Toxic Phytoplankton Blooms in the Sea
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USE OF REMOTELY-SENSED SEA SURFACE TEMPERATURES IN STUDIES OF *Alexandrium tamarense* BLOOM DYNAMICS

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ABSTRACT

Remote sensing of sea surface temperatures (SST) has proven to be a useful tool in studies of the bloom dynamics of *Alexandrium tamarense* and the onset of PSP in the southwestern Gulf of Maine. A warm coastal current (= plume) formed from spring runoff that is believed to be responsible for the southerly transport of *A. tamarense* along the coast in this region was easily resolved in SST imagery. Coastal upwelling, which moved the warmer *A. tamarense*-containing buoyant plume offshore and away from nearshore shellfish, was detected in two of the three years of this study. The imagery provides valuable insights into the short-term oceanographic processes responsible for the development and behavior of the plume and the distribution of *A. tamarense*. Remotely-sensed SST has great promise as a tool to provide early warning of the conditions conducive for bloom development, transport and the initiation of PSP in this region.

INTRODUCTION

Remote sensing is a technique for studying the distribution of red tide organisms over larger spatial and shorter time scales than is possible with ship-based sampling [1]. Multi-spectral scanners (e.g. Coastal Zone Color Scanner; CZCS) have been used to detect the reflectance of chlorophyll a and other pigments, but these efforts have been constrained by the inability of the sensors to discriminate phytoplankton populations at the species level. More progress has been made by first linking specific water masses to organisms and then identifying that water mass with an appropriate remote sensing technique. In particular, remotely-sensed sea surface temperatures (SST) have been used to locate and track the movement of fronts, water masses, or other physical features where phytoplankton accumulate. The advection of *Gymnodinium breve* from Florida into the nearshore waters of North Carolina via the Gulf Stream has been followed with this approach [2].

In the southwestern Gulf of Maine, shellfish resources have been affected by Paralytic Shellfish Poisoning (PSP) annually since 1972 due to blooms of the dinoflagellate, *Alexandrium tamarense*. Prior research suggests that the blooms are associated with a warmer and less-saline coastally trapped buoyant plume formed from the outflows of the Androscoggin and Kennebec Rivers in Maine [3]. The plume is believed to be responsible for the southerly transport of the blooms into Massachusetts coastal waters and possibly further offshore onto Georges Bank [4]. The warmer buoyant plume was visible in an Advanced Very High Resolution Radiometry (AVHRR) image of SST during a bloom of *A. tamarense* in 1988, extending more than 200 kilometers along the coast [3].

We have subsequently obtained AVHRR imagery of SST during 1989, 1990 and 1991. Here we examine the utility of remotely-sensed SST as a tool to improve our understanding of *A. tamarense* blooms and the patterns of PSP in the Gulf of Maine.

Descriptions of hydrography and bloom details from cruises will be presented elsewhere. Geographic features in the discussion which follows include, from north to south: the Androscoggin and Kennebec rivers in southern Maine; Cape Ann, which forms the northern border of Massachusetts Bay; Boston; the "south shore" communities south of Boston; and Cape Cod, which defines the Bay's southern and eastern boundaries (Fig. 1).

METHODS

All images were acquired by the NOAA-11 satellite which passes over the Gulf of Maine twice a day at approximately 0400 and 1400 hrs local time. The satellite houses an AVHRR multi-spectral sensor measuring both visible and infrared radiation with a maximum resolution of 1 km. In 1990, SST data were purchased from the University of Miami satellite receiver and data processing center and viewed on a Sun workstation using SDPS software [5]. In 1991, images were obtained from the NOAA Coastwatch near real time satellite system. SST images accessed from the Northeast data communications node at Narragansett, Rhode Island using a 9600 baud modem were viewed on a NEC 386SX computer using the NOAA-supplied software program IDIDAS. Coastwatch can provide imagery that is hours to several days old. Several images from 1990 and a single 1989 image were also supplied by NOAA in the Coastwatch format from their archives. Supporting data were provided by cruises, during which Conductivity-Temperature-Depth (CTD) profiles were taken at various stations and discrete water samples collected for *A. tamarense* cell counts. Shellfish toxicity was determined by the MA Department of Public Health, MA Division of Marine Fisheries and the ME Department of Natural Resources. Moored CTD data from a station east of Boston in Stellwagen Basin (Fig. 2) were provided by J. Irish.

RESULTS AND DISCUSSION

SST images and ancillary ground truth data document a hydrographic feature along the coast of the southwestern Gulf of Maine which we interpret to be a coastally-trapped buoyant plume [3]. On SST images, this feature appears as a warm water mass along the coast (Figs. 1-4; black is warm, white is cold), sometimes extending from southern Maine to Cape Cod. Cruise data confirm that the feature is a warmer and less-saline buoyant plume 10-20 m deep and 10-40 km wide. The SST data agree well with both the ship-collected and moored CTD observations. Surface water temperatures ranged from approximately 8-11 °C within the plume to 6-8 °C outside the plume and offshore. The plume, which is influenced greatly by nearshore wind stress [3], originated as river outflow in southern Maine, supplemented by the Merrimack River in Massachusetts [4]. *A. tamarense* cells were generally associated with the plume, ranging from hundreds to several thousand per liter within it to barely detectable outside it.

The nearshore distributions of *A. tamarense* in 1989 and 1990 were consistent with PSP patterns which included shellfish closures in southern Maine and northern and southern Massachusetts in May. However, 1991 was quite different as PSP levels were low north of Cape Ann and remained below detection limits to the south. SST images reveal variations in hydrography between years which are useful in interpreting these toxicity results.

Only one SST image was obtained for 1989, but it was for an important date relative to the onset of toxicity along the southern coast of Massachusetts. PSP was first detected north of Cape Ann on May 17, and not on the south shore until May 22. Cruises documented the southward movement of the buoyant plume and *A. tamarense* cells to Cape Ann at that time, as well as the subsequent separation of the plume from shore following an interval of upwelling-favorable winds [3]. The SST image for May 22, 1989 (Fig. 1) shows a band of nearshore colder (upwelled) water north of Cape Ann, with the warmer plume located offshore. The image also shows that the plume, though offshore of Cape Ann due to upwelling at that time, had nevertheless travelled into and across Massachusetts Bay to reach the shoreline south of Boston. This coincided with the date when toxicity was first recorded in that area. We thus believe that the toxic cells were delivered to that site as a result of the advection of the plume. Transport of established bloom populations is the probable cause of toxicity, not *in situ* growth of indigenous, local cells. In this instance, a single SST image provided a level of spatial coverage that greatly enhanced information obtained from a limited number of cruises in one restricted area north of Cape Ann.

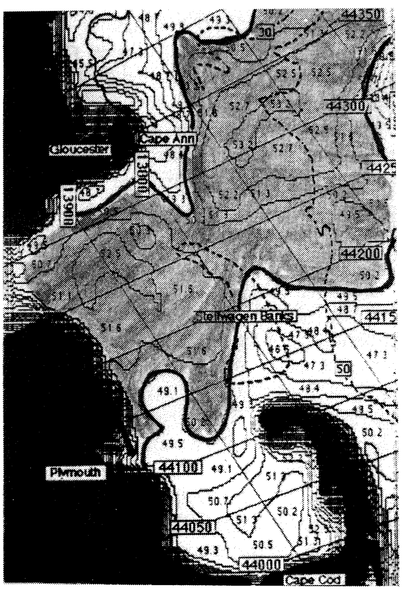

FIG. 1. NOAA Coastwatch SST image, May 22, 1989 at 1318 hrs local time. Shellfish toxicity was first detected on Boston's "south shore" as the warmer (darker) plume impacted the coast. Upwelling conditions (cold water is white) were prevalent to the north of Cape Ann, moving the warmer plume offshore. Important geographical features from north to south: Androscoggin and Kennebec Rivers (KR); southern Maine (sM); Cape Ann, Massachusetts (CA); Boston, Massachusetts (B); "south shore" (SS); and Cape Cod (CC).

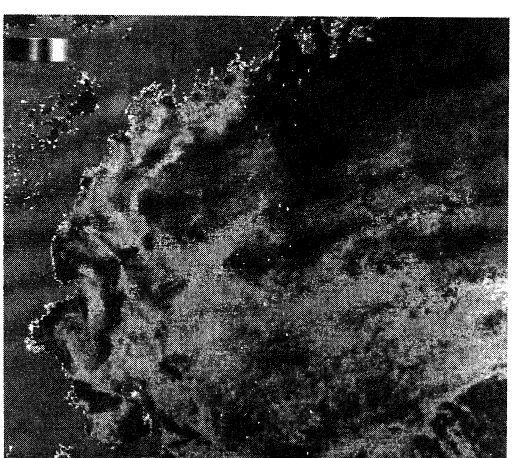

FIG. 2. NOAA Coastwatch SST image from May 28, 1990 at 1359 hrs local time during a major runoff event. The warmer (darker) plume extends along the coast from southern Maine (sM) into Massachusetts coastal waters where PSP occurred in nearshore shellfish during this time. The location of moored CTD observations are designated by an asterisk (*).

In 1990, PSP was first detected in southern Maine in early May, near Cape Ann on 24 May, and then on the south shore of Massachusetts less than one week later. Once again, cruise data document the formation (during April) and southward movement (May) of the buoyant plume and *A. tamarense* cells along the coast, into and across Massachusetts Bay [4]. Moored CTD instruments also recorded the passage of a mass of warmer, low salinity water through Massachusetts Bay during the last week of May [6], and high *A. tamarense* cell concentrations were detected in that water mass [4]. SST images (Fig. 2), taken near the time that toxicity was first detected on the south shore, confirm the extension of the warmer plume waters into Massachusetts Bay and directly over the CTD mooring location in Stellwagen Basin. These combined observations are especially interesting because they document the close temporal association between the arrival of the plume to the south shore and the onset of PSP toxicity there. In addition, toxicity was detected in offshore shellfish on Georges Bank and Nantucket Shoals at that time. It may be that the plume remained relatively intact and transported *A. tamarense* cells to shellfish in both the nearshore and offshore waters [4]. Our ability to use SST imagery to detect the plume as it moved further from shore was constrained by the dilution and dispersion of the water mass through time as well as by surface heating of stratified, offshore waters. Thus, the warmer waters seen at the edge of Georges Bank in the lower right corner of Figure 2 could reflect either the presence of remnants of the buoyant plume or local heating effects.

In 1991, near real time images were received from NOAA's Coastwatch program. Shellfishing was closed in southern Maine in late April following a major runoff event, consistent with the plume hypothesis [3]. However, this early onset was followed by decreasing toxicity in those shellfish, and it was not until 1 month later in June that PSP levels increased in southern Maine and on Cape Ann. Toxicity remained below detection limits to the south. Shipboard and moored CTD observations recorded a warmer, less-saline water mass as it moved through Mass Bay in late April [6]. In May, cruise transects showed that the plume had spread out over a much larger area to the east, with the highest *A. tamarense* concentrations offshore. The SST images of this interval document three important features: 1) the presence of the buoyant plume in the nearshore waters following the April runoff event (Fig. 3); 2) an interval of coastal upwelling north of Cape Ann (Fig. 4); and 3) the movement of the plume back towards shore following relaxation of the upwelling (image not shown). We believe that the initial runoff event started the "normal" bloom progression, forming a plume that carried a relatively small *A. tamarense* population across Massachusetts Bay without causing toxicity in the southern waters. Subsequently, meteorological conditions changed, bringing a jet stream pattern to the region that allowed tropical air to flow to the northeast. Instead of the cold, wet northeast winds characteristic of springtime, strong upwelling-favorable winds from the south/southwest dominated [7]. These winds caused the plume to move offshore, spread out, and to be replaced by cold, upwelled waters containing few, if any *A. tamarense* cells. This would explain the lack of toxicity near Cape Ann, as well as the decrease in toxicity that was observed in southern Maine shellfish in May. When upwelling relaxed, the plume and the *A. tamarense* cells returned to shore resulting in low but detectable levels of PSP north of Cape Ann. The general low level of PSP throughout the region in 1991 may thus be linked to the quantity and timing of the runoff that formed the plume and the upwelling that displaced it offshore.

In both 1989 and 1991, upwelling had a significant impact on the development, transport and possibly decline of the toxic blooms. In this region, upwelling occurs very rapidly in response to wind stress and is detectable after as few as 6 hours of sustained southwest winds above 15 knots in Massachusetts Bay [8]. The typical rapid rise and fall of toxicity in this south shore region could be partly due to the transport of populations away from nearshore shellfish due to upwelling, and their return as upwelling relaxes. It is only by chance that such short term features would be sampled by cruises scheduled at a bi-weekly or even weekly frequency. Similarly, frequent runoff events producing significant amounts of rainfall cannot be sampled adequately on the short time scales necessary to understand the dynamics of bloom development and transport in a region where a buoyant coastal current dominates. SST imagery has considerably enhanced our understanding of these short term processes.

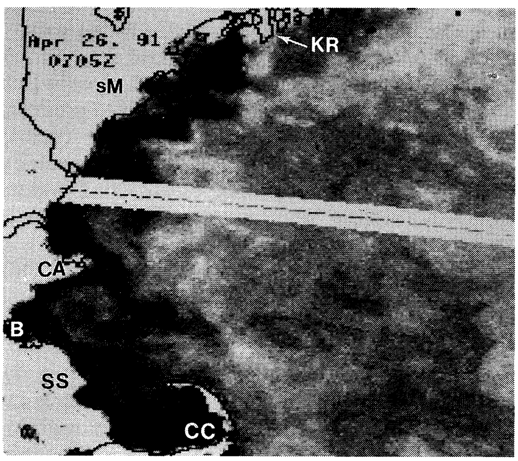

FIG. 3. NOAA Coastwatch SST image from April 26, 1991 at 0305 hrs local time during an early spring runoff event. The warmer (darker) plume extends along the coast. Shellfish toxicity was detected only in southern Maine (sM) at this time. Low concentrations of *A. tamarense* were detected within the plume further to the south, but well offshore in Massachusetts Bay just north of Cape Cod (CC).

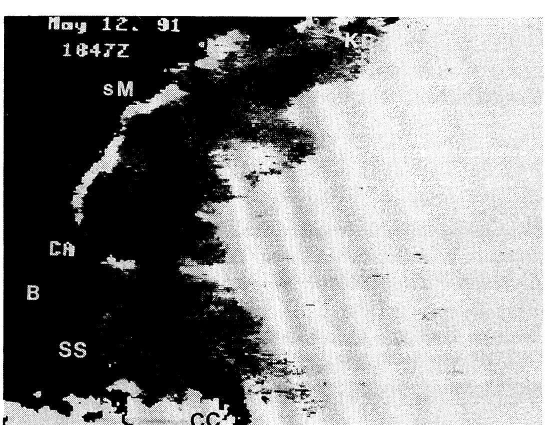

FIG. 4. NOAA Coastwatch SST image from May 12, 1991 at 1447 hrs local time, about two weeks after FIG. 3. The narrow band of colder water (white) along the coast north of Cape Ann (CA) signifies nearshore upwelling which has moved the warmer plume (dark) and *A. tamarense* cells offshore, resulting in decreasing toxicity in southern Maine (sM) shellfish and no toxicity in Massachusetts during this time.

One benefit of the near real time imagery in 1991 has been that field sampling design can be adjusted based on the features observed in the most recent images. For instance, when the plume was first detected in late April, cruises were rescheduled to obtain samples. When upwelling became visible in the SST images (Fig. 4), planned transects were relocated and extended further offshore to sample the eastern edge of the plume. Coastwatch images have thus facilitated an efficient, interactive sampling program that is responsive to short term events. This capability is not possible if the SST information comes from archived imagery.

There are several limitations to the use of SST imagery as applied to *A. tamarense* bloom dynamics. One obvious limitation is that clouds and fog, especially in the spring, can reduce the number of useable images to as few as one or two good images per week. Another limitation may be resolution, as the pixel size of the NOAA Coastwatch images is approximately 1 km. We found this to be adequate, but some satellite products have only about 4 km resolution which would generally not resolve either coastal upwelling or the buoyant plume in our region. One major problem that is especially apparent in the 1990 image (Fig. 2) is that local surface heating of stratified waters adjacent to the plume may blurr the distinction between water masses. This problem is especially severe in summer as the temperature differential between the plume and adjacent waters becomes quite small. Therefore, SST images are most useful at times when the river inputs are significantly different in temperature from the ambient coastal surface waters. We have also had minor problems in the interpretation of images due to diurnal variations in the SST. At times of atmospheric high pressure and light winds, afternoon images may show aberrations of the SST of several °C due to heating of the "sea skin" in areas of calm seas. Despite these limitations, our experience to date leads us to believe that near real time SST imagery shows promise not only as a tool for increasing our understanding of bloom dynamics, but also for the early warning of coastal oceanographic conditions conducive to the formation and transport of toxic algal blooms in the southwestern Gulf of Maine.

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