Dye tracing of a subsurface chlorophyll maximum of a red-tide dinoflagellate to surface frontal regions

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Abstract

Rhodamine dye (370 l) was injected into a 22-m subsurface chlorophyll maximum of the red-tide forming dinoflagellate Prorocentrum mariae-lebouriae var. minimum in the northern Chesapeake Bay (USA) and traced for a six-day period as it spread over a 600 km² area. The precise physical mechanisms, which resulted in the transfer of dye and organisms to the surface, are documented. The major component of the dye and organisms was transported from the central bay into major tributary estuaries via net nontidal flow of bottom waters and surfaced upstream in frontal regions. Once in surface waters, the dye and organisms flowed downriver toward the bay. Due to the three-layer flow of the rivers at this time, the dinoflagellate and the rhodamine re-entered the bay proper at mid-depth below the fresher Susquehanna plume, thus forming a near-surface chlorophyll maximum (4–6 m) flowing in an opposite direction to the deep subsurface chlorophyll maximum (18–26 m). Current meter arrays verified the opposite flows of these two lenses. The near-surface, southward-flowing lens was followed downstream to an area where the influence of the Susquehanna begins to subside as indicated by isopycnals inclined to the surface. Here the near-surface lens is mixed upward to the surface forming massive red tides (25 000 cells ml⁻¹) delineated by a frontal region. In addition to the predominant along channel flow, major cross stream Ekman transport and upwelling of dye and organisms was detected in response to wind forcing resulting in localized surface patch formation along the western shore shoaling regions of the bay proper. Thus, annual variations in the locations of surface red tides can be correlated to streamflow and wind-induced variations in the locations of frontal regions.

Introduction

Subsurface concentration maxima of phytoplankton are widely documented phenomena observed on almost every scale from small lakes to the ocean (Steele and Yentsch, 1960; Steele, 1964; Anderson, 1969; Venrick et al., 1972; Pingree et al., 1975, 1976, 1978; Fee, 1976; Reid et al., 1978). In most cases, these maxima are associated with some physical discontinuity (density, temperature, salinity) in the water column (Hobson and Lorenzen, 1972; Blasco, 1978). Productivity of these layers or lenses can be quite high if the accumulations are within the euphotic zone (Aruga, 1966). Mechanisms for their formation range from sinking or migration from the surface layers (Riley et al., 1949; Goering et al., 1970; Revelante and Gilmartin, 1973; Kamykowski, 1974), upward swimming from bottom waters (Seliger et al., 1970), or horizontal advection of cells from other areas by appropriate currents (Tyler and Seliger, 1978). In populations which exhibit diurnal migrations, the subsurface maxima may appear only at certain hours of the day. Nonmotile or entrapped populations may be oscillated in a vertical plane by internal waves or tidal action, or transported horizontally by subsurface currents viewed as a propagation along isopycnal, isohaline or isothermal lines. The horizontal journey may actually begin at a convergence zone where high concentrations of surface plankton accumulate and are transported downward along a frontal interface as it submerges to become an observed pycnocline in the water column (Seliger et al., 1979; Tyler and Seliger, 1981; Tyler et al., 1982). In areas where the discontinuity intersects either the surface or the bottom, a front results. In cases of a benthic front, the contents of the subsurface maxima may be deposited in beds such as was demonstrated for dinoflagellate cysts (Tyler et al., 1982) and for oyster spat (Seliger et al., 1982). In cases where the force (wind mixing or tidal stirring) of the intruding waters is of significant enough velocity to displace the receiving waters, an upwelling usually results and the contents of the bottom waters may be brought to the surface.

The resultant species composition in surface waters near an upwelling zone reflects that of the source waters and studies on the physiology of these organisms in coastal
and estuarine waters would be difficult to interpret without a knowledge of the origin and thus prehistory of the study organism. In many cases, the physics of frontal circulation, Ekman transport, etc. are analogous to ocean and coastal waters, only on a smaller scale. Thus detailed study of the estuaries may define the importance of physical dynamics on phytoplankton distributions in general.

In the Chesapeake Bay we have studied over 10 years a red tide organism, *Prorocentrum mariae-lebouriae*, which undergoes a 240-km seasonal subsurface transport from the lower bay in mid-winter to the northern bay in early summer. The translocation is effected in 3 steps: (1) the submergence of a surface population in the lower bay at a convergence zone; (2) an up-estuary transport of a subsurface chlorophyll maxima below the pycnocline via net nontidal flow; and (3) a transport from bottom water to the surface to form blooms in the upper estuary. Steps 1 and 2 have been well documented (Tyler and Seliger, 1978, 1981). The exact mechanisms which result in the transfer of subsurface concentrations of the phytoplankton and their nutrient-rich waters to the surface is the subject of this investigation.

Rhodamine dye and the dinoflagellate *Prorocentrum mariae-lebouriae* are used as Lagrangian tracers to follow the surfacing of a subsurface chlorophyll maxima in frontal regions. The production of an intermediate near-surface bloom as well as wind-induced bloom formation are also demonstrated. In a separate paper (Tyler et al., in preparation), physiological responses of various sympatric species of phytoplankton in this area are measured and their responses interpreted in light of their diverse geographic origins and disparate nutrient and light preconditions (prehistory).

**Methods of collection and measurement**

The area investigated encompassed the northern portion of the Chesapeake Bay from Lat. 38°45'N to 39°20'N (Fig. 1). Measurements of temperature and conductivity were made with a Plessey System CTD, Inter-Ocean ICTI's Model 513 and Chesapeake Bay Institute flow cell ICTI. Water samples for vertical profiles were taken with a submersible impeller pump with a 0.4 liter rain maximum flow rate. Current vectors were measured by in-situ moorings of Endeco and Braincon current meters.

Three strings of meters were placed south of the Bay Bridge and three strings placed in the shallower area north of the Bay Bridge. Each string contained 3–4 meters depending upon depth of water. Locations of moorings were: (1) Lat. 38°58'21", Long. 76°23'43"; (2) Lat. 38°58'29", Long. 76°22'36"; (3) Lat. 38°58'22", Long. 76°22'03"; (4) Lat. 39°02'46", Long. 76°22'54"; (5) Lat. 39°02'26", Long. 76°21'25"; (6) Lat. 39°02'31", Long. 76°19'54". Current meter records encompassed the experimental period from 1 May 1980 to 12 May 1980. The locations were chosen because of the rapid change in hydrography in that area.

As the subsurface lens of *Prorocentrum mariae-lebouriae* approached the northern bay shoaling area, rhodamine dye was injected into its center (at 22 m) at Lat. 38°57'N, Long. 76°24'W (x on Fig. 1), in the central deep channel (> 30 m) of the bay. The route of the subsurface chlorophyll maxima could then be traced via Lagrangian tracer. Rhodamine dye injection was made by trailing a hose at depth from the stern of the ship. Three-hundred-seventy liters of 20% rhodamine dye were injected as a 100-m trail into a 22-m subsurface chlorophyll (*P. mariae-lebouriae*) maximum, on a flooding tide. Three ships monitored the progress of the dye plus the organism distribution over a seven-day period by continuous vertical profiles of temperature, conductivity, dye fluorescence, chlorophyll fluorescence, and whole water samples for cell counts. Daily monitoring occurred at the same stage of the tide (three hours each side of maximum flood) to minimize variations due to non-synoptic sampling. Turner fluorometers, Model 111 and Turner Designs fluorometer, Model 10 were used to monitor fluorescence. Final dye concentrations, corrected for temperature and regional background fluorescence, were determined by spectrophotometric measurements.

Chlorophyll *a* standing crops were determined by in-vivo fluorescence calibrated with acetone extracted samples using the fluorometric techniques (Loftus and Carpenter, 1971). Phytoplankton cell counts were made on board ship or preserved in lugols and enumerated later in the laboratory. Samples were counted in a Sedgwick-Rafter counting cell at 200× magnification. Dissolved oxygen concentrations were determined using the Winkler dissolved oxygen technique (Strickland and Parsons, 1968).

**Results**

**Transfer of a subsurface chlorophyll maxima to surface frontal regions**

In 1980, a subsurface chlorophyll maxima consisting of the dinoflagellate *Prorocentrum mariae-lebouriae* was monitored over a five-month period. This subsurface lens was followed for 200 km as it was transported up-estuary via net nontidal flow. During this transport, the growth rate of *P. mariae-lebouriae* is minimal (µ < 0.05 d⁻¹). To determine which physical mechanisms result in the transfer of *P. mariae-lebouriae* from bottom waters into surface waters of the northern bay at the end of its journey, rhodamine dye was injected into the subsurface lens and followed over a 6-d period. Fig. 2 illustrates the time course of the dye in bottom waters subsequent to its injection on 7 May 1980. Dye concentrations are expressed in parts per billion. Lowest plotted value is 10× limit of detection. Fig. 2A illustrates the position of the dye "below" the pycnocline approximately six hours after its injection into the bottom water *P. mariae-lebouriae* lens. While the injection point occurred well south of the Bay Bridge, the flooding tide has carried the dye to the latitude of Sandy