ago, PSP was virtually unknown in New England, yet now, significant portions of the region's intertidal shellfish resources are closed annually due to toxicity. A further expansion of the problem occurred recently when the offshore shellfish resources of Georges Bank and Nantucket Shoals were shown to contain dangerous levels of toxin (White et al., 1993).

Prior research in the region revealed a strong association between a buoyant coastal current, *Alexandrium fundyense* cells, and patterns of PSP toxicity in that region (Franks and Anderson, 1992a,b). This current, (termed the Western Maine Coastal Current or WMCC) is responsible for the southerly transport of toxic cells into Massachusetts coastal waters (Franks and Anderson, 1992a) and possibly further offshore onto Georges Bank (Anderson and Keafer, 1992). Anderson (1997) provided an overall review of the known *A. fundyense* habitats in the New England region. More recently, the results of larger scale regional research programs, RMRP (Regional Marine Research Program) and ECOHAB (Ecology and Oceanography of Harmful Algal Blooms), are now becoming available. Populations of *A. fundyense* have been consistently detected in the WMCC from Penobscot Bay to Massachusetts Bay (Anderson et al., in prep). Further north and east in the Gulf of Maine (GOM), a large population of *A. fundyense* has been discovered in the offshore waters of eastern Maine associated with a colder, nutrient rich water mass known as the Eastern Maine Coastal Current (EMCC; Townsend et al., 2001). This eastern Maine population is now believed to be the probable source population for *A. fundyense* blooms that occur in the western GOM (Anderson et al., 2000a).

In a previous report to the Massachusetts Water Resources Authority (MWRA), Anderson et al. (2000b) suggested that eastern Maine populations may even extend as far south as Cape Ann underneath the Merrimack River plume and the WMCC. New or supplementary data were

[1] In the Gulf of Maine, *Alexandrium fundyense* and *Alexandrium tamarense* are both known to be toxic and cause PSP. The morphological characters used for distinquishing the two species are sometimes difficult to discern under the light microscope and such fine levels of discrimination are not feasible in monitoring programs or studies that generate large numbers of samples. Based upon RNA gene sequence data, *A. fundyense and A. tamarense* are not distinguishable from one another. Therefore, it is probable that these species represent morphological variants of a single species group, commonly referred to as the "tamarensis" complex. Recent discovery of the widespread presence of *Alexandrium ostenfeldii* in the Gulf of Maine further confounds the *Alexandrium* species identification issue. Although *Alexandrium ostenfeldii* may contain food vacuoles and is slightly larger than *Alexandrium fundyense/tamarense*, their size distribution may overlap. Therefore, it is possible that past field studies may have included smaller *Alexandrium ostenfeldii* cells in the counts that were attributed to *Alexandrium fundyense*. The methods used in this study can now distinguish between the *Alexandrium fundyense/tamarense* species complex and *Alexandrium ostenfeldii.* In this report, we use *Alexandrium fundyense* to refer to the known causative species of PSP in the Gulf of Maine, both in past studies using less specific methods for identification and in this study using more specific methods.

needed at the “downstream” extremity of this transport pathway near Cape Ann and in Massachusetts Bay, especially given the public concern over the possible effects of the new sewage outfall that now releases treated sewage from Boston into Massachusetts Bay. At a cost of over $4 billion, the MWRA built a new primary and secondary treatment and sludge processing plant along with a 9.5 mile, 24 foot diameter tunnel that recently (Fall, 2000) began discharging treated effluent into Massachusetts Bay at a site noted in Fig. 1. The possible effects of the outfall have highlighted how little is known about the PSP phenomenon within the Bay. One of the public concerns has been that the nutrients contained in the effluent could stimulate harmful or nuisance algae, including toxic *A. fundyense* species. Early on this concern was amplified by the finding offshore shellfish on Georges Bank and Nantucket Shoals have accumulated PSP toxins (White et al., 1993), and that these toxins may originate from toxic cells that are advected across Massachusetts Bay in the buoyant plume (Anderson and Keafer, 1992). The prospect that the PSP problem in coastal communities just south of the outfall might worsen, and that the same might be true for the offshore shellfish resource of Georges Bank is disconcerting to many. Likewise, there is a concern that the endangered northern right whale or other marine mammals will be adversely affected by toxic blooms within the Bay.

The NPDES permit for operation of the Deer Island treatment facility and outfall requires the MWRA to conduct an extensive program of monitoring to characterize post-outfall chemical and biological conditions in Massachusetts and Cape Cod Bay. The purpose of the work presented in this report is to augment this ambient monitoring program and to determine any effects of the MWRA discharge on *A. fundyense* blooms in Massachusetts Bay.

Sampling programs in Massachusetts Bay in recent years (ours and those associated with the Harbor Outfall Monitoring Program) have not detected high densities of *A. fundyense* within the Bay sufficient to cause shellfish toxicity (Anderson et al., 1997, 2000b). However, even in years when no shellfish toxicity was detected in the Bay, low densities of *A. fundyense* cells were observed, most commonly near Cape Ann where upstream populations extend from the north. The fates of those upstream populations are extremely important to our general understanding of blooms within the Bay. The timing of downwelling- and upwelling-favorable wind conditions are believed to be critical factors in the transport of the cells either into Massachusetts Bay (under downwelling-favorable conditions) or offshore of Stellwagen Bank (during upwelling conditions). Physical-biological coupled circulation models of *A. fundyense* dynamics in the WMCC using real wind and runoff data from 1993 (see http://crusty.er.usgs.gov/wgulf/modeling.html) demonstrate that the bulk of the cells transported near Cape Ann will pass offshore of Stellwagen Bank during upwelling conditions (May 16-18, 1993), while other cells will enter the Bay during downwelling-favorable conditions (May 23-30). Thus, understanding the variability of populations within the Bay is critical to accessing whether populations within the Bay are due to the advection from established populations or stimulation of growth via enrichment from the outfall.

Objectives

The objectives of the 2001 survey for *A. fundyense* populations within Massachusetts Bay were to:

- Provide background data on the distribution of *A. fundyense* within Massachusetts Bay to help characterize the interannual variability of these populations after the new outfall was

operational.

· Determine the meteorological and oceanographic mechanisms that regulate whether *A. fundyense* populations in the WMCC enter the Bay or are advected past the Bay along Stellwagen Bank.

Methods

Our approach for sampling *A. fundyense* populations within Massachusetts Bay in 2001 was to maintain several transects previously sampled within the Bay (Anderson et al., 1998) but also to maintain northerly transects sampled in 1999 near Cape Ann that focused on the incoming populations (Fig. 1; Anderson et al., 2000b). Two nearshore stations were added between transects D and E to obtain higher resolution sampling just downstream of the outfall. The field operation was mounted in May and early June, 2001 to collect water samples and associated hydrographic data during the time most likely for *A. fundyense* bloom initiation within the Bay. Four cruises were scheduled in Massachusetts Bay, but the last cruise was cancelled due to lack of significant *A. fundyense* abundance within the Bay, based on shellfish toxicity data and cell counts from the previous cruises. The dates of the completed cruises aboard the R/V Gulf Challenger (University of New Hampshire) were as follows:

Cruise 1	April 30-May 1
Cruise 2	May 21-22
Cruise 3	May 31- June 1

Hydrographic data was acquired using a Seabird SeaCat Profiler, while water samples were collected from Niskin bottles hung from the hydro-wire. In addition, one satellite-tracked Davis-type surface drifter was deployed on each of the 3 cruises at a pre-determined site (A4) that was chosen as a likely location for determining the fate of surface *A. fundyense* populations that may be present within the WMCC. Samples for both quantification of the *A. fundyense* abundance and nutrients were collected at 1m, 5m, and 10m and 20m. The vertical resolution of sampling differed slightly from our 1999 survey in that every station was sampled to 20m to ensure that we did not miss subsurface populations entering the Bay or stimulated in the nutrient rich environment of the outfall.

A. fundyense water samples were collected by sieving through 20 µm Nitex, backwashing particulates off the sieve and then preserving the resuspended material in formalin (5% final). After about 12-24 hours, the samples were centrifuged, the supernatant was removed, and the cells were resuspended in 100% cold methanol to remove internal chlorophyll and stabilize rRNA, the target of a new species-specific staining procedure now routinely used in the Anderson laboratory.

In recent *A. fundyense* surveys in Massachusetts Bay conducted by the Anderson lab, an immunofluorescent protocol used a genus-specific antibody (M-8751-1) to determine *A. fundyense* abundance in the field (e.g., Anderson et al., 2000b; Turner et al., 2000). While this method was useful and accurate at the genus level, there was some confusion in the identification of two co-occurring species of *Alexandrium*; the toxic *Alexandrium fundyense/tamarense* species complex and *Alexandrium ostenfeldii*. Although it has been demonstrated that *A. ostenfeldii* from other geographic locations can sometimes produce the saxitoxins responsible for PSP (Hansen et

al., 1992), *A. ostenfeldii* populations from the GOM have not been shown to produce saxitoxins in the limited number of samples that have been analyzed thus far. However, it has now been demonstrated that isolates of *A. ostenfeldii* from the GOM produce another toxin called spirolides, a family of highly potent, fast-acting toxins (Cembella et al., 1999; Gribble et al. 2002). Spirolides are 2.5X more potent than saxitoxins in mice, and are currently being tested by Health Canada in animal studies to determine appropriate regulatory limits for human consumption. At the present time, spirolides in shellfish tissues are not regulated in the United States, but are likely to be once the Canadian studies are complete, given preliminary reports of their pharmacological effects.

Given the limitations of the genus-specific antibody, an alternative molecular method that utilizes an oligonucleotide probe (NA-1) to target large subunit ribosomal RNA (LSU rRNA; Scholin et al., 1997) was tested concurrently with the antibody method in 1998 and 2000 during the ECOHAB program. Results generally agreed. This method has now been shown to distinguish the *A. fundyense/tamarense* species complex without labeling *A. ostenfeldii* (Kulis et al., 2000) and has become the method of choice for quantification of the known PSP-producer, *A. fundyense*. Details of the oliognucleotide methodology used in the GOM studies will be published elsewhere. Briefly, the NA-1 probe was synthesized and coupled to a fluorochrome (CY3) for visualization of the target cells (Integrated DNA technologies, Inc.). To probe the preserved phytoplankton samples, 7ml aliquots were filtered (equivalent to 1 Liter of seawater on the filter) and then incubated on the filter with a prehybridization buffer solution at RT. Hybridization of the NA-1 probe to the target cell LSU rRNA was completed directly on the filter at 50 ^{o}C for one hr. The filter was washed once in 0.2X SET (Saline EDTA Tris) buffer, mounted on a slide, and observed at 100x using an epifluorescent microscope equipped with a CY3 filter set (Chroma set #41032). The target cells were labeled internally (hence the need to remove chlorophyll autofluorescence with methanol) with an orangish fluorescence allowing the full slide to be counted easily and accurately.

A dual labeling approach has now been developed where NA-1 is coupled to a CY3 fluorochrome (as above), while another oligonucleotide probe (AOST01), specific for *A. ostenfeldii*, is coupled to fluorescein (FITC). Using a dual-label filter set (Chroma set #51009 FITC/CY3) with an upgraded fluorescence objective on the microscope, we can now easily distinguish both species of *Alexandrium* in a single field of view; the *A. fundyense/tamarense* cells label bright reddish-orange, while the *A. ostenfeldii* are green. This protocol was tested in 2001 during the ECOHAB program. *A. fundyense* and *A. ostenfeldii* were generally found to co-occur, but with subtle differences that may reflect slightly different habitats or water mass preferences. All *Alexandrium* sp. data reported here used the single labeling approach with the NA-1/CY3 probe to identify PSP-producing *Alexandrium fundyense/tamarense* cells, with the exception of a few selected samples where the AOST01/FITC probe was used to determine if *A. ostenfeldii* was present in the Bay. Since those selected samples were all negative for *A. ostenfeldii*, the results are included in the appendix, but are not discussed below.

Samples for nutrient analyses were collected from the same Niskin bottles used for the *A. fundyense* collections. Aliquots of 45 ml were filtered through 0.45-µm pore-size membrane filters (Millipore HA) to ensure that measured nutrients were dissolved. The samples were then stored frozen to prevent degradation until nutrient analyses were run. A 3-channel Latchat QuikChem 6000 Flow Injection Analyzer was used with standard Latchat "brackish water" methods to analyze the samples for inorganic nutrients including ammonium, nitrate+nitrite,

phosphate, and silicate. These data are included in the appendix at the end of this report.

Results and Discussion

The physical environment and A. fundyense *distributions*

The largest sources of freshwater into Massachusetts Bay originate from the rivers of the western GOM including the nearby Merrimack River where less-saline surface waters have been consistently observed during spring runoff when *A. fundyense* blooms have been detected along the coast (e.g., Anderson et al., 1998, 2000b). The discharge from the Merrimack River during spring, 2001 was typical for this time of year with higher discharge recorded in April due to early spring rains and snow melt (Fig. 2). Lower discharges were observed in May and June as the conditions generally improved, but freshets, indicative of storm-related events, can occur at any time (Fig. 2). Less than 1 week prior to Cruise 1 (i.e., late April), a freshet from the nearby Merrimack River was detected at the streamflow gages within the river (note the second peak in Fig. 2). The freshwater was observed in the "downstream" study area as a tongue of less-saline, warmer surface water (28-31 PSU, 8-9 ^{o}C) that extended southward around Cape Ann and well into the Bay, while higher salinity, colder waters (31.5 PSU, 7.5 ^{o}C) were located offshore northeast of Cape Ann (Fig. 3).

The influence of the western GOM rivers on the hydrography in the Bay was not as strong during Cruise 2 and Cruise 3, but was still apparent (Figs. 4, 5). During Cruise 2 (Fig. 4), the salinity was higher (30.25-30.5 PSU) reflecting the decline in the runoff and the surface temperature was warmer (11.5 ^{o}C) due to vernal warming (see Fig. 2). While the average monthly mean runoff in April was above normal, the average surface runoff conditions in May were below normal (USGS, MA & RI district website). During Cruise 3, the salinity within the Bay remained about the same as Cruise 2 (30.25-30.5; 11.5 ^{o}C) with the lower salinities separated from the more saline, colder (>31.0, <11.0 ^{o}C) offshore waters by a frontal boundary that extended from Cape Ann to Stellwagen Bank (Fig. 5).

A. fundyense was detected at extremely low concentrations (<10 cells L^{-1}) in the study area during all 3 cruises, while within the Bay itself the abundance never exceeded 2 cells L^{-1} (Fig 3, 4, 5). Not surprising given the low abundance, no shellfish toxicity was detected in Massachusetts coastal waters in spring of 2001 (Massachusetts Division of Marine Fisheries; data not shown). Even in years when no shellfish toxicity was detected, 50-100 cells L^{-1} of *A. fundyense* were commonly observed in the study area, but in 2001 the abundance was at least one order of magnitude less than observed in previous years. [Note: The low cell counts of *A. fundyense* observed in the GOM region during 2001 (see below) were not due to methodogical differences using the oligonucleotide probe as selected samples from 2001 were validated using the antibody protocol.] Because the populations were so low, we did not analyze every sample collected. Every surface sample was analyzed within the sampling domain, while selected stations (including the outfall station- D5) were analyzed at all depths. All the deeper samples from stations across the northernmost transect (i.e, the A-line) were analyzed to ensure that deeper incoming populations were not missed.

The maximum cell concentration from all 3 surveys was only 7 cells L^{-1}, observed offshore at the northernmost transect during Cruise 1 (Fig. 3; station A2 at 5m depth). When cell abundances are so low, counting errors are correspondingly high making it difficult to determine the

association of the toxic cells with water masses. Despite this limitation, the data consistently showed that there were more cells in the waters near Cape Ann than in the Bay (Fig. 3). Most cells were associated with the more saline, colder waters (31.5psu, 6-7 C) just offshore of the plume front or within the outer plume waters (Fig. 3; Fig. 6). Comparison of the temperature and salinity properties of the offshore population at station A2 are consistent with the hydrographic properties from eastern Maine *A. fundyense* populations collected during an early May ECOHAB survey suggesting that the offshore population found near Cape Ann may have originated in eastern Maine.

A. fundyense was barely detectable during Cruise 2 with only 1 station reporting ≥2 cells/L, the innermost station on the A-line (Fig. 4). Toxic cells were not detected at depth across the A-line or B-line (see Appendix), but *A. fundyense* was detected near the outfall site at 20m. Likewise, very few cells were detected during Cruise 3. Virtually no cells were observed within the Bay near the outfall site, while ≥2 cells L^{-1} were consistently observed at several stations near Cape Ann associated with the frontal boundary between the less-saline plume waters and the more saline and colder waters offshore (Fig. 5).

The lack of cells during the 2001 bloom season reflects the general low abundance of cells in the larger scale GOM domain during May. During a 10-day ECOHAB survey that sampled the coastal Maine waters in the interim between Cruise 1 and Cruise 2, lower than normal *A. fundyense* concentrations were observed. The maximum abundance found in those putative source waters was 100-200 cells L^{-1} in a narrow band 10-15km offshore of the eastern Penobscot Bay area (ECOHAB, unpublished data). In western Maine, only about 20 cells L^{-1} were detected when cell concentrations of >200-300 cells L^{-1} are more commonly observed. Thus, as was the case in Massachusetts Bay, the abundance of *A. fundyense* along the Maine coast and near Cape Ann in May was about 1 order of magnitude less than observed in other years.

Even though the cell numbers were very low, the pattern of these observations were not unlike those reported during May, 1999 when *A. fundyense* cells were located both within the WMCC waters and adjacent to its outer boundary near Cape Ann (Anderson et al., 2000b). In both 1999 and 2001, more *A. fundyense* cells were generally observed across the northern transects when saltier surface conditions (>31 PSU) were present within the domain near Cape Ann. This pattern is likely a result of downwelling-favorable conditions which transported toxic cells from the colder, saltier offshore (and upstream) waters of the EMCC nearer to the coast of Cape Ann (e.g. Cruise 1). Conversely, fewer cells were present in the domain when there was no influence from the colder, saltier waters near Cape Ann, a result of prior upwelling-favorable conditions that spread the less-saline waters of the Merrimack River/WMCC further offshore (e.g. Cruise 2; however, note that a downwelling event during and following cruise 2 brought the drifters into the Bay). These observations support the hypothesis that populations near Cape Ann can originate from already established populations within the less-saline WMCC (i.e. the plume advection hypothesis), but populations can also be transported into the domain from offshore populations associated with the EMCC that are adjacent to the WMCC populations. This eastern influence is important because eastern Maine populations of *A. fundyense* are generally more abundant and persist longer than western Maine populations and likely serve as the "upstream" source populations for the populations associated with the WMCC.

Analysis of trajectories from satellite-tracked surface drifters released in eastern Maine also

support the hypothesis that *A. fundyense* populations observed at Cape Ann likely originate from eastern Maine waters. Drifter patterns suggest that linkages between the eastern Maine areas and the western Maine areas can form and dissipate over a period of a few weeks and may be related to the wind-driven circulation (J. Churchill, unpublished). This is nicely illustrated by the tracks of drifters deployed in the EMCC over the April-May period (Fig. 7). In April, the drifter trajectories show the EMCC extending from the eastern Penobscot Bay region and then veering sharply offshore, a period when the mean wind conditions were slightly upwelling-favorable. In contrast when mean wind conditions changed to more downwelling-favorable in mid-May, the drifters deployed within the EMCC, all followed paths along the coast into the western Gulf of Maine confirming the linkage between the EMCC and WMCC.

The drifter trajectories also indicated that the flow to the west is faster during periods of downwelling and slower during periods of upwelling, serving to pulse populations further west during downwelling-favorable periods. One drifter was actually released within a known patch of 100-200 cells L^{-1} (see Fig. 7, red trajectory) in early May. While the mean transit time from eastern Maine to Cape Ann and offshore of Stellwagen Bank was about 2-3 weeks, a closer examination shows that the drifter covered longer distances during downwelling-favorable periods. [Note the longer distances covered by the red trajectory during the downwelling period from May 20-27 (count the red dots from the May 10 release) and the shorter distances during interim upwelling-favorable periods.] Downwelling conditions therefore not only favor the delivery of populations to Cape Ann by facilitating the transport from eastern to western Maine, but also by getting them there faster, yielding a much higher flux of cells to the west than during upwelling-favorable conditions.

The fate of that eastern population tracked by the drifter noted above is unknown since our subsequent surveys in later May never detected concentrations as high as 100-200 cells L^{-1} near Cape Ann. The population may have been lost due to grazing (Turner et al., 2000) or mixing during the 2-3 week transit. Some *A. fundyense* cells associated with the EMCC are believed to become incorporated into the WMCC via complex behavior of the two coastal currents influenced by winds, runoff and the larger scale GOM circulation. At times, populations can skirt the outside of plume fronts near the Penobscot, Kennebec, and Merrimack Rivers or they can be subducted underneath the less-dense waters (Anderson et al., 2000a,b) where they can inoculate the overlying waters by swimming upwards to obtain light necessary for photosynthesis. However, examination of all samples across the A-line as well as other deeper samples in the study area did not reveal any populations entering the region at depth, with the exception of a few cells L^{-1} detected at 20m below the pycnocline at station A3 during Cruise 1 (Fig. 6). Thus, the *A. fundyense* cells that we observed near Cape Ann in 2001 were likely only downstream remnants of weak upstream populations within the coastal flow where upwelling and downwelling processes can contribute to their fate. Since many of these processes are difficult to observe directly, numerical models are currently being used to understand the dynamics associated with the river plumes and to generate hypotheses that might explain how *A. fundyense* cells are entrained in the WMCC given an offshore source population of either germinating benthic cysts (McGillicuddy et al, submitted) or vegetative cells (Hetland et al, submitted).

Sea surface temperature imagery also provided strong supporting evidence for the potential transport of eastern populations along the western Maine coastline. During early May when upwelling-favorable conditions were dominant, the imagery showed that the warmer waters of the WMCC were spread to the east >50 km offshore, while the colder waters of the EMCC were

generally deflected offshore (Fig. 8 A-C). In contrast, imagery from later May indicated that a narrow band of colder EMCC water (<10km wide) intruded well into the western GOM coincident with downwelling-favorable conditions (Fig. 8E-F) and perhaps delivered eastern Maine *A. fundyense* populations towards Cape Ann. Intrusions of colder EMCC waters into the western GOM have also been noted in SST imagery coincident with downwelling and shellfish toxicity outbreaks in other years. In June 1993, the last year that relatively high shellfish toxicity was recorded in Massachusetts Bay, a cold water intrusion into the western GOM was detected in satellite imagery that was likely responsible for a second spike of shellfish toxicity along the western Maine coast and the continuation of toxicity in the Bay (Anderson et al., manuscript in prep). While these same processes were apparent in 2001, given the limited number of *A. fundyense* cells in the source region, very few cells were actually observed further south near Cape Ann.

A particularly noteworthy feature for monitoring *A. fundyense* populations transported to the west is the western branch of the EMCC, identified by a short protuberance of colder water intruding into the warmer waters of the WMCC near the Penobscot and Casco Bay vicinity. When populations exceed 200 cells L^{-1} in the upstream waters (usually during May and June in most years) and this feature extends further into the western Gulf (e.g., during downwelling-favorable conditions), the probability of shellfish toxicity outbreaks along the coast from western Maine to Massachusetts Bay is high. While SST imagery cannot directly determine the abundance of *A. fundyense* from satellites, it does provide useful information on the location of the water masses (EMCC and WMCC) that contain the toxic cells (Keafer and Anderson, 1993). Using seasonal mean estimates of the *A. fundyense* population in the western Gulf in conjunction with SST observations, near real-time SST imagery and wind fields can be valuable monitoring tools for determining if PSP outbreaks are likely or not.

Once populations reach Cape Ann, their ultimate pathway either into or offshore of Massachusetts Bay is dependant on the general circulation patterns of the alongshore flow which again can be influenced by the local winds. Evidence from surface drifters released at station A4 (see Fig. 1 for release location) during the first day of all three cruises demonstrated the variability of the trajectories (Fig. 9). Deployment in the less-saline plume waters at the start of Cruise 1 confirmed the offshore pathway of the flow during a time period of upwelling favorable winds in early May (Fig. 9, 10). In contrast, deployment during Cruise 2 verified the coastal flow into the Bay during a downwelling time frame (May 21-28; Fig. 9, 10). That drifter transited very close to the outfall site, but when wind conditions changed to more upwelling-favorable, the drifter looped back and transited out of the Bay. The 3rd release followed the flow offshore as well, with a short-lived shoreward excursion into the Bay coincident with a strong SE wind event on June 2 (Fig. 9, 10). These results are in general agreement with the modeled simulations noted in the introduction above and validates the hypothesis that the wind is a critical factor in determining whether *A. fundyense* populations within the coastal flow will ultimately enter into the Bay or remain outside of Stellwagen Bank.

Nutrient distributions and response of the* A. fundyense *population

The distribution of nutrients indicates that concentrations were generally low for all three sampling dates with an overall decrease from Cruises 1 to 3. In fact, many of the concentrations are reported as below the detection limit. As is typical for this time of the year the surface waters had very low concentrations, while the higher concentrations were found below the pycnocline at

10 and 20m. During Cruise 1, the highest concentrations at 20m were found either in the vicinity of the outfall site or near the NW tip of Stellwagen bank. Even those values were relatively low considering they were near the outfall with the highest 4 stations ranging from 3.0 to 4.6 µM for nitrate + nitrite and 1.5 to 3.8 for ammonium. The highest phosphate concentrations were also found at these stations with concentrations ranging from about 0.5 to 0.8 µM. Everywhere else concentrations were lower.

Interestingly enough, the highest surface concentrations of nutrients were found off Cape Ann associated with the Merrimack River plume as shown by the salinity contours in Fig. 2. Within the plume (stations A4, A5, and B3-B5) surface concentrations ranged from: 1.3-2.4µM for nitrate + nitrite, 0.8-1.6µM for ammonium and about 0.1-0.2 µM for phosphate. The initial silicate analysis from these five stations indicated high silicate values, which are indicative of a river source. These levels of nutrients are low but probably not too low to have prevented *A. fundyense* from growing there since we have observed much higher *A. fundyense* cell counts in even lower nutrient waters in the coastal plume north of Cape Ann in past years. Outside of the plume (e.g., stations A2 and A3), all the surface nutrients were very low (about 0.1µM or lower), which would not likely support much growth of the phytoplankton community. This suggests that there was not a sufficient seed population available at that time to take advantage of the slightly elevated nutrients in the Merrimack River plume and probably minimal time for growth given that the drifters passed through the general study area in less than 1 week (see Fig. 9).

With the exception of the surface waters at the NW tip of Stellwagen Bank, where the Merrimack plume extended, the remainder of the surface waters throughout Massachusetts Bay had very low nutrient concentrations. This is typical of this region during this time of the year, after the earlier spring diatom bloom has stripped the water column of nutrients and the stratification due to warming and freshwater influx has capped off the deeper waters. It appears that the capping was working very well in the general region of the outfall where the deep water concentrations were relatively high, while the surface concentrations were much lower than those found near Cape Ann.

Nutrient concentrations during Cruise 2 were generally lower than observed during Cruise 1. The stations with the highest deep (20m) concentrations were found southeast of the outfall, around Cape Ann and offshore (Station A1), scattered with no strong trends. The highest surface concentrations were just outside Boston Harbor, though even there, the concentrations were all less than 1 µM. Similarly, nutrient concentrations during Cruise 3 were on average not significantly different than Cruise 2. Again the stations with the highest deep (20m) concentrations were found southeast of the outfall and around Cape Ann with no strong trends. The highest surface concentrations were just outside Boston Harbor and around Cape Ann, though with the exception of stations D7 and C4, all the surface concentrations were all less than 1 µM.

Based on the distribution of inorganic nutrients and *A. fundyense* during May, 2001, it appears that the *A. fundyense* populations were most likely nutrient limited throughout the Bay. We found no evidence that the low *A. fundyense* concentrations were stimulated by nutrient inputs near the outfall site, or anywhere else within the study region. The inorganic nutrients were low throughout the Bay and remained relatively low near the outfall site with no local response of the *A. fundyense* population. When slightly higher concentrations of *A. fundyense* were noted, the populations were related to incoming populations from upstream sources. This view is also

supported by the pattern of shellfish toxicity confirming that there was no significant local growth.

Synthesis and Summary:

The observations and dynamics presented here are critical to understanding the variability of *A. fundyense* populations near Cape Ann and their potential delivery into the Bay during the spring season. Abundances near Cape Ann and throughout the Bay were the lowest recorded (based on maximum abundances) during our recent sampling efforts in the Bay; a full order of magnitude lower than other years (e.g., 1994, 1995, 1996, 1997, and 1999). The spatial distributions of the few cells detected were consistent with previous observations that noted higher populations near Cape Ann than within the Bay. The populations near Cape Ann were associated with both the less-saline waters of the WMCC coming from the north and the adjacent offshore waters of the EMCC when it extends as far south as Cape Ann (most prominent during downwelling-favorable conditions).

The potential for toxic cell delivery to the shorelines of Massachusetts Bay is dependent upon the biological and physical mechanisms both remotely in the upstream coastal flow as well as locally near Cape Ann and within the Bay. A conceptual model describing that larger scale distribution and dynamics is shown in Fig. 11 where eastern Maine populations are thought to be the "source" populations that can be transported all the way to Massachusetts Bay. The bulk of the *A. fundyense* population in the western GOM (derived from eastern populations) is confined to the waters north of Cape Ann during most years. For toxicity to occur at the downstream extremity of the transport pathway in Massachusetts Bay, a sufficient population must be present in the upstream waters near Cape Ann accompanied by favorable wind and hydrographic conditions to drive the population into the Bay, otherwise the population will pass by in the offshore waters.

Within the Bay, blooms can theoretically result from either local growth or the transport of populations from upstream. In 2001, neither local growth nor transport into the Bay was an important factor for bloom development in Massachusetts Bay largely because the incoming populations were so small and passed offshore and the surface nutrient conditions within the Bay were low, even near the outfall. Typically, the overall spatial trend of *A. fundyense* abundance in the western GOM is one of decreasing abundance during the transit south and into the Bay, not increasing. This observation is also mirrored in the analysis of a 20-year historical record of toxicity in Massachusetts (Anderson et al. report to Sea Grant and MWRA, in prep). "In only one case, was toxicity found at a station without toxicity being found at the station immediately to its north". This trend is strong evidence that supports our view that transport of upstream populations is the major cause of blooms in the Bay, not local growth. Local growth, however, may become a factor at times when sufficient populations are transported into the Bay and in the subsequent days the residence time of water in the Bay increases (e.g., during sustained upwelling) providing ample time for growth. This may have been the case in 1993 when populations (500-1000 cells L^{-1}) remained in the Bay for at least 2 weeks before flushing out of the system, while causing the highest shellfish toxicities ever recorded within the Bay.

Whether the outfall can enhance local growth beyond usual levels is still unclear since during the first year of operation, it would have been hard to detect moderate stimulation given the low abundance of *A. fundyense*. The 2001 data did show that the low background *A. fundyense* abundance remained low and did not bloom into toxic proportions after entering the waters near

the outfall. Thus, the abundance of *A. fundyense* within the Bay is related to the populations found in the larger scale circulation rather than to local nutrient sources. However, we need to continue to monitor the situation to make sure this remains the case in years to come.

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APPENDIX

Cruise Designation: 01-MB-1
Cruise 1 dates: April 30 - May 1, 2001

			Cells/liter	CONCENTRATION (uM)			
LINE	**STATION**	**DEPTH (m)**	***A. fundyense***	**N + N**	**NH4**	**PO_4**	**NO_2**
A	**1**	0-1	2	0.12	1.92	0.04	BDL
		5	0	0.08	0.32	0.07	0.02
		10	0	0.22	0.43	0.14	0.02
		20	0	2.22	0.33	0.23	0.09
A	**2**	0-1	0	0.02	BDL	0.07	BDL
		5	7*	0.01	BDL	0.09	0.02
		10	1	0.52	BDL	0.12	0.02
		20	0	2.76	0.88	0.31	0.09
A	**3**	0-1	1	0.09	0.23	0.08	BDL
		5	3*	0.06	0.06	0.06	BDL
		10	0	0.57	0.20	0.12	0.02
		20	2	2.93	0.71	0.36	0.08
A	**4**	0-1	3*	1.46	0.96	0.12	0.04
		5	1	0.59	0.50	0.15	0.01
		10	1	0.89	0.46	0.20	0.02
		20	0	2.43	0.94	0.35	0.06
A	**5**	0-1	1	2.43	1.55	0.11	0.05
		5	0	0.78	0.50	0.19	0.04
		10	0	0.47	0.35	0.11	0.01
		20	0	1.42	1.01	0.27	0.03
A	**6**	0-1	1	0.90	0.29	0.05	0.04
		5	0	0.95	0.29	0.10	0.03
B	**1**	0-1	0	0.01	BDL	0.08	BDL
		5	0	1.63	0.46	0.26	0.09
		10	0	1.75	0.59	0.27	0.09
		20	0	1.97	0.80	0.23	0.08
B	**2**	0-1	1	0.50	0.40	0.08	0.03
		5	0	BDL	BDL	0.08	BDL
		10	0	1.32	0.25	0.22	0.07
		20	0	3.11	1.16	0.44	0.11
B	**3**	0-1	4	1.32	0.75	0.16	0.06
		5	0	0.02	0.01	0.07	BDL
		10	0	BDL	BDL	0.10	BDL
		20	0	1.99	1.49	0.35	0.13
B	**4**	0-1	1	1.34	0.84	0.15	0.04
		5	0	0.27	0.19	0.08	0.01
		10	0	0.03	BDL	0.09	BDL
		20	0	2.64	1.02	0.35	0.08

A = archived
BDL indicates concentrations were Below Detection Limit
*Dual labeled with NA1/CY3 and AOST01/FITC probes - no *A.ostenfeldii* detected

Cruise 1 (continued)

			Cells/liter	CONCENTRATION (uM)			
LINE	**STATION**	**DEPTH (m)**	***A. fundyense***	**N + N**	**NH4**	**PO_4**	**NO_2**
B	**5**	0-1	1	1.93	0.70	0.14	0.11
		5	0	0.99	0.54	0.16	0.04
		10	0	1.04	0.75	0.24	0.05
		20	1	2.02	0.99	0.33	0.07
C	**1**	0-1	0	1.00	0.37	0.09	0.03
		5	A	0.44	BDL	0.11	0.04
		10	A	1.46	0.23	0.21	0.07
		20	A	2.57	1.17	0.31	0.10
C	**2**	0-1	0	0.29	0.18	0.01	0.01
		5	0	0.33	0.19	0.02	0.02
		10	0	0.28	BDL	0.08	0.02
		20	0	2.32	0.46	0.28	0.09
C	**3**	0-1	1	0.04	0.21	0.01	BDL
		5	0	BDL	0.28	0.02	0.01
		10	0	1.14	0.55	0.13	0.04
		20	0	2.78	1.85	0.38	0.08
C	**4**	0-1	1	0.30	0.03	0.02	0.02
		5	A	0.62	0.32	0.14	0.04
		10	A	0.81	0.39	0.14	0.03
		20	A	2.11	0.94	0.30	0.09
D	**1**	0-1	1	0.70	0.22	0.19	0.05
		5	0	BDL	Sample lost	0.22	0.03
		10	A	BDL	BDL	0.23	0.02
		20	A	3.34	1.89	0.56	0.09
D	**2**	0-1	1	0.26	0.38	0.14	0.03
		5	0	0.39	0.21	0.17	0.04
		10	0	1.55	0.09	0.33	0.09
		20	0	3.03	1.50	0.53	0.10
D	**3**	0-1	0	0.39	0.22	0.14	0.03
		5	0	0.01	0.05	0.15	0.01
		10	A	0.02	0.13	0.16	0.02
		20	A	2.46	1.48	0.46	0.12
D	**4**	0-1	0	0.02	0.08	0.12	0.01
		5	0	BDL	0.02	0.11	BDL
		10	A	BDL	0.14	0.11	BDL
		20	A	0.06	0.10	0.16	0.02
D	**5**	0-1	0	BDL	BDL	0.08	BDL
		5	1	BDL	0.14	0.08	BDL
		10	0	0.22	0.21	0.20	0.04
		20	0	3.01	2.18	0.54	0.11
D	**6**	0-1	0	0.01	0.11	0.13	BDL
		5	0	BDL	0.07	0.13	BDL
		10	A	0.03	0.06	0.10	BDL
D	**7**	0-1	0	0.13	BDL	BDL	0.02
		5	0	0.13	0.11	BDL	0.02
		10	A	0.14	0.19	BDL	0.04

Cruise 1 (continued)

			Cells/liter	CONCENTRATION (uM)			
LINE	**STATION**	**DEPTH (m)**	***A. fundyense***	**N + N**	**NH4**	**PO_4**	**NO_2**
D	8	0-1	1	BDL	0.10	0.07	BDL
		5	0	BDL	0.02	0.07	BDL
		10	0	BDL	BDL	0.08	0.01
		20	0	4.60	3.80	0.78	0.16
E	**1**	0-1	0	BDL	0.04	0.19	0.01
		5	A	0.79	0.39	0.25	0.04
		10	A	1.59	0.84	0.35	0.06
		20	A	2.03	1.06	0.40	0.07
E	**2**	0-1	1	BDL	0.09	0.18	0.01
		5	A	BDL	0.39	0.18	0.01
		10	A	0.02	0.15	0.19	0.01
		20	A	2.48	1.70	0.48	0.12
E	**3**	0-1	0	0.02	0.02	0.19	0.02
		5	A	BDL	0.05	0.18	0.02
		10	A	BDL	0.26	0.16	0.01
		20	A	0.34	0.22	0.19	0.03
E	**4**	0-1	0	0.02	0.27	0.18	0.03
		5	0	BDL	0.13	0.17	0.02
		10	0	0.58	0.48	0.26	0.04
		20	0	2.10	1.37	0.46	0.07
E	**5**	0-1	2	BDL	0.01	0.12	0.02
		5	A	BDL	0.01	0.15	0.02
E	**6**	0-1	1	0.02	BDL	0.17	0.03
		5	A	BDL	BDL	0.17	0.02
		10	A	BDL	0.03	0.21	0.02
		20	A				

Cruise Designation: 01-MB-2
Cruise 2 dates: May 21 –22, 2001

			Cells/liter	CONCENTRATION (uM)			
LINE	**STATION**	**DEPTH (m)**	***A. fundyense***	**N + N**	**NH4**	**PO_4**	**NO_2**
A	**1**	0-1	0	0.30	0.23	0.03	0.02
		5	0	0.06	0.17	0.04	0.02
		10	0	0.02	BDL	0.05	0.02
		20	0	1.75	2.30	0.35	0.14
A	**2**	0-1	0	0.12	0.21	BDL	0.02
		5	0	0.03	BDL	0.01	0.01
		10	0	0.03	BDL	0.01	0.01
		20	0	0.37	0.84	0.19	0.05
A	**3**	0-1	1	0.05	0.03	0.05	0.02
		5	0	0.07	BDL	0.05	0.01
		10	0	1.23	0.81	0.30	0.10
		20	0	0.04	0.11	0.13	0.01
A	**4**	0-1	1	0.21	0.18	0.02	0.03
		5	0	0.03	BDL	0.03	0.02
		10	0	0.11	0.49	0.12	0.02
		20	0	0.09	0.15	0.14	0.02
A	**5**	0-1	0	0.02	BDL	BDL	0.01
		5	0	0.03	0.05	0.05	0.01
		10	0	0.11	0.53	0.10	0.02
		20	0	1.25	2.31	0.33	0.08
A	**6**	0-1	2	0.04	BDL	BDL	0.02
		5	0	0.02	BDL	0.07	0.03
B	**1**	0-1	0	0.02	0.17	BDL	0.01
		5	0	BDL	0.25	BDL	0.02
		10	0	BDL	0.17	0.02	0.03
		20	0	0.80	1.89	0.21	0.07
B	**2**	0-1	0	0.01	0.01	0.02	0.03
		5	0	0.03	BDL	0.01	0.03
		10	0	BDL	0.39	0.01	0.02
		20	0	0.37	BDL	0.18	0.06
B	**3**	0-1	0	0.04	0.10	BDL	0.02
		5	0	BDL	BDL	BDL	0.03
		10	0	0.02	BDL	0.01	0.01
		20	0	0.01	0.50	0.07	0.02
B	**4**	0-1	0	0.03	BDL	BDL	0.01
		5	0	0.31	0.32	0.04	0.03
		10	0	BDL	BDL	BDL	0.02
		20	0	0.19	0.23	0.16	0.03
B	**5**	0-1	0	0.01	BDL	0.06	0.02
		5	0	0.03	BDL	0.05	0.03
		10	0	0.01	BDL	0.05	0.02
		20	0	1.36	1.46	0.35	0.08

Cruise 2 (continued)

			Cells/liter	CONCENTRATION (uM)			
LINE	**STATION**	**DEPTH (m)**	***A. fundyense***	**N + N**	**NH4**	**PO_4**	**NO_2**
C	**1**	0-1	0	0.02	BDL	BDL	0.03
		5	A	0.01	0.02	BDL	0.03
		10	A	0.02	0.14	BDL	0.04
		20	A	1.02	2.11	0.28	0.08
C	**2**	0-1	0	0.02	0.07	BDL	0.03
		5	0	BDL	BDL	BDL	0.03
		10	0	BDL	BDL	BDL	0.02
		20	0	0.04	1.06	0.11	0.04
C	**3**	0-1	0	0.02	0.05	BDL	0.02
		5	0	0.03	BDL	BDL	0.04
		10	0	BDL	0.03	BDL	0.02
		20	0	0.22	0.82	0.16	0.05
C	**4**	0-1	0	0.03	BDL	BDL	0.03
		5	A	0.02	BDL	BDL	0.03
		10	A	BDL	BDL	BDL	0.04
		20	A	0.95	1.42	0.27	0.09
D	**3**	0-1	0	BDL	0.08	BDL	BDL
		5	0	BDL	BDL	BDL	BDL
		10	1	BDL	0.06	BDL	BDL
		20	0	BDL	0.08	BDL	BDL
D	**4**	0-1	0	BDL	0.03	BDL	0.01
		5	0	BDL	BDL	BDL	BDL
		10	A	BDL	0.12	BDL	BDL
		20	A	BDL	0.19	0.01	BDL
D	**5**	0-1	0	0.01	0.12	BDL	BDL
		5	0	BDL	0.11	BDL	BDL
		10	0	BDL	0.01	BDL	BDL
		20	1	0.22	0.90	0.10	BDL
D	**6**	0-1	0	0.64	0.81	0.11	0.10
		5	0	0.65	0.82	0.11	0.04
		10	0	1.11	1.87	0.21	0.07
D	**7**	0-1	1	0.20	0.75	0.14	0.09
		5	0	0.16	0.51	0.13	0.06
		10	0	0.20	0.53	0.14	0.07
D	8	0-1	0	BDL	0.17	BDL	BDL
		5	1	BDL	0.11	BDL	0.01
		10	0	BDL	0.09	BDL	BDL
		20	0	0.28	1.36	0.14	0.04

Cruise 2 (continued)

E	**1**	Station dropped due to harsh weather conditions					
E	**2**	Station dropped due to harsh weather conditions					
E	**3**	0-1	0	0.07	0.48	BDL	BDL
		5	0	BDL	0.09	BDL	BDL
		10	0	BDL	BDL	BDL	0.01
		20	0	0.79	1.98	0.23	0.04
E	**4**	0-1	0	BDL	BDL	BDL	BDL
		5	0	0.13	0.15	0.03	0.02
		10	0	1.13	1.89	0.26	0.07
		20	0	1.77	2.75	0.35	0.11
E	**5**	0-1	0	0.21	0.14	0.03	0.03
		5	A	0.15	0.11	0.04	0.03
E	**6**	0-1	0	0.02	BDL	BDL	0.01
		5	A	BDL	BDL	0.26	0.01
		10	A	BDL	0.09	BDL	0.01
		20	A				

Cruise Designation: 01-MB-3
Cruise 3 dates: May 31 - June 1, 2001

			Cells/liter	CONCENTRATION (uM)			
LINE	**STATION**	**DEPTH (m)**	***A. fundyense***	**N + N**	**NH4**	**PO_4**	**NO_2**
A	**1**	Station dropped due to harsh weather conditions					
A	**2**	0-1	0	0.00	BDL	0.06	BDL
		5	2	BDL	0.00	0.05	BDL
		10	0	BDL	BDL	0.07	BDL
		20	1	0.43	0.24	0.14	0.01
A	**3**	0-1	0	BDL	0.11	0.06	BDL
		5	0	BDL	BDL	0.06	BDL
		10	sample dropped	BDL	BDL	0.06	0.02
		20	0	0.12	0.03	0.13	BDL
A	**4**	0-1	1	0.27	0.41	0.15	0.01
		5	0	0.23	0.49	0.13	BDL
		10	1	0.25	0.40	0.15	BDL
		20	1	0.19	0.38	0.13	BDL
A	**5**	0-1	3	0.25	0.49	0.03	BDL
		5	3	0.25	0.15	0.05	BDL
		10	1	0.09	0.10	0.04	BDL
		20	0	0.04	0.08	0.02	BDL
A	**6**	0-1	0	0.43	0.54	0.01	0.01
		5	1	0.45	0.41	0.01	0.02
B	**2**	0-1	0	0.02	0.08	0.04	BDL
		5	0	BDL	BDL	0.04	BDL
		10	0	BDL	BDL	0.04	BDL
		20	0				
B	**3**	0-1	0	0.05	0.04	0.08	BDL
		5	0	0.01	0.04	0.07	BDL
		10	0	BDL	BDL	0.08	BDL
		20	A	BDL	BDL	0.09	BDL
B	**4**	0-1	0	BDL	BDL	0.05	BDL
		5	0	0.01	0.00	0.06	BDL
		10	0	BDL	0.01	0.06	BDL
		20	0	BDL	BDL	0.09	BDL
B	**5**	0-1	1	0.32	0.64	0.10	0.01
		5	2	0.29	0.33	0.11	0.04
		10	2	0.34	0.54	0.13	0.01
		20	A	0.23	0.65	0.12	BDL

Cruise 3 (continued)

			Cells/liter	CONCENTRATION (uM)			
LINE	**STATION**	**DEPTH (m)**	***A. fundyense***	**N + N**	**NH4**	**PO_4**	**NO_2**
C	**1**	0-1	0	BDL	0.11	0.04	0.03
		5	A	BDL	0.28	0.04	0.03
		10	A	BDL	0.24	0.04	0.01
		20	A	BDL	BDL	0.13	0.01
C	**2**	0-1	1	0.09	BDL	0.06	0.00
		5	0	0.08	0.03	0.06	BDL
		10	0	0.12	0.35	0.09	0.02
		20	1	0.32	0.99	0.18	0.04
C	**3**	0-1	2	0.15	0.31	0.06	0.00
		5	0	0.12	0.29	0.06	BDL
		10	0	0.17	0.86	0.08	0.01
		20	0	0.42	1.54	0.20	0.02
C	**4**	0-1	0	0.40	1.55	0.17	0.02
		5	A	0.39	1.55	0.17	0.01
		10	A	0.33	1.63	0.14	0.01
		20	A	0.93	2.25	0.31	0.05
D	**1**	0-1	0	BDL	BDL	0.11	0.04
		5	2	BDL	0.20	0.07	0.04
		10	A	BDL	BDL	0.10	0.04
		20	A	BDL	BDL	0.09	0.04
D	**2**	0-1	1	0.14	0.34	0.13	0.05
		5	0	0.09	0.14	0.13	0.04
		10	0	0.05	0.11	0.26	0.02
		20	0	0.06	0.04	0.18	0.06
D	**3**	0-1	0	BDL	0.18	0.08	0.01
		5	0	BDL	0.24	0.08	0.01
		10	A	0.06	0.20	0.13	0.04
		20	A	0.23	0.79	0.25	0.05
D	**4**	0-1	0	BDL	0.19	0.09	0.01
		5	1	BDL	0.07	0.09	0.01
		10	A	BDL	0.11	0.09	0.01
		20	A	BDL	0.17	0.11	0.02
D	**5**	0-1	0	0.04	0.19	0.01	0.06
		5	0	0.00	0.01	0.02	0.05
		10	0	0.01	0.21	0.01	0.04
		20	0	1.18	1.44	0.27	0.12
D	**6**	0-1	0	0.91	0.66	0.20	0.13
		5	0	0.99	0.47	0.18	0.14
		10	A	0.95	0.84	0.22	0.13
D	**7**	0-1	0	1.65	2.10	0.32	0.16
		5	1	1.78	1.65	0.35	0.18
		10	A	1.89	1.91	0.35	0.20
D	**8**	0-1	0	0.02	0.27	BDL	0.05
		5	0	0.02	0.26	0.01	0.06
		10	0	0.02	0.44	0.08	0.01
		20	0	1.49	2.08	0.43	0.08

Cruise 3 (continued)

			Cells/liter	CONCENTRATION (uM)			
LINE	**STATION**	**DEPTH (m)**	***A. fundyense***	**N + N**	**NH4**	**PO_4**	**NO_2**
E	**1**	0-1	0	BDL	BDL	0.10	0.05
		5	A	BDL	BDL	0.11	0.04
		10	A	0.02	0.35	0.11	0.06
		20	A	0.98	1.25	0.34	0.07
E	**2**	0-1	0	BDL	0.10	0.10	0.03
		5	A	BDL	BDL	0.09	0.02
		10	A	0.13	0.16	0.29	BDL
		20	A	1.05	1.12	0.39	0.06
E	**3**	0-1	0	BDL	BDL	0.10	0.01
		5	A	BDL	0.31	0.09	0.00
		10	A	0.04	0.16	0.10	0.00
		20	A	0.04	0.01	0.13	0.01
E	**4**	0-1	0	0.06	0.04	0.12	0.03
		5	0	0.01	0.25	0.11	0.02
		10	0	0.03	0.07	0.13	0.02
		20	0	0.87	1.48	0.32	0.07
E	**5**	0-1	0	0.00	BDL	0.08	0.00
		5	A	0.04	0.08	0.12	0.01
E	**6**	0-1	0	BDL	BDL	0.08	0.01
		5	A	BDL	BDL	0.08	0.01
		10	A	0.03	0.05	0.11	0.02
		20	A				

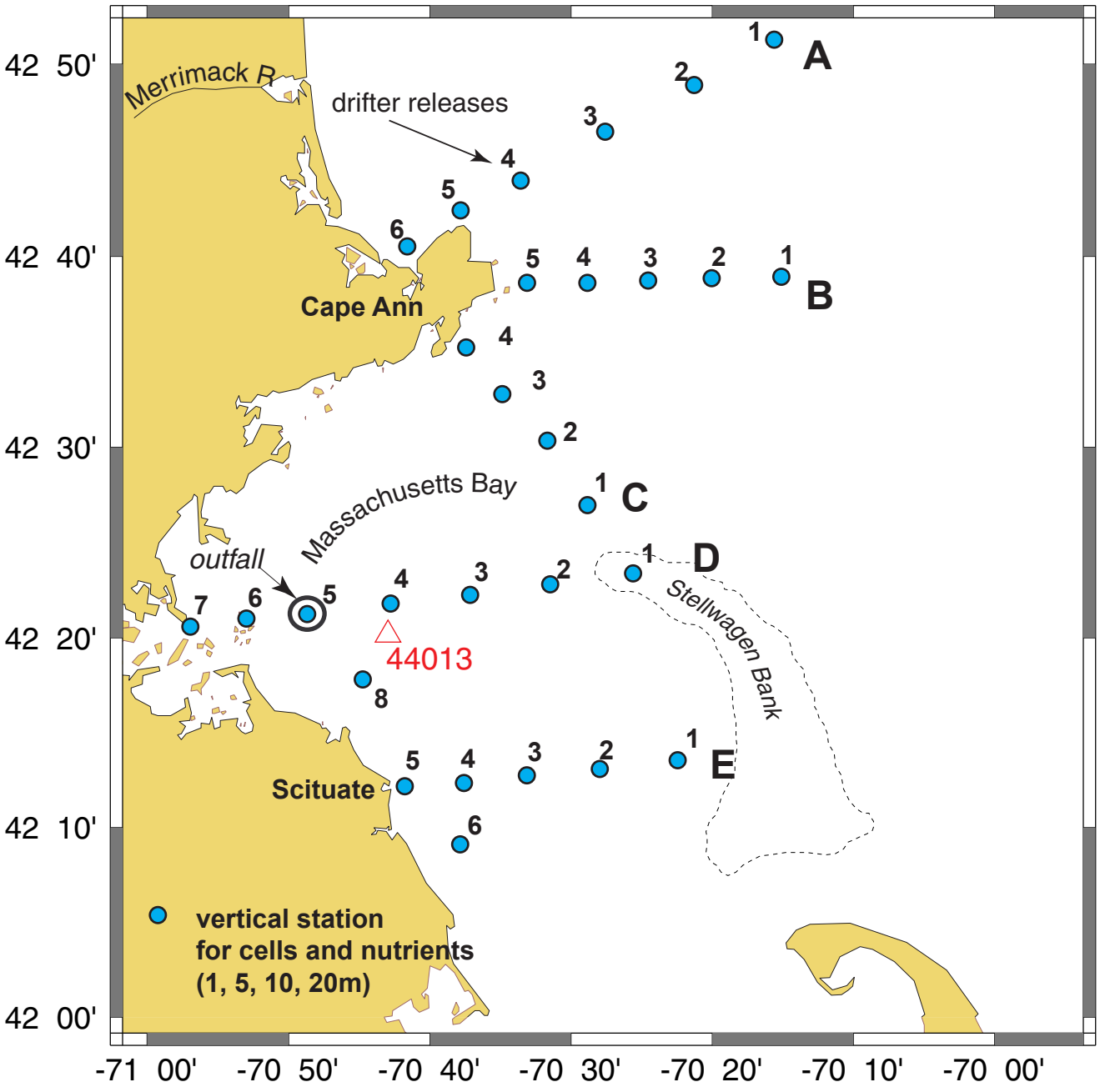

Fig. 1. Sampling station designations and locations for 3 cruises in Massachusetts Bay in spring, 2001. Surface drifters were released at Station A4. Wind data was acquired from NOAA buoy #44013.

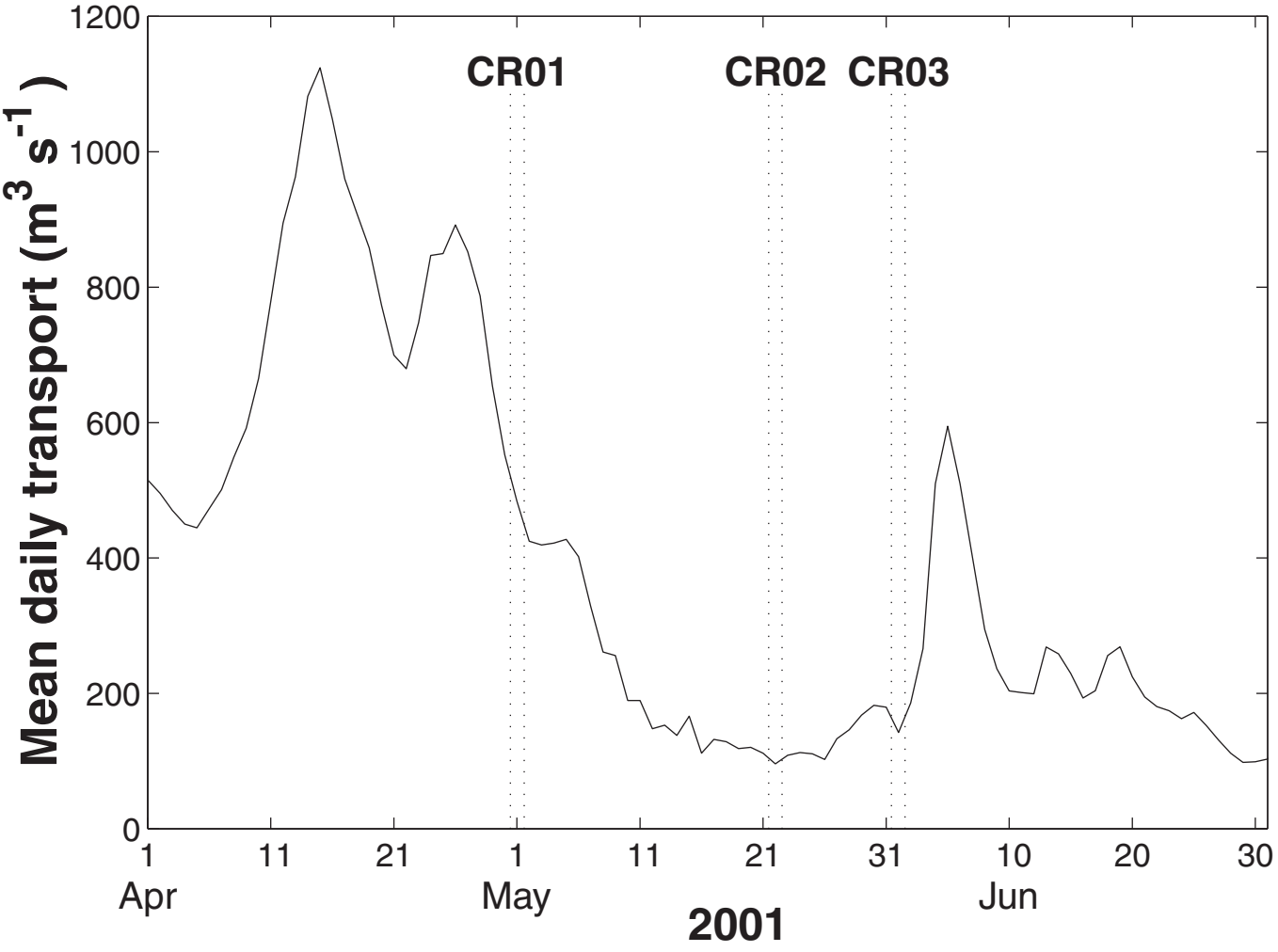

Fig. 2. Volume of freshwater discharge from the Merrimack River at Lowell, MA. The timing and duration of each cruise is noted by the dotted vertical lines.

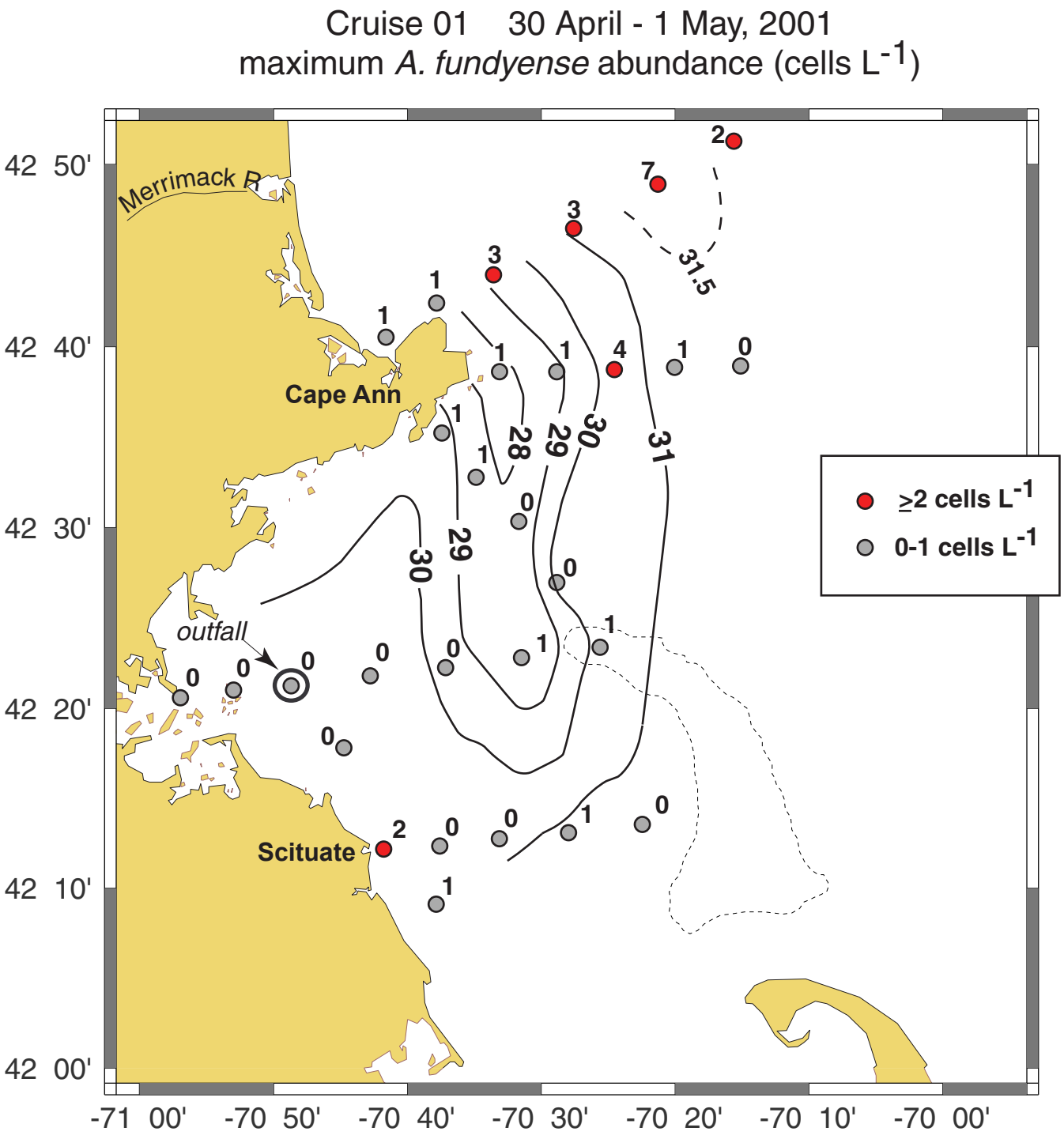

Fig. 3. Distribution of near-surface salinity and *A. fundyense* abundance in Massachusetts Bay during Cruise 1. For each station, the maximal concentration of *A. fundyense* is posted regardless of depth.

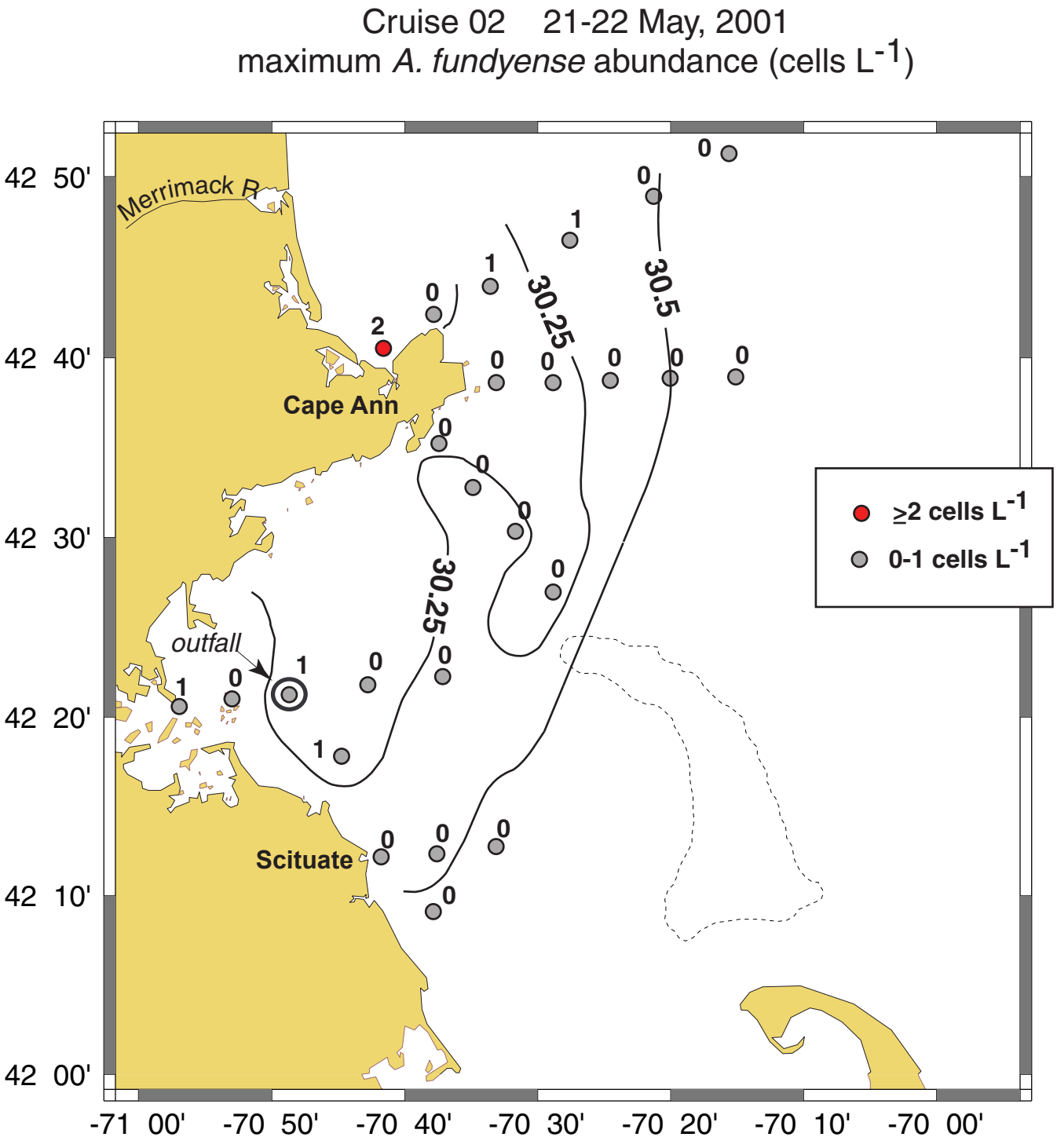

Fig. 4. Distribution of near-surface salinity and *A. fundyense* abundance in Massachusetts Bay during Cruise 2. For each station, the maximal concentration of *A. fundyense* is posted regardless of depth.

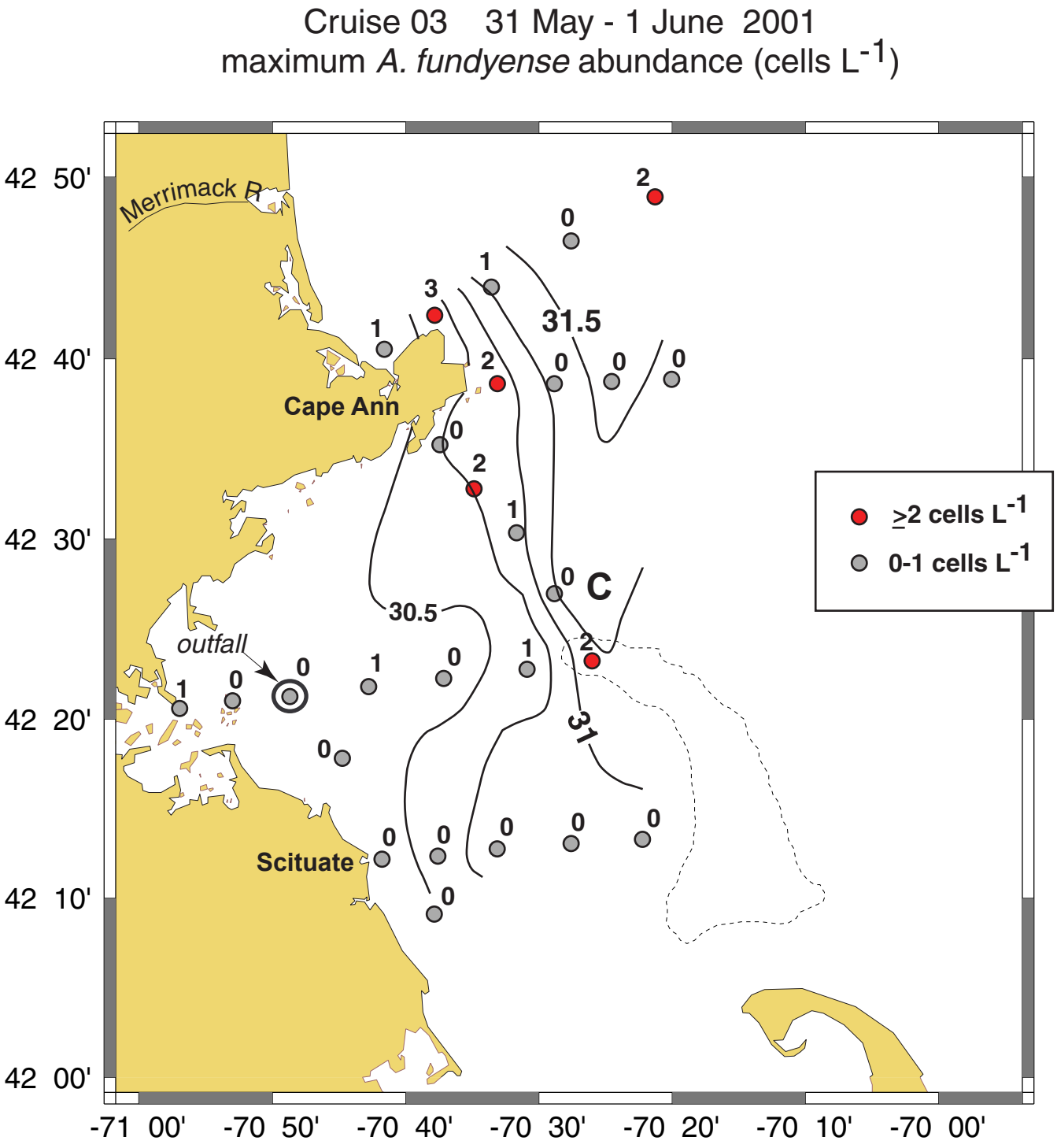

Fig. 5. Distribution of near-surface salinity distribution and *A. fundyense* abundance in Massachusetts Bay during Cruise 3. For each station, the maximal concentration of *A. fundyense* is posted regardless of depth.

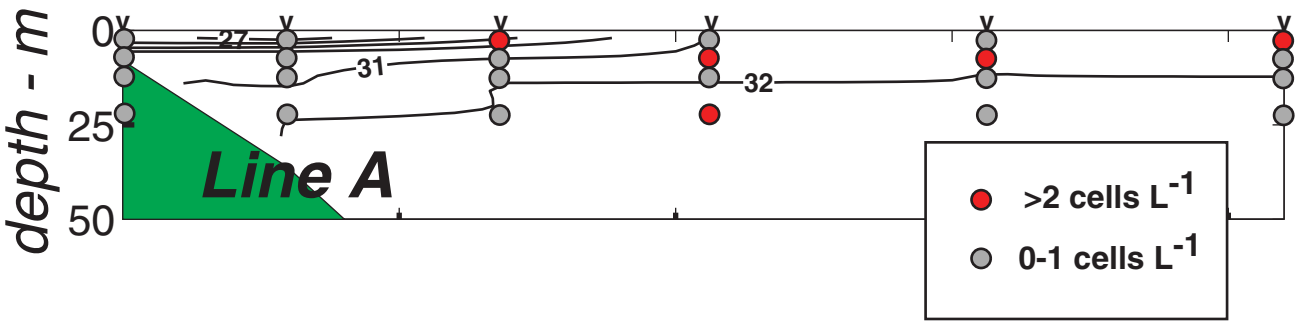

Fig. 6. Vertical section of salinity and *A. fundyense* abundance across the northernmost line (A) during Cruise 1. The *A. fundyense* abundance was higher both within the outer edge of the coastal plume and the adjacent offshore waters.

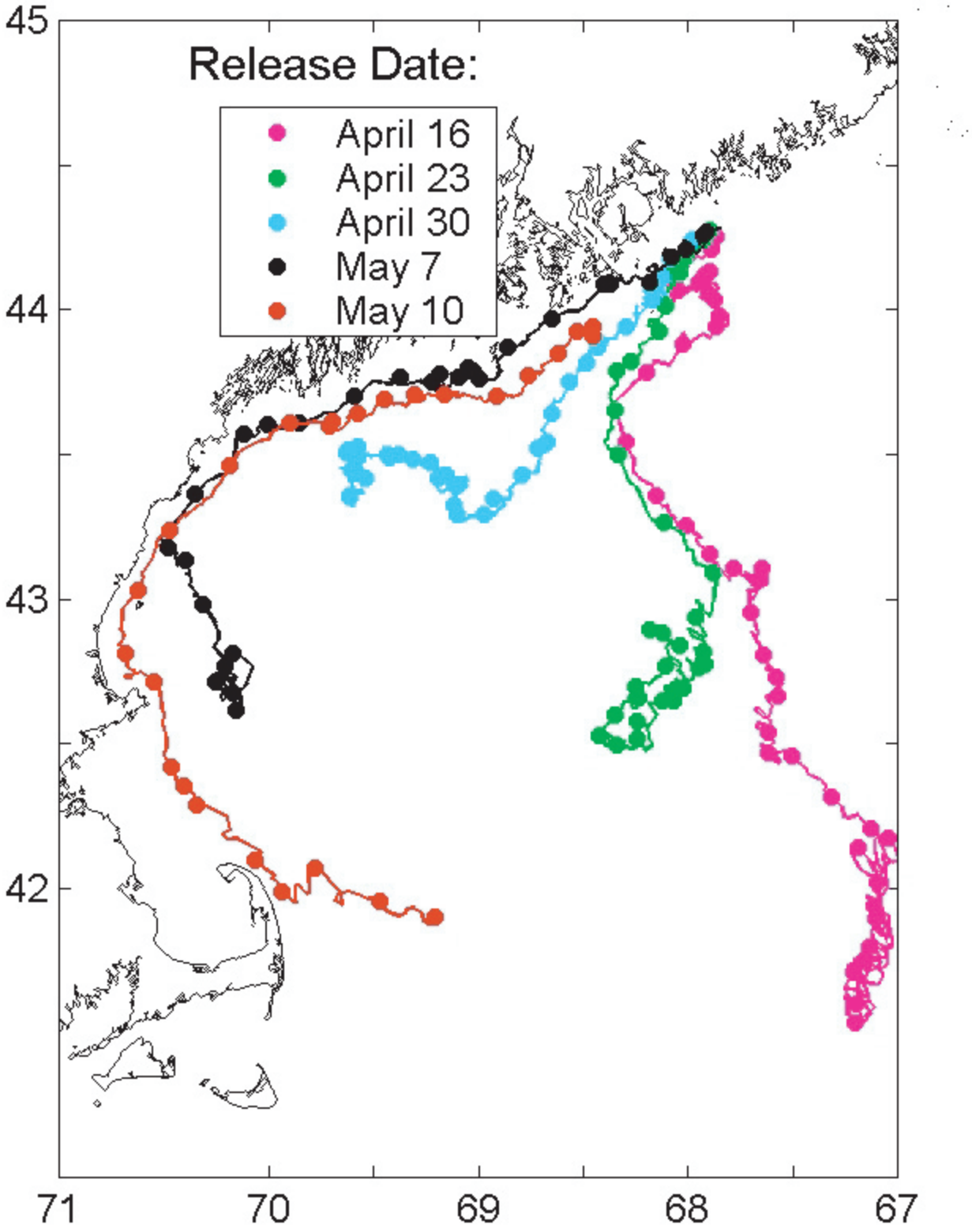

Fig. 7. Trajectories from satellite-tracked surface drifters released in the coastal waters of eastern Maine (dots plotted through June 5, 2001). The drifter shown by the red trajectory was released within a patch of *A. fundyense* cells and tracked to Massachusetts Bay within 2-3 weeks. Each dot represents a 24-hour interval.

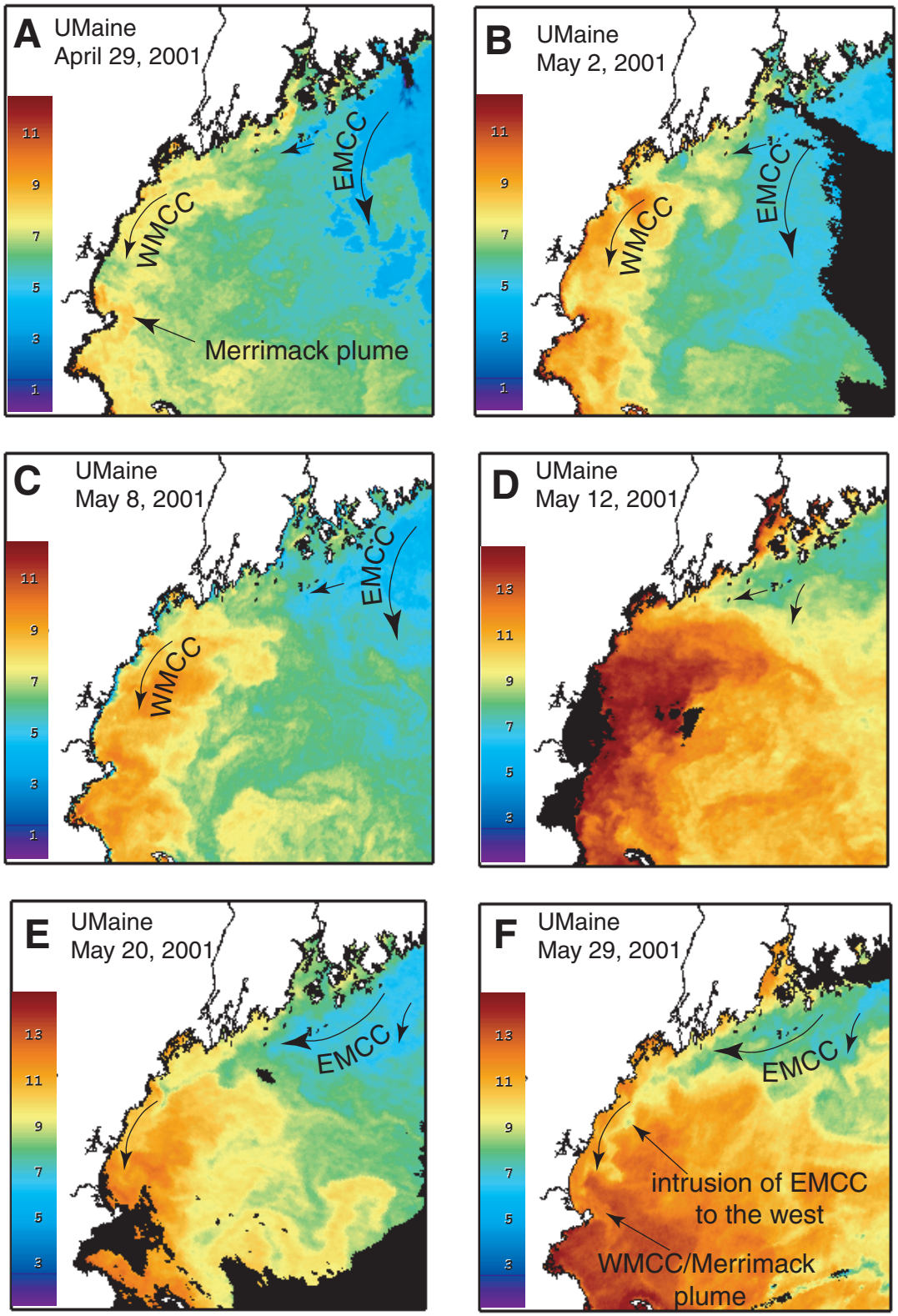

Fig. 8. Sequence of sea surface temperature (SST) imagery during *A. fundyense* sampling in Massachusetts Bay. Images from April 29-May 12 (panels A-D) generally depict the warmer WMCC spreading further to the east with upwelling-favorable conditions (see Fig. 9 for wind vectors), while the colder EMCC waters were deflected offshore. During later May, a narrow intrusion of colder water (8-9 ^{o}C) extended alongshore from the EMCC waters well into the western GOM coincident with a period of predominantly downwelling-favorable conditions (panels E-F). *A. fundyense* populations associated with the EMCC may be a source of western GOM populations. Note scale change between images C-D as vernal warming progressed. (imagery courtesy of Andy Thomas - University of Maine)

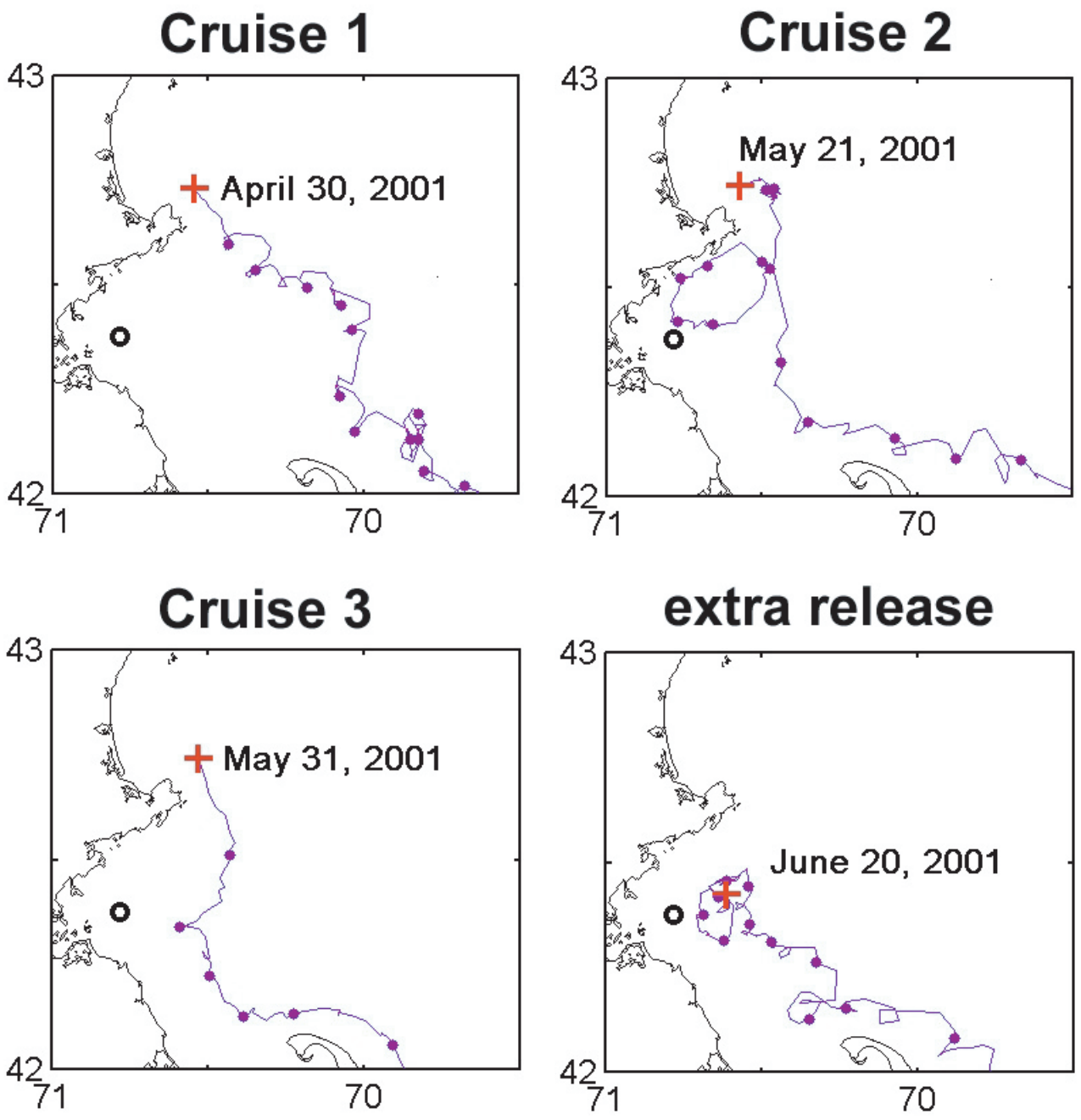

Fig. 9. Trajectories from satellite-tracked drifters released at Station A4 (see Fig. 1) during each of the 3 Massachusetts Bay cruises. An additional drifter was also released within the Bay later in the bloom season as part of another study. Each dot represents a 24-hour interval.

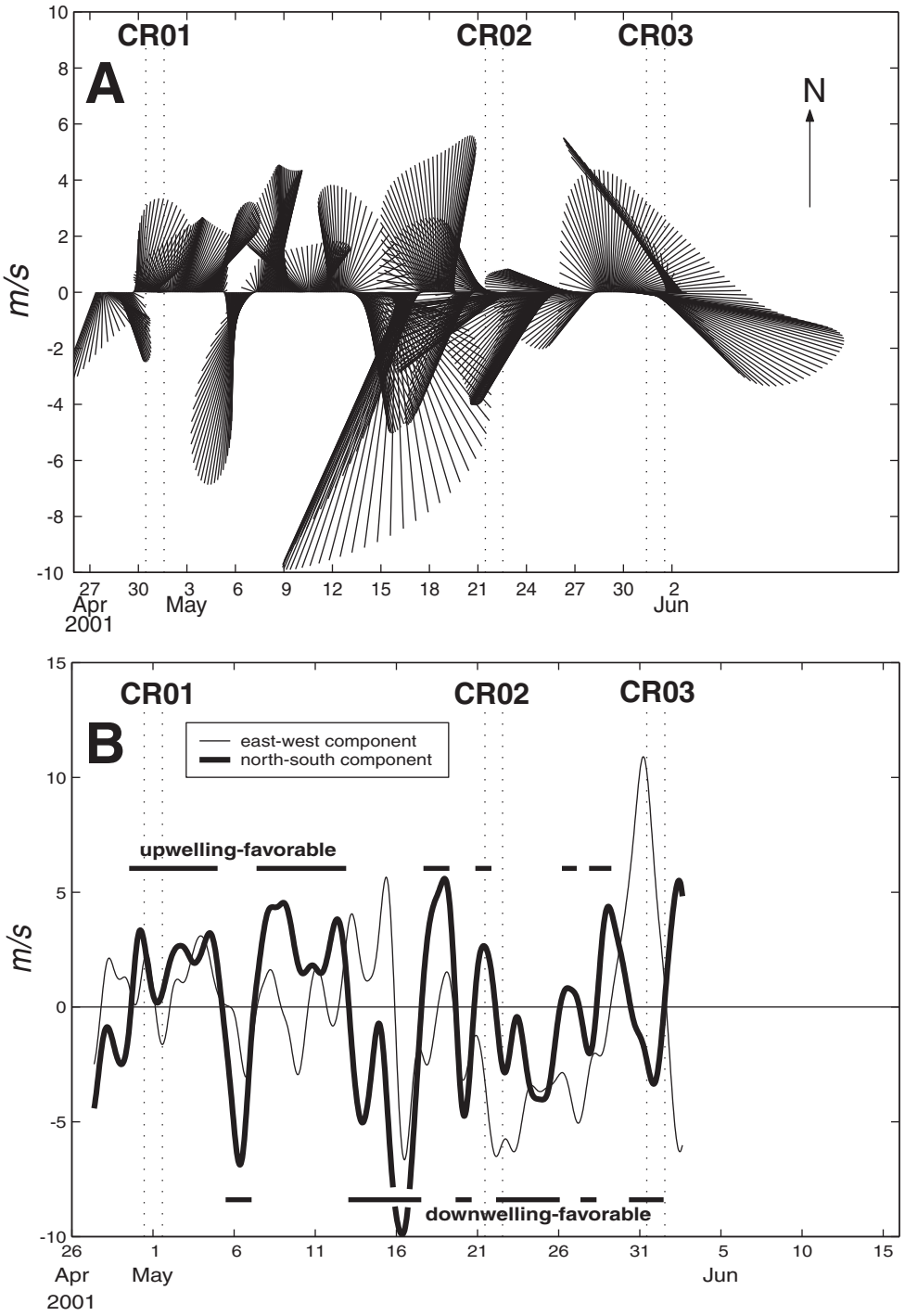

Fig. 10. Vector (A) and line plot (B) representations of winds at #44013 (see Fig. 1 for buoy location). The bold line (panel B) generally represents upwelling- and downwelling-favorable events; upwelling is above zero and downwelling is below zero. Early May was more upwelling-favorable and later May was more downwelling-favorable. The times of the 3 hydrographic cruises are bracketed by dashed lines.

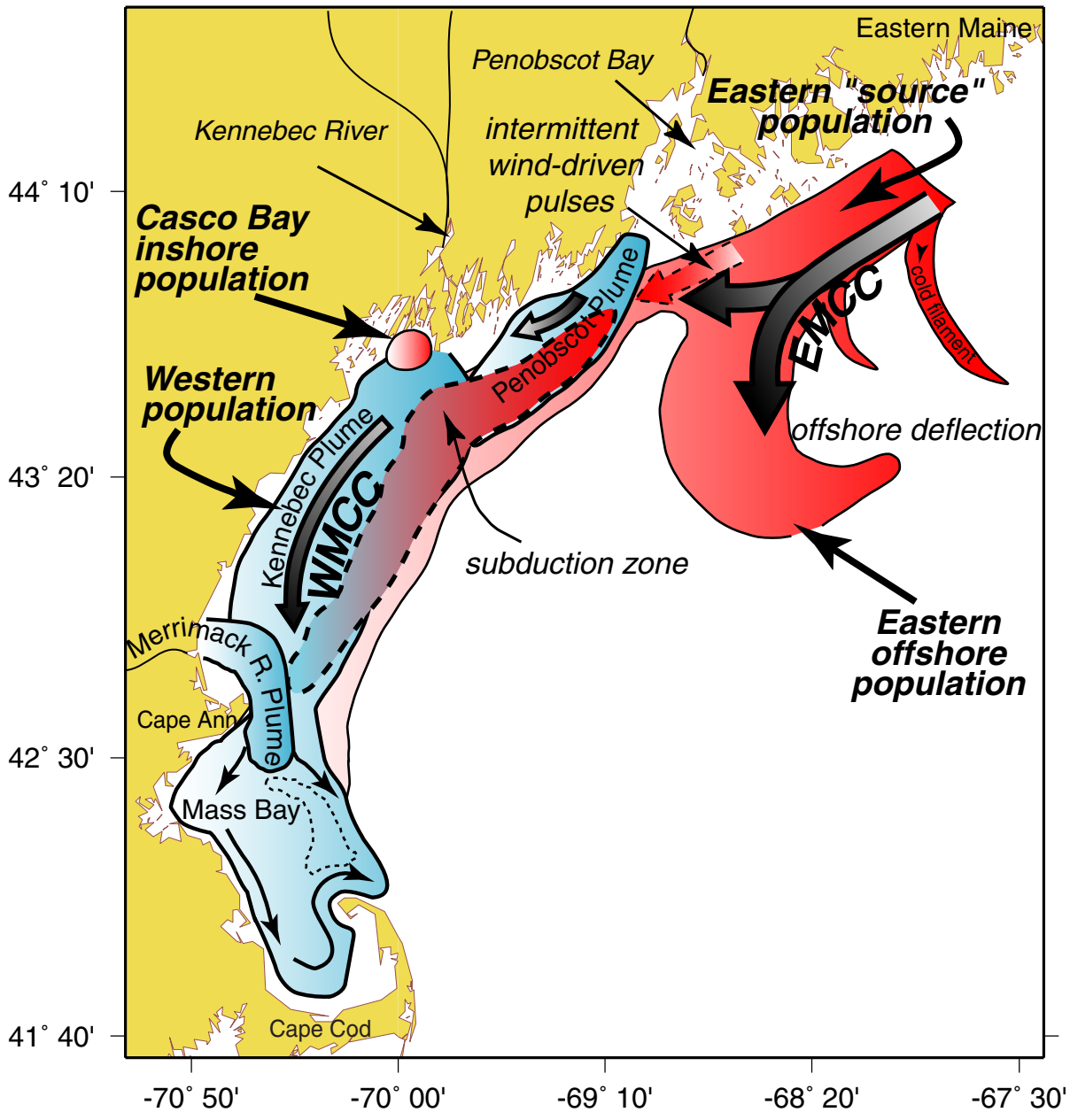

Fig. 11. Conceptual model of *A. fundyense* dynamics in the western Gulf of Maine. The large scale distribution of *A. fundyense* extends from eastern Maine to Massachusetts Bay, at least 400 km "downstream" from a possible source in eastern Maine. *A. fundyense* populations are associated with the WMCC and the EMCC and are generally transported within the general GOM circulaton. They can transit alongshore and/or be deflected offshore. In the western GOM, populations may pass offshore of the WMCC or subduct underneath the less-dense river plumes, supplying light-seeking (i.e., vertically swimming) cells to the overlying waters. Transport to the west is more rapid during downwelling-favorable conditions and slower during upwelling favorable conditions, pulsing cells to the west. Near Cape Ann, the populations may either be transported into the Bay, more likely during downwelling-favorable conditions or pass offshore along Stellwagen Bank, more likely during upwelling-favorable conditions. Thus, the variability of *A. fundyense* abundance in the Bay depends on both near- and far-field processes.