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Heterosigma akashiwo (Raphidophyceae): On prediction of the week of bloom initiation and maximum during the initial pulse of its bimodal bloom cycle in Narragansett Bay

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Abstract: A 38-year time series based on weekly sampling of the annual cycle of the ichthyotoxic raphidophyte, *Heterosigma akashiwo*, in Narragansett Bay was analyzed in quest of establishing whether predictive indices of its blooms there were possible. The objective was to aid potential managers of the aquaculture and fish-farming activities being proposed for Narragansett Bay in their development of harmful algal bloom monitoring strategies to protect against product and financial loss. There was a 94% probability that *Heterosigma akashiwo* would appear during a given year, with detectable levels (100 cells l^{-1}) rarely occurring before week 20. There was an 86% probability that the initial, annual appearance of *Heterosigma akashiwo* would not occur until watermass temperatures reached a threshold of 10 to 11°C. Following *Heterosigma*'s appearance, there is then an 80% probability that its bloom maximum will occur sometime between weeks 23 to 26, and a 66% probability that a second bloom would occur between weeks 43 to 46. The application of these predictors in developing a monitoring strategy for use by local aquaculturists and fish-farmers is then outlined.

Key words: *Heterosigma akashiwo*, bloom cycle, prediction, aquaculture, Narragansett Bay

Introduction

The raphidophyte species, *Heterosigma akashiwo*, has become well known for its ichthyotoxic blooms in such diverse regions as the Seto Inland Sea (Honjo 1992, 1994), New Zealand (Chang et al. 1990), Scotland (Ayres et al. 1982), Puget Sound and British Columbia (Taylor & Haigh 1993; Taylor et al. 1994), and Chile (Clement & Lembeye 1993). The initiation of salmonid fish farming often appears to provide a bloom stimulus by some unknown factor(s) in regions where *H. akashiwo* was previously unimportant, or not recorded (see Smayda 1998a). In South Korean waters, blooms began after initiation of shellfish aquaculture (Park et al. 1989). There are many regions, however, where *Heterosigma* blooms in the absence of fish-farming activities, as in Narragansett Bay, historically the site of pronounced blooms (Tomas 1980) and now being considered for extensive aquaculture and fish-farming initiatives (Anderson et al. 1998). Given this and the apparent, positive association between the initiation of fish-farming and aquacultural activities and subsequent *Heterosigma* bloom events, an issue of practical interest to local aquaculturists and fish-farmers has arisen. That is, what is the potential impact of the proposed fish-farming and shellfish aquacultural initiatives in Narragansett Bay in stimulating and altering *Heterosigma*'s bloom dynamics? Will these responses be similar to those experienced elsewhere in aquaculturally modified habitats within its distributional range? This paper addresses the first concern by considering the extent to which bloom events of *H. akashiwo* in Narragansett Bay occur in predictable fashion. We specifically seek to identify periods within the annual phytoplankton cycle when potential blooms of *H. akashiwo* may compromise the proposed aquacultural and fish-farming activities. A 35-year subset of a 38-year time series on phytoplankton dynamics available for Narragansett Bay is used in this analysis (see also Smayda 1998b; Karentz & Smayda 1984, 1998).

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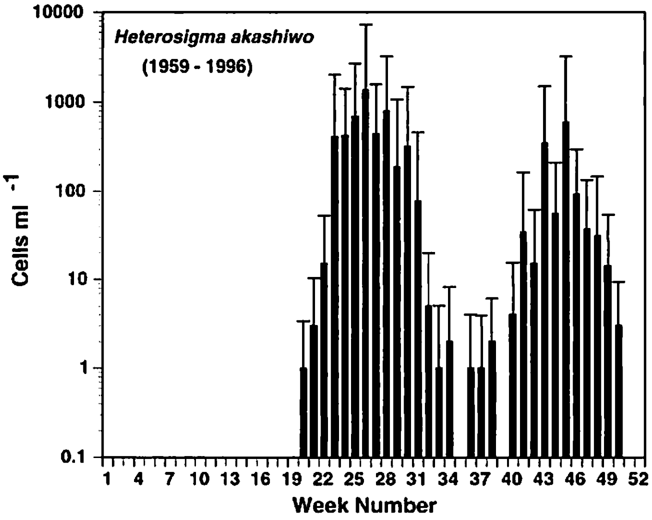

Fig. 1. Mean weekly surface abundance of *Heterosigma akashiwo* in lower Narragansett Bay during the years from 1959 to 1996. Range bars above histograms indicate one standard deviation.

Material and Methods

The *H. akashiwo* data analyzed were collected as part of a long-term, quantitative data set based on weekly sampling carried out since 1959 at a permanent station (41°34'07"N, 71°23'03"W) located in well-mixed, unpolluted Narragansett Bay (see Fig. 1 in Tomas 1980) where the mean depth is 9 m. Weekly measurements made at top, mid and bottom water column depths included temperature, salinity, Secchi Disc, various nutrients, chlorophyll, phytoplankton species composition and numerical abundance and zooplankton. Further information on the sampling program is given in Borkman & Smayda (1998), Li & Smayda (1998), Smayda (1998b) and Karentz & Smayda (1984, 1998). *H. akashiwo* was enumerated by counting 1-ml aliquots of unpreserved samples in a Sedgwick–Rafter counting chamber soon after collection. Three of the 38-years in the time series could not be reliably used because of sampling discontinuities in these years during *Heterosigma*'s growth season.

Results

Figure 1 presents the mean weekly surface abundance of *H. akashiwo* from 1959 to 1996 recorded at the long term monitoring station in lower Narragansett Bay. Three prominent features characterize *Heterosigma*'s bloom cycle. It suddenly appears (i.e., <0.1 cells ml^{-1}) during mid-May (week 20), and then begins an exponential growth phase which, on average, yields a maximal population during week 26. During this growth period, which lasts 6 weeks, the population can increase in abundance by about 10,000-fold. This first growth phase is followed by an equally precipitous population decrease, during which abundance reaches a lower threshold of only 1 cell ml^{-1} sometime during weeks 33–36 (i.e., in August). This nadir is followed by renewed exponential growth and a second maximum in late October–early November (ca. weeks 43–45). A rapid decrease then follows, and *H. akashiwo* disappears by week 51.

The average, annual synchrony of *H. akashiwo* dynamics in Narragansett Bay therefore consists of a sharply defined entrance into the plankton; a growth cycle usually consisting of two bloom-pulses, and significant intra-season oscillations in abundance, followed by a decline and disappearance. These events tend to be rhythmic, notwithstanding the precipitous surges and declines in population growth evident in Fig. 1. While this averaged bloom behavior generally mirrored that for the individual years comprising the data set, interannual variations in bloom magnitude occurred and in 11 years a secondary pulse was not recorded. These variations in bloom characteristics, which will be elaborated upon elsewhere, are of minor consequence to the conclusions presented here. Based on the 38-year data set, there was a 94% probability that *H. akashiwo* would appear during a given year, and usually not before week 20 (i.e., it occurred in 31 of the 33 years for which a complete annual cycle is available), with an 88% probability (29 of 33 years) that its bloom maximum would then develop during weeks 23 to 28. This extraordinarily persistent bloom behavior of *H. akashiwo* from year-to-year prompted evaluation of the potential role of temperature in the observed population events. Figure 2 shows the range of temperatures accompanying the spring-summer occurrences (i.e., first population pulse) of *H. akashiwo*. The lowest temperature in the annual bar graphs is that recorded at the time of initial detection by the weekly sampling program in that year. The uppermost value is the highest temperature encountered by *H. akashiwo* during its first bloom pulse. The range of temperatures over which *H. akashiwo* was recruited into the plankton varied from ca. 7 to 18°C. More interesting, however, in 25 years of the 29 years during which the first bloom pulse was recorded, *H. akashiwo* did not appear until temperature exceeded 10 to 11°C.

Figure 3 shows the temperature-presence relationship during *H. akashiwo*'s second bloom phase which occurred during weeks 38–50 for the 21 years of the time series in which a second bloom occurred. Temperature varied from about 12 to 20°C at the time when renewed growth began to yield a second bloom pulse. Unlike the first bloom pulse, a "threshold" temperature was not found which could be associated with initiation of this second, rapid growth period. Similarly, the temperature at the time of bloom termination and *H. akashiwo*'s disappearance from the plankton also varied. *H. akashiwo* still persisted at <10°C in 10 of the 21 years in which a second bloom pulse was found. And, in 8 of these years *H. akashiwo* disappeared before temperatures reached 5°C. This temperature-uncoupled behavior reveals that although *H. akashiwo* appears to require temperatures >10°C for its initial, yearly recruitment into the plankton, it can survive at significantly lower temperature levels

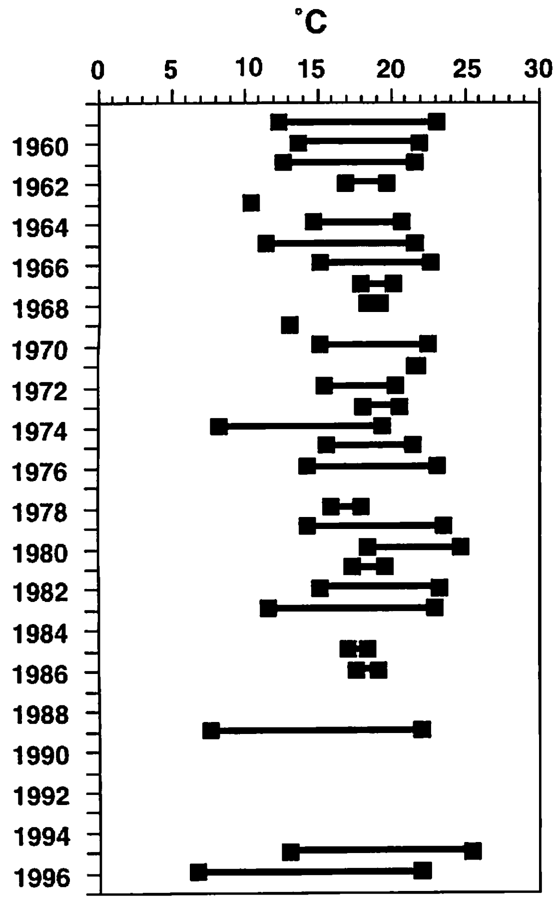

Fig. 2. Temperature range during the first bloom period of the bimodal bloom cycle of *Heterosigma akashiwo*; i.e., spring–summer occurrence. Lower temperature in each year is that during initial appearance of *H. akashiwo*; highest temperature is the maximum encountered during the bloom period, and not that occurring during the population maximum.

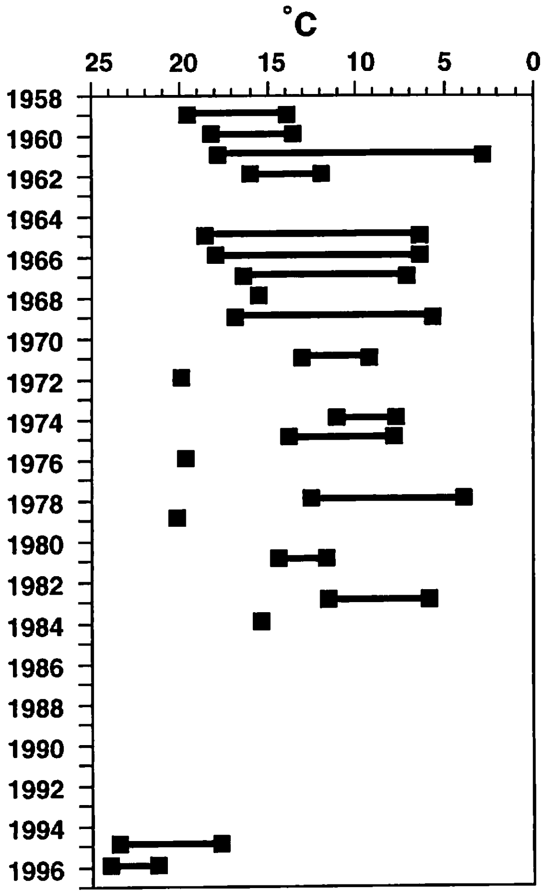

Fig. 3. Temperature range during the second period of *Heterosigma akashiwo*'s bimodal bloom cycle, i.e., autumn–winter occurrence. Lowest temperature for each year is that accompanying the final recorded occurrence during that bloom period, and therefore for that year.

thereafter prior to its ultimate, annual disappearance.

Figure 4 shows the frequency with which *H. akashiwo* reached its first maximum which was always recorded between weeks 23 and 28. In 20 of these years, the bloom peak was specifically reached during the four-week interval between weeks 23 to 26. Given the considerable variability in bloom occurrences and time of blooming which characterize harmful algal species, this interannual persistence in period of maximal bloom occurrence characterizing *H. akashiwo* in Narragansett Bay is remarkable.

Discussion

We have limited our examination of whether there are easily measured parameters of potential managerial use to aquaculturists and fish-farmers in Narragansett Bay in alerting them to potential product loss and economic hardship as a result of *H. akashiwo* blooms. Thus, we have focused on the easily measured temperature parameter from the perspective of the apparent association between this parameter

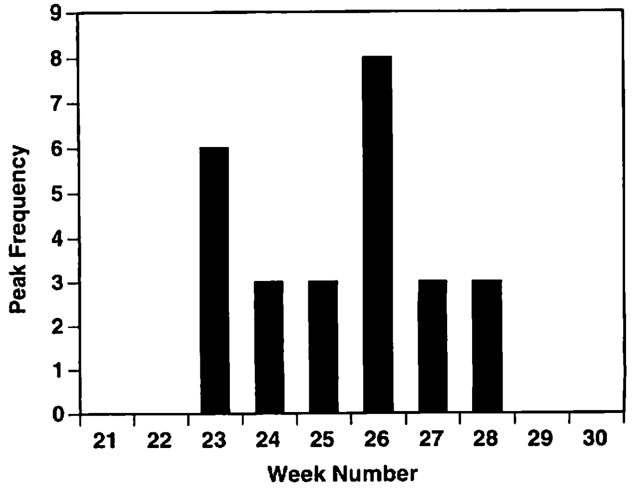

Fig. 4. The frequency with which *Heterosigma akashiwo* achieved its peak abundance during week numbers 23 to 28, respectively, during the first bloom period of its annual bimodal bloom cycle from 1959 to 1996.

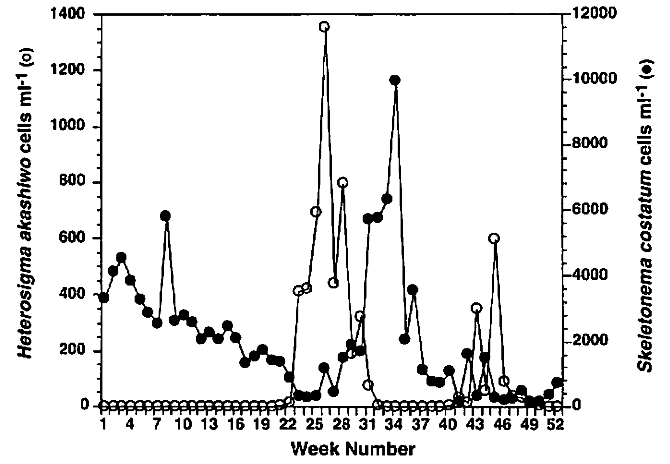

Fig. 5. Weekly mean surface abundance of *Heterosigma akashiwo* and the diatom, *Skeletonema costatum*, by week number for the years 1959 to 1996.

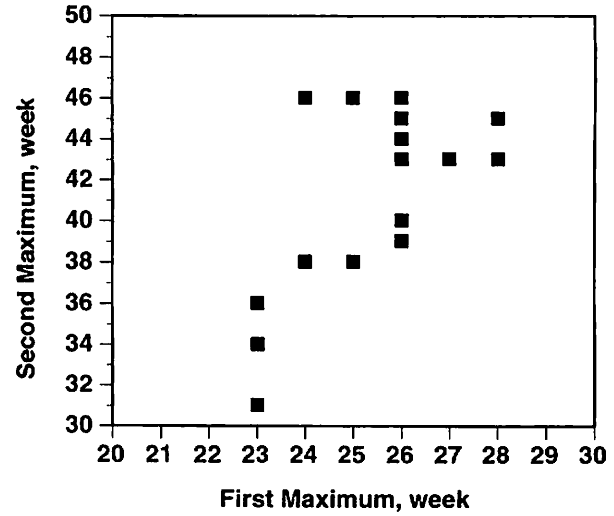

Fig. 6. Relationship between the weeks of the first and second bloom maxima of *Heterosigma akashiwo*.

and *H. akashiwo* dynamics in Narragansett Bay revealed by the time-series. Another factor regulating *H. akashiwo*'s bloom behavior is clearly its allelochemical competition with the diatom, *Skeletonema costatum*, as evident from Fig. 5, and which confirms both Pratt's (1966) earlier findings for Narragansett Bay and Honjo's (Honjo 1994; Honjo et al. 1978) observations in Japanese waters. However, the applied use of such knowledge to local aquaculturists and fish-farmers who wish to initiate monitoring programs to protect against *H. akashiwo* blooms would appear to be limited. The competition between these two species is under such complex and poorly understood regulation that the practical value to aquaculturists of monitoring *Skeletonema*'s abundance as an index of potential *Heterosigma* dynamics is dubious. We will present a more detailed evaluation of environmental and trophodynamic regulation of the observed *H. akashiwo* bloom dynamics in the time series elsewhere.

With the foregoing in mind as well as the limitations of averaging the 38-year data for the present purposes, two predictive features of *H. akashiwo* dynamics in Narragansett Bay emerge of potential use to local aquaculturists and fish-farmers. First, over a 38-year period the spring–summer appearance of *H. akashiwo* was delayed in 86% of the years until watermass temperatures exceeded 10 to 11°C. That is, in only 14 of every 100 years would a spring–summer bloom initiate at lower temperatures. The second prediction is that once the first spring–summer bloom pulse begins in Narragansett Bay, the bloom maximum will occur sometime between weeks 23 to 26, as it did in 80% ($n=20$) of the 26 years in the time series. We did not find a correlation between temperature and the magnitude of this bloom, nor, and unlike reported for Osaka Bay (Yamochi 1989) and Sechelt Inlet, British Columbia (Taylor & Haigh 1993), a correlation between blooms and river runoff which those investigators suggested reflected the dependency of *H. akashiwo* on riverine delivery of iron needed to bloom. Other than the high probability that a first pulse bloom of *H. akashiwo* in Narragansett Bay will lead to a second pulse (Fig. 1), we found no predictive relationship between bloom dynamics during that growth phase and temperature.

Our advice to local aquaculturists and fish-farmers seeking to establish a monitoring system to ward against potential inimical *H. akashiwo* effects on their industry in Narragansett Bay would be as follows. Routine measurement of water column temperature should be made, and when the threshold level of 10°C is reached quantitative enumeration of *H. akashiwo* should begin. Since the waters of Narragansett Bay are relatively well-mixed year-round, a pooled water column sample collected from the surface, mid-depth and bottom layers can be used to monitor *H. akashiwo* abundance. Should a bloom pulse be indicated by the population changes, preparation for emergency responses, particularly applied between weeks 23 to 26 should be commenced. No correlation has been found, as yet, between the first and second bloom events (Figs 1, 6). A second bloom did not develop in ten of the years, and when a second bloom maximum did occur after a week 26 maximum, for example, it developed over the wide interval of 13 to 20 weeks later (Fig. 6). Given this variability and the greater unpredictability of the second bloom event, in situ abundance of *H. akashiwo* should be monitored throughout this period for use as a guide to product-protection and required management responses. A caveat to these recommendations is: given the apparent stimulation of salmonid and other fish-farmed species on *H. akashiwo* dynamics (see Smayda 1998a), the possibility that the apparent temperature–bloom relationship described here might be modified by fish-farm effluent and excreta can not be ignored.

Acknowledgments

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