CHARLES C. SARABUN, ALAN BRANDT, MARY A. TYLER, and GORDON D. SMITH

BIOLOGICAL TRANSPORT, INTERNAL WAVES, AND MIXING IN THE CHESAPEAKE BAY

The interactions between the biological and physical systems in the Chesapeake Bay are rather complex. This article discusses the problem of anoxic waters in the Bay and how the onset of anoxic conditions relates to the physical oceanography of the Bay. A field test conducted in May 1984 revealed significant high-frequency internal wave activity with significant implications for physical mixing, biological community evolution, and sampling strategies.

THE RESOURCES AND PROBLEMS OF THE CHESAPEAKE BAY

The Chesapeake Bay has long been a major source of several commercially important seafood species, among them blue crabs, oysters, menhaden, bluefish, striped bass, and white perch. An abrupt and marked decline in the production levels of some of these species prompted Congress in 1976 to establish a 5-year water-quality program for the Bay under the direction of the Environmental Protection Agency (EPA). The technical program, which was concluded in 1981, culminated in a series of reports published in 1983.[1-4] Reference 4 provides an overview of the entire study and a list of specific recommendations to improve water quality. These recommendations emphasize the control of nutrients from water treatment plants and urban and agricultural runoff, and the monitoring and control of the levels of toxic compounds.

One of the principal reasons for concern about nutrient levels in the Bay, particularly nitrogen and phosphorus, is the strong historical correlation between an increase in these nutrient levels and a decrease in dissolved oxygen in the deeper areas of the Bay. The mechanism underlying this connection is postulated to be an increase in algae growth resulting from the increase in nutrients—algae that ultimately fall to the bottom, become light-limited, and die. Bacteria attack the dead cells, and this process of decay consumes large amounts of dissolved oxygen from the water. The decrease in dissolved oxygen levels is hypothesized to be a major contributor to the decline in the harvest levels of several commercially important species.

In response to the problems highlighted in the EPA study, the Johns Hopkins community initiated a multidisciplinary effort to address some of the issues, first concentrating on the reduced levels of dissolved oxygen. The team now consists of biologists and physical oceanographers from the Homewood Campus, the Applied Physics Laboratory, the Chesapeake Bay Institute, and the University of Delaware. This article discusses the physical and biochemical processes that contribute to the reduced oxygen levels and the impact that these processes have on sampling techniques and analyses of data.

OXYGEN DEPLETION IN THE CHESAPEAKE BAY

A lower-than-normal level of dissolved oxygen in an ecosystem like the Chesapeake Bay is a condition referred to as hypoxia. The extreme case of a total absence of dissolved oxygen is called anoxia. Anoxia occurs annually from May to September in the deeper waters of the central region of the Chesapeake Bay and generally extends from Baltimore to the mouth of the Potomac estuary.[5,6] At its peak, the condition may exist in over five billion cubic meters of water. Large numbers of benthic organisms as well as deep-water planktonic species may be killed in the central Chesapeake during the summer when increased temperatures (which increase respiration rates) and extended exposures to low oxygen levels exceed their tolerances. The biota affected include oysters, clams, other mollusks, coelenterates, crustaceans, worms, algae, phytoplankton, and fish in various states of development. Crab pots are often filled with dead crabs, and sediments are black and foul smelling. The invasion of anoxic waters into the shallows can result in massive fish kills and crabs actually leaving the waters. The suitable feeding habitat for finfish is greatly reduced during this summer season, particularly for species such as spot and croaker, which feed on the bottom (cf. Ref. 5).

Over the past three decades, the spatial extent of the anoxic bottom waters appears to have increased.[4] Figure 1 contrasts the affected areas for the years 1950 and 1980. In recent years, low-oxygen water has been reported somewhat farther south, near the mouth of the Bay, in addition to a cross-estuary spreading from the Bay proper into the shoals and deeper tributaries.[6] Vertical sections through the spine of the Bay (shown in Fig. 2) show that anoxic waters existed within 12 meters of the surface in 1980, whereas anoxia was confined to the deep trenches, deeper than 24 meters, in the northern Bay in 1949-50. One of the

Figure 1—The area of Chesapeake Bay bottom affected by low dissolved oxygen levels: (a) summer 1950, and (b) summer 1980.[5]

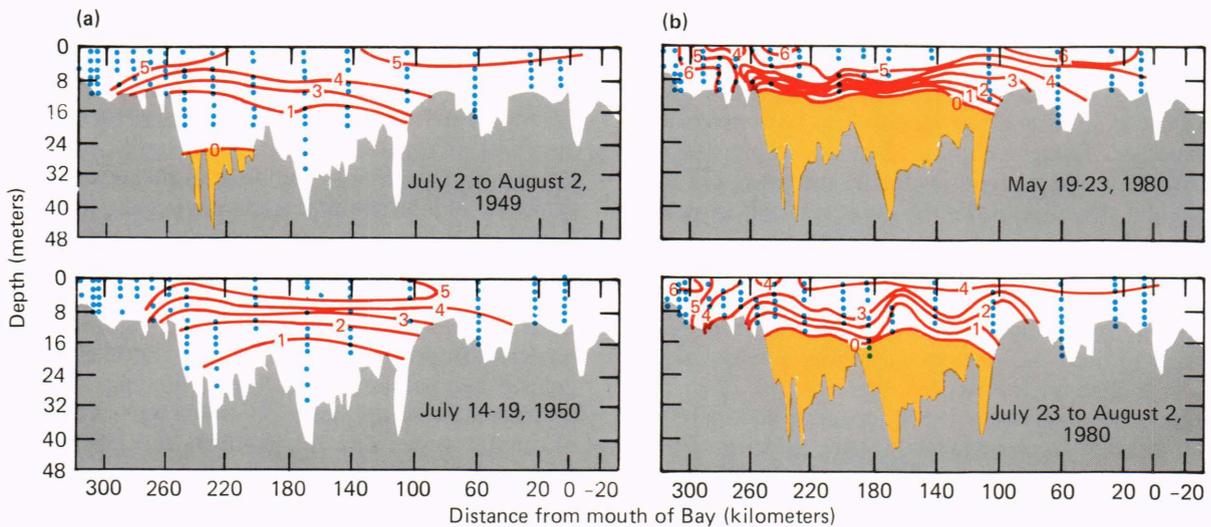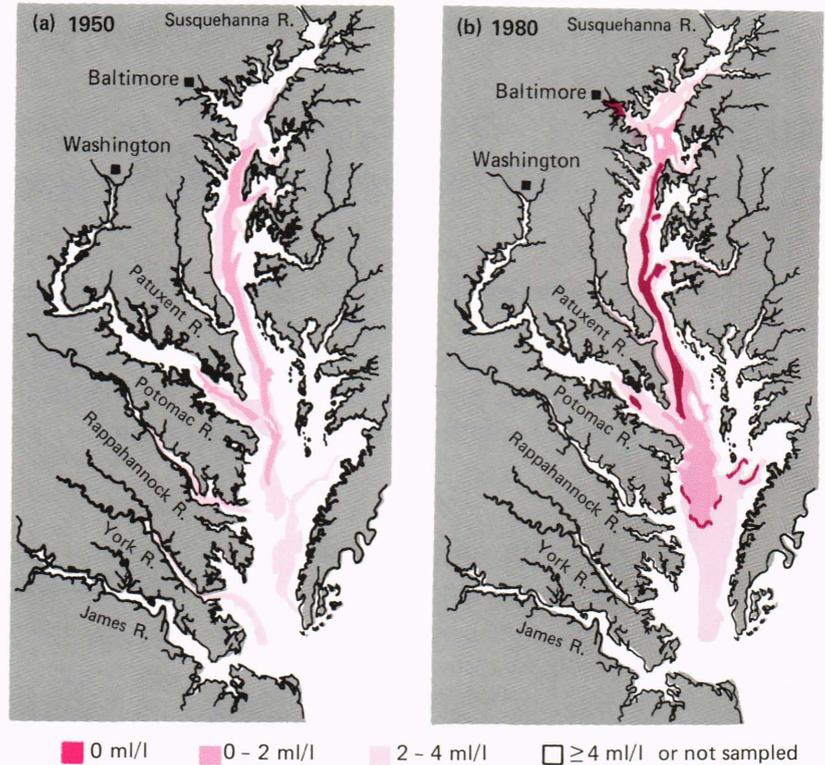■ 0 ml/l　■ 0 – 2 ml/l　■ 2 – 4 ml/l　□ ≥ 4 ml/l　or not sampled

Figure 2—Numbers are dissolved oxygen levels (milliliters per liter) along the main channel of the Chesapeake Bay (a) in summer 1949 and 1950, and (b) in summer 1980. Dots indicate measurement locations.[5]

most severe years of record anoxia was 1984, when the pycnocline extended to a depth of 6 meters before the fall overturning.[6]

Figure 3 shows that the duration of anoxia also appears to have changed since the late 1930s. Analysis of historical data sets, collected for three consecutive years in the 1930s, indicates very brief anoxic episodes lasting from days to weeks. However, in the years since 1970, reports of anoxia in the mid-channel of the Bay show anoxic conditions commencing in late May and extending into September. Major tributaries such as the Patapsco, Chester, Patuxent, Potomac, and Rappahannock Rivers have significant anoxic episodes, usually commencing in late June and extending into September.

Conceptually, the development of anoxia can be directly related to the onset of stratification in the Bay, which, in turn, is governed mainly by the spring river flow "pulse."[5,6] Large spring runoff events create a strong two-layered system with fresh water overlay-
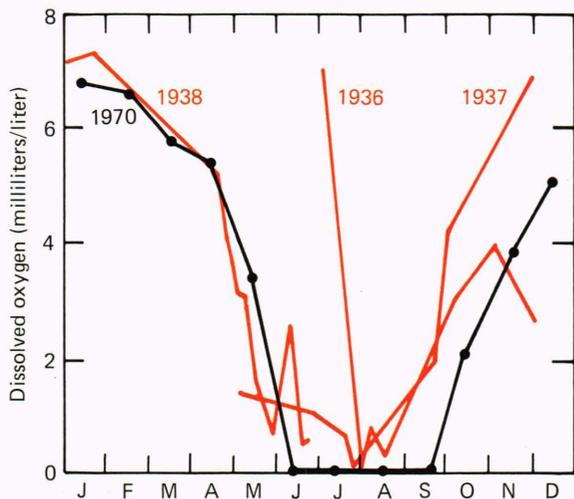
Figure 3—Comparison of seasonal dissolved oxygen levels at 20-meter depth at a station in the Chesapeake Bay channel off the mouth of the Patuxent estuary, 1936 to 1938 and 1970.[5]

so that stratification was greatly reduced and more mixing between surface and bottom layers took place. As a result, extensive, prolonged anoxic conditions did not develop in 1981. These data suggest that there is a close relationship between the river runoff, the degree of stratification, and the oxygen concentrations (and hence the extent of anoxia) in the bottom waters of the Bay.

ANOXIA AND THE FOOD CHAIN

One effect of extensive anoxic waters on the Bay biota may be seen in the shift of the dominant phytoplankton species from a diatom-dominated system characteristic of clear unpolluted waters to one in which flagellates prevail.[7] Early historical reports[5] on the middle and upper Bay show a summer minimum of dinoflagellates and prominent spring and fall-winter maxima dominated by diatoms. Today the same region shows a summer maximum dominated by small flagellates and a sparse showing of diatoms in later winter and spring.

One reason for the shift lies in the phytoplankton's range of responses to the ambient environment encountered as they are transported northward by the gravitational circulation, as reported by Tyler and Seliger;[8,9] the transport pathway process is shown in Fig. 6. Upon encountering anoxic waters during their northward transport, the dinoflagellate *Prorocentrum* swims upward to a point just below the pycnocline to avoid the oxygen-depleted waters; however, diatoms cannot swim upward to avoid the anoxic regions. When diatoms encounter these anoxic waters, they sink to the bottom and are deposited in the sediment, where their survival as a seed population is not likely, as shown by Davis et al.[10]

Because the effect of anoxia may propagate up the food chain, it is important to examine what consequences, if any, anoxic conditions can have at the higher trophic levels. Many larval forms of fish, as well as macro- and micro-zooplankton, use the same sub-
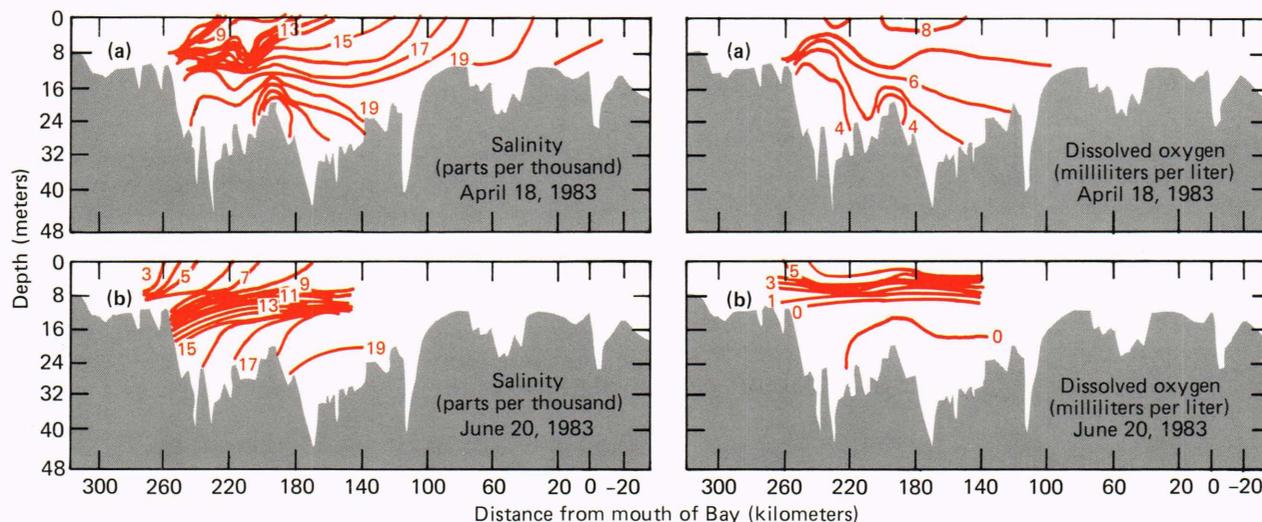
ing the more saline coastal waters, one consequence of which is the curtailment of the vertical transfer of oxygen across the sharp halocline. Increased biomass deposition and benthic processes in late spring deplete the oxygen supply in bottom waters. However, anoxia may not develop if the water column does not stratify significantly. For example, 1983 was a high-runoff year, and strong stratification developed in mid-April, peaked the first week in May, and continued into late June (Fig. 4). Oxygen depletion occurred rapidly, starting in the deep hole just below the Bay Bridge, moving southward, and eventually moving into the tributaries. In late May and June, the anoxia was readily evident at depths below 12 meters. In contrast, 1981 was a drought year with a minimal spring river-flow pulse as shown in Fig. 5. Near-surface water salinities in April and May remained high (11 parts per thousand as compared with 3 parts per thousand in 1983),

Figure 4—Axial distributions of salinity and dissolved oxygen for (a) April 1983, and (b) June 1983.
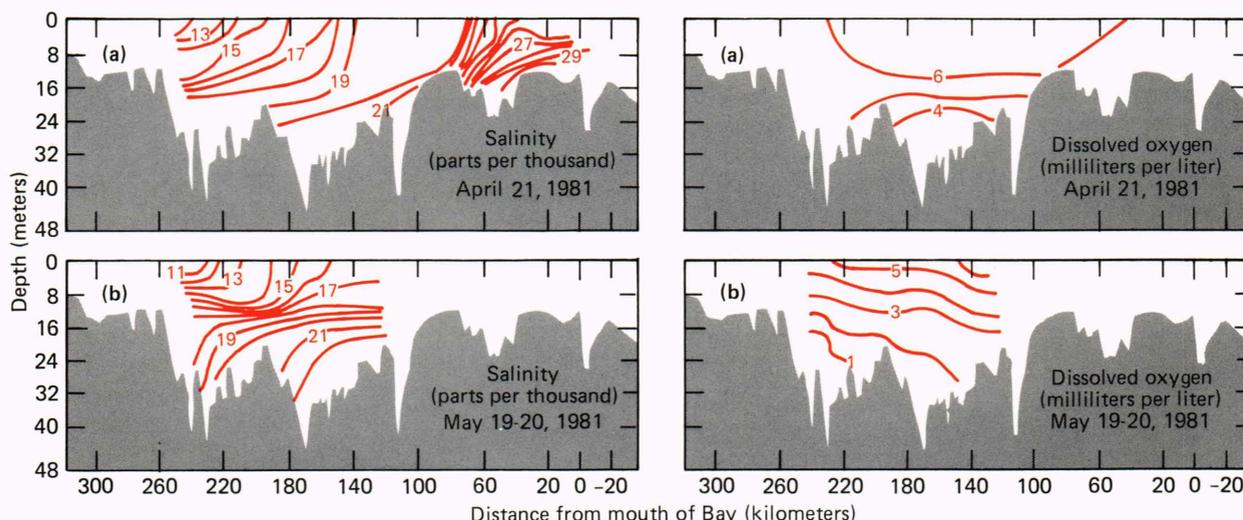
Figure 5—Axial distributions of salinity and dissolved oxygen for (a) April 1981, and (b) May 1981.
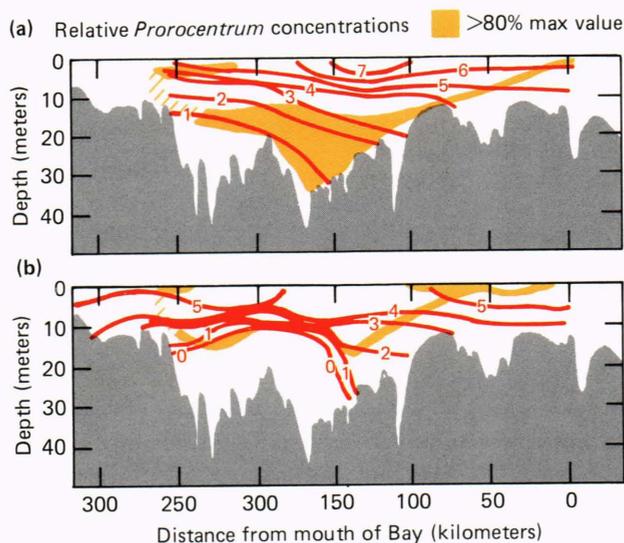

Figure 6—Axial distributions of *Prorocentrum* and dissolved oxygen (in parts per million): (a) May 1975, and (b) June 1978.

Figure 7—Vertical distribution of acoustic scatterers in the lower Chesapeake Bay in late spring (Tyler, unpublished data). The pycnocline is at 14 meters.

surface transport route as do *Prorocentrum* as part of their seasonal migration circuit.[11,12] If anoxia develops at the northern portion of the route during a critical period for delivery of these organisms, it may affect them severely. In 1983, anoxic conditions developed below the pycnocline at the Bay Bridge during the second week in May, the critical spawning period for many higher trophic level species. Figure 7 is a vertical profile of organism distributions that shows bacteria, *Prorocentrum*, and the mysid shrimp *Neomysis americana* accumulated below the pycnocline and just above the anoxic layer. Tows in that mid-depth organism maximum produced larval anchovy, and reports by numerous fishing boats in the area indicated that bluefish were being caught at about 30 feet (9 meters), approximately the depth of the pycnocline.
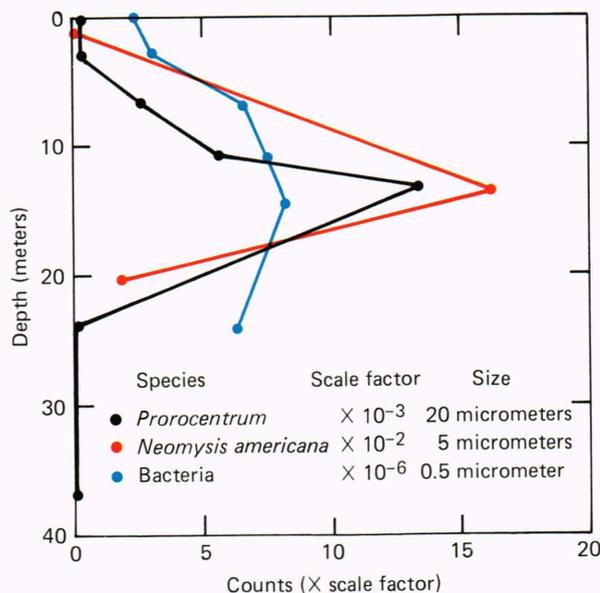
These data illustrate the extreme degree to which life-supporting conditions can be confined to a very narrow, subpycnocline band and be impressed on a large part of a particular food chain during strong anoxic conditions. While evidence does not establish a direct link between anoxia and the status of higher trophic levels, these data do show that a significant impact is possible.

STRATIFICATION, CIRCULATION, AND MIXING

As discussed above, there appears to be a direct relationship between the degree of vertical stratification

(especially during the critical spring high-runoff period) and the onset and severity of anoxic events in the Chesapeake Bay. A principal physical consequence of increased stratification is the inhibiting effect that it exerts on the vertical mixing processes that tend to homogenize the water column.

The processes affecting the degree of vertical mixing can be classified on the basis of three time scales: seasonal processes, short-term processes, and very short-period, small-scale mixing processes. Within the first class, there are two major forces working to affect the degree of stratification: solar heating and fresh water inflows. On the short-term, subseasonal time scales, the principal forces are wind, spring neap-tidal variations, the tidal variations themselves, long-period internal waves, cross-Bay seiching, and diurnal variations in heat flux. Finally, in the third class are the very short-period internal waves and convective, turbulent, and mixing processes. Each of these temporal classes of physical phenomena plays a direct role in developing, maintaining, or destroying the degree of vertical stratification.

In the Chesapeake Bay, the principal driving force on the seasonal time scale is fresh water inflow, primarily from the Susquehanna River. This river influx establishes the gravitational estuarine circulation and, hence, the efficacy of the subsurface transport pathway that is so important to the biological communities.

The gravitational estuarine circulation is a consequence of the mixing of fresh river water with the saline ocean water from the continental shelf. In the Chesapeake Bay during the spring runoff period, the Bay is basically a two-layered system (Fig. 8) with the fresher, lighter river water flowing over deeper, more saline water from the continental shelf. The boundary between the fresh river water and saltier deep water is called the halocline. As the fresh water moves toward the Bay mouth, salt from the deep water is mixed upward, increasing the salinity of the outflowing water. Thus, more saline ocean water must be continually transported inward in the deeper waters to furnish the salt mixed upward across the halocline. The end result is the estuarine circulation pattern of inward-flowing deeper (and more saline) water and outward-flowing surface waters.

During the maximum river-flow period, the boundary between the two layers is very sharp, and vertical mixing is suppressed. The reduced mixing reduces the requirement for replacement salt in the lower layers, effectively reducing the strength of the estuarine circulation. During periods of lower river flow, the halocline may be weaker (thicker and with a reduced salt gradient), resulting in increased vertical mixing of salt and, consequently, a stronger estuarine circulation. This process has been illustrated in numerical experiments by Wang and Kravitz.[13]

The degree of vertical mixing has important consequences for the biological communities in the Bay, especially with respect to the development and maintenance of anoxic conditions. When the halocline is strong enough to suppress vertical mixing, there is an
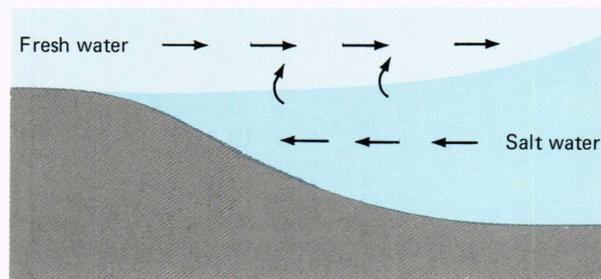

Figure 8—Schematic diagram of vertical salt-flux-driven estuarine circulation in an idealized estuary. Salt is mixed upward into fresh river water as it flows seaward. This process requires an influx of saltier water at depth to replace the salt mixed upward.

effective isolation of the deeper layer from both the downward mixing of dissolved oxygen and the subsurface transport of more oxygenated water from the mouth of the Bay.

Thus, on longer time scales, factors that control the degree of vertical stratification are important to the primary biological processes associated with anoxic conditions. However, the dynamics of the mixing processes themselves have important effects at much shorter time scales. At time scales of hours to weeks, there are a number of physical mechanisms that can impart significant energy to the processes that result in mixing. The largest energy source is, of course, tidal, but other mechanisms such as wind forcing, internal waves, and seiching can also be important. The actual dynamics of these mechanisms is only now being studied as other than a mean, averaged effect. Studies such as the one by Partch and Smith[14] have shown that, for a strongly two-layered system, significant vertical exchange at the interface may occur during limited portions of the tidal cycle and is often related to the breaking of internal waves.

This may also be true in the Chesapeake Bay. Figure 9 shows a time series of salinity from the Chesapeake Bay just below the Bay Bridge, obtained in the spring of 1983. The contours were derived from hourly profiles made from an anchored ship. Even though the data are sparsely sampled in time, the time series shows several wave-like events in which significant vertical displacements occur. Similar phenomena have also been observed in the Delaware Bay.[15] These and other data suggest that during stratified conditions in the Chesapeake Bay one could expect to encounter significant internal-wave activity as well as localized regions of strong turbulent mixing. Because of the implications of such processes on the transport-dominated biological communities in the Chesapeake Bay, a multidisciplinary team was formed within The Johns Hopkins University community to study the problem. In the spring of 1984, two 5-day cruises were conducted as part of an initial field study.

SHORT-PERIOD, SUBTIDAL PROCESSES

The multidisciplinary field study conducted in the spring of 1984 was focused primarily on short-period
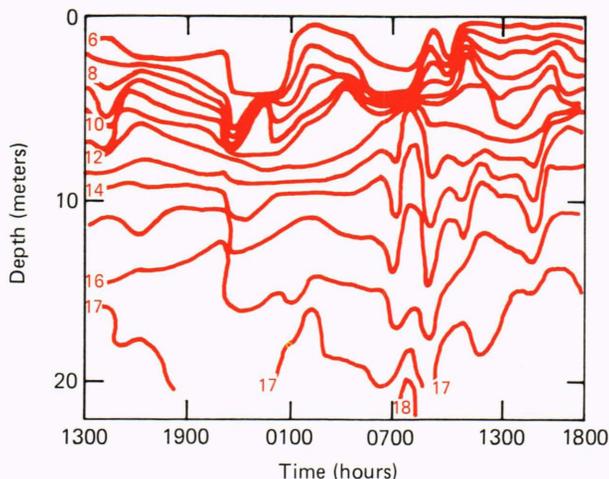
Figure 9—Thirty-hour time series of salinity from late spring, just below the Chesapeake Bay Bridge (Tyler, unpublished data). Numbers on contours are salinities in parts per thousand.

Figure 10—Thermistor-chain system, which measures the temperature fluctuations associated with vertical displacements of the water column. The observed temperature fluctuations are indicative of internal-wave and turbulent mixing activity.
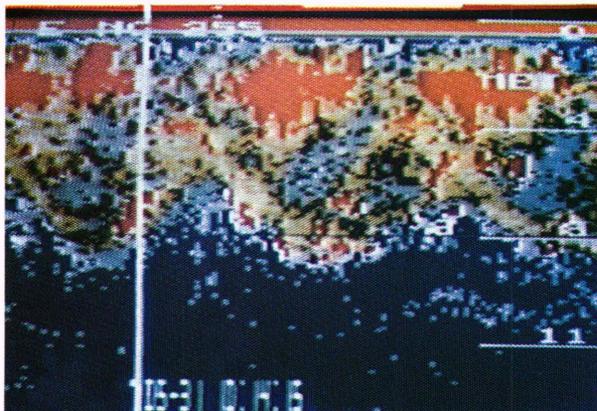
(less than the tidal period) processes. During the two cruises, research vessels occupied a series of stations at fixed locations along the axis of the upper Bay. Each station was occupied for one to two tidal cycles (13 to 26 hours). The primary physical oceanographic instruments deployed were a conductivity-temperature-depth profiler, a current meter used in a vertical profiling mode, a 200 kilohertz narrow-beam acoustic echo sounder, and a 10-element, high-frequency-response thermistor chain array. Figures 10 and 11 show photographs of the thermistor chain and the real-time display from the echo sounder. These instruments were the key for measuring high-frequency processes.

Figure 12 shows a "conventional" time-series of salinity and axial tidal currents during one of the 26-hour observations. These series show the tidally driven evolution of the velocity and salinity fields. What they do not show is the high level of activity at much shorter periods.

The echo sounder and thermistor-chain data from this time period show strong, high-frequency internal-wave and mixing activity in the middle of the water column. Figure 13 is a gray-scale encoded plot of acoustic backscatter intensity for a short portion of the 26-hour period. A train of high-frequency (1- to 2-minute period) internal waves is clearly evident, with the largest waves attaining wave heights of 6 to 7 meters. Between the wave crests of the largest waves are clouds of acoustic scatterers that have been concentrated by convergences in the wave's velocity field. During this period, the acoustic scatterers were small zooplankton (copepods) that accumulated in the pycnocline along with the algae.

Figure 14, thermistor-chain records taken at about the same time as the echo sounder record in Fig. 13, also shows the large-amplitude internal waves. In Fig. 14, two wave packets are evident as periodic, wavelike changes in temperature. Associated with the 1- to 2-minute waves are bursts of high-frequency turbulent fluctuations with periods on the order of seconds. In

Figure 11—Two-hundred-kilohertz echo sounder system. A narrow-beam acoustic pulse is projected that reflects off zooplankton in the water column. The intensity of the backscattered sound is related to the density of zooplankton in the water column.

Fig. 15, thermistor data from a different location in the Bay give evidence of long-period internal waves (20- to 30-minute periods), high-frequency internal waves having approximately 1- to 2-minute periods, and turbulent motions with fluctuations measured in
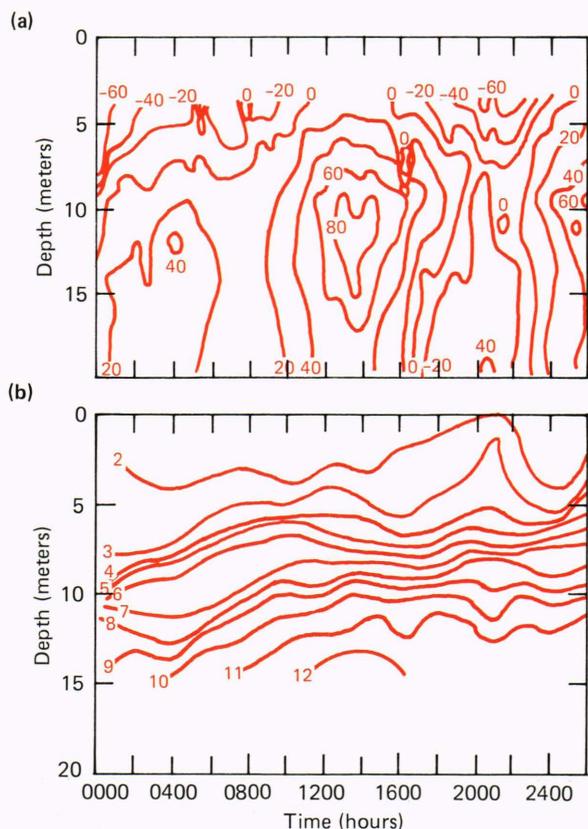
(a)

(b)

Figure 12—Time series of vertical distributions of (a) axial tidal currents (in centimeters per second), and (b) salinity (in parts per thousand) for the 26-hour station occupied on May 30, 1984, just south of the Chesapeake Bay Bridge.

Figure 13—Time series of gray-scale encoded acoustic back-scatter intensity versus depth, taken at a station just below the Chesapeake Bay Bridge on May 31, 1984.

sonal controlling factor in the Chesapeake Bay, much of the vertical mixing resides in phenomena having considerably shorter time scales. It follows, therefore, that any realistic attempt to understand the Bay's biological and chemical processes must, of necessity, be carried out in close conjunction with the study of the physical transport and mixing processes that can have such a profound effect.

IMPLICATIONS FOR MEASUREMENT STRATEGIES

As we have seen, the biological systems in the Chesapeake Bay can be strongly influenced by physical transport and mixing processes. In particular, the physical dynamics will play a major role in determining the spatial and temporal distributions of biological activity. On a long-term mean basis, the estuarine circulation coupled with the physiology of the organisms gives rise to a strong layering in the vertical and intermittency in the horizontal and temporal dimensions. This interaction means that sampling strategies must take account of these factors in order to monitor properly the seasonal development and distribution of the biological organisms. For example, Fig. 6

seconds. (Note that the temperature scale on Fig. 15 is about four times larger than that on Fig. 14.)

The spring 1984 data graphically illustrate the energetic nature of high-frequency activity present in the Bay. While the mean stratification is an important *sea-*
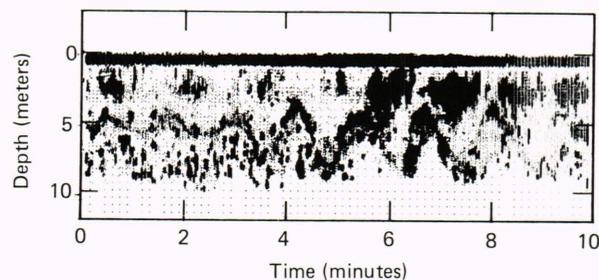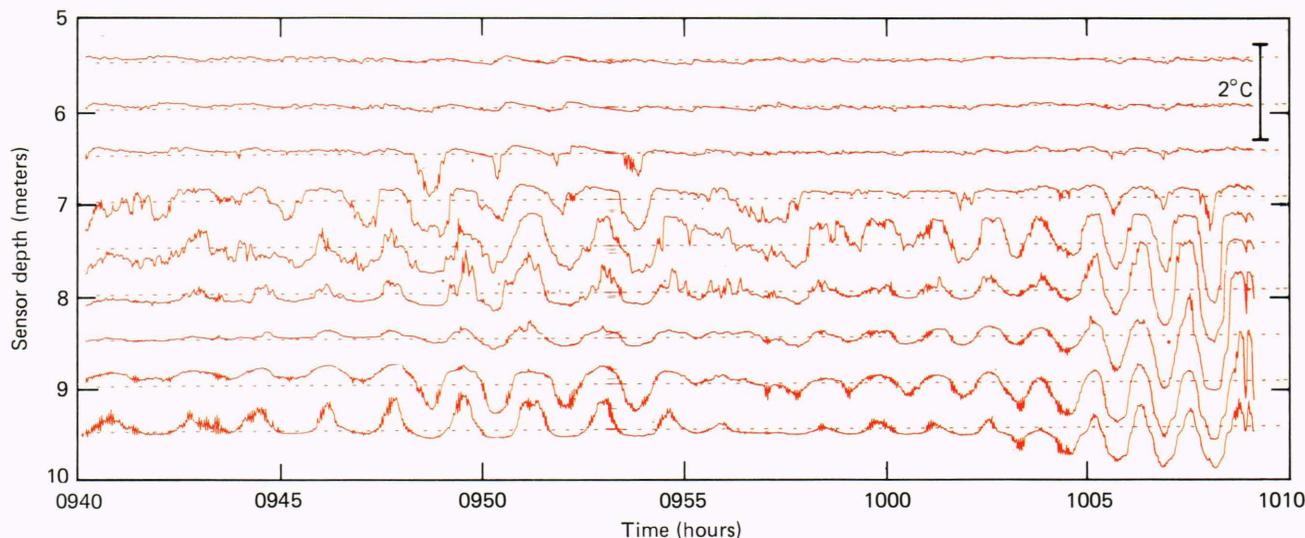

Figure 14—Time series of temperature for the thermistor chain for May 31, 1984, taken just below the Chesapeake Bay Bridge. Thermistors are separated by 0.5 meter. Note the two wave packets between time periods 0945-0955 and 1002-1009.
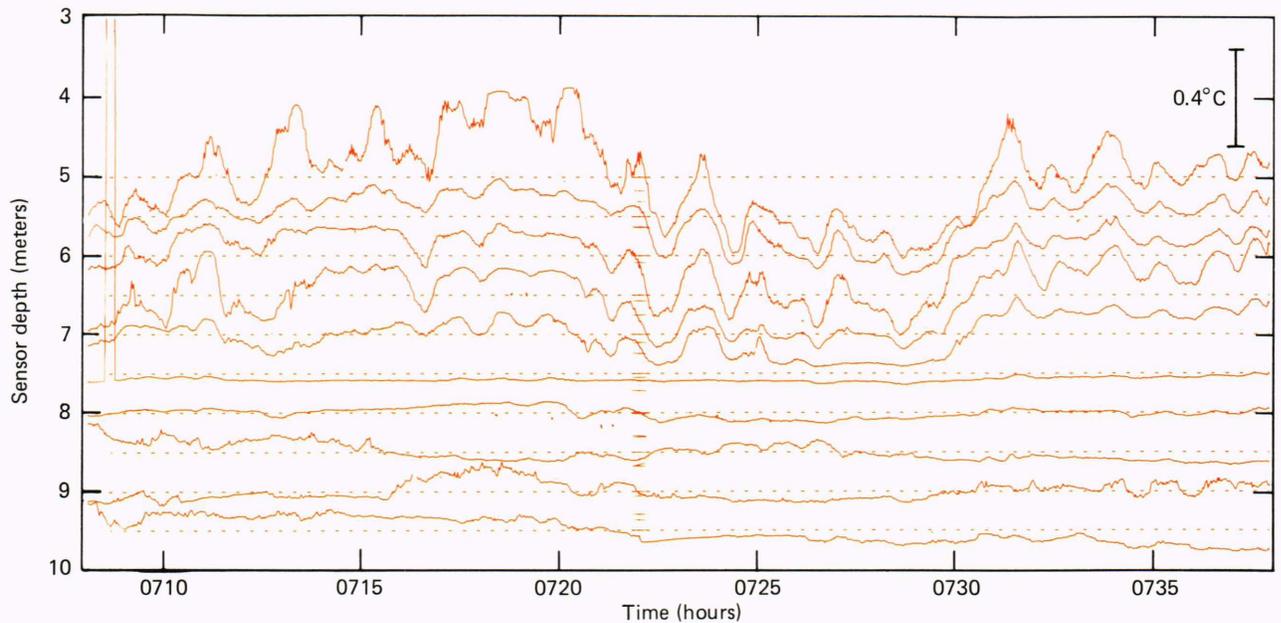
Figure 15—Time series of temperature for the thermistor chain from May 24, 1984, taken in mid-Bay just south of Tilghman Island. Thermistors are separated by 0.5 meter. Note the difference in character from the more organized traces in Fig. 14.

shows clearly that sampling at a limited number of preset depths might easily miss the rather thin layer of *Prorocentrum* at mid-depth.

The sampling problem is further complicated by energetic motions at time scales much shorter than seasonal. In addition to the periodic effects of the tides, wind and internal wave activity can significantly affect the depth in the water column at which high concentrations of organisms can be found. The short-period internal waves shown in Figs. 13 through 15 have crest-to-trough heights of up to 25 percent of the total water column depth. A water sample drawn from a depth of 8 meters at the time the data shown in Fig. 13 were obtained could be in the pycnocline, above it, or below it, all within the space of less than 2 minutes. In addition, there is the problem of when (or where horizontally) to sample. The high-frequency, strongly nonlinear internal waves have two further compounding effects apart from the periodic vertical displacement of layers. The periodic velocity field associated with the internal waves gives rise to convergence zones between the crests that have resulted in the concentration of scatterers between the crests, as seen in Fig. 13. Thus, if one were to sample in a region clearly above the greatest vertical displacement of the pycnocline, one must still contend with the spatial/temporal intermittency engendered by the internal-wave velocity field. Also, periodic breaking of the internal waves can occur, resulting in actual physical exchange across the pycnocline.

To complicate further an already complex situation, even where there is no clearly evident physical mechanism to break up the biological layers, "patchiness" may still occur. Figure 16 is an acoustic backscatter series from the Chester River in which no strong internal-wave activity is present, but in which the in-
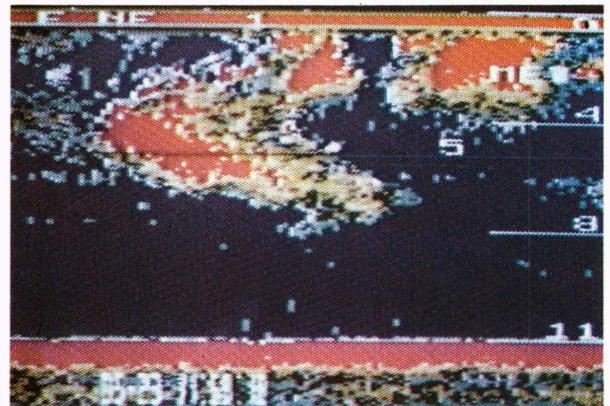

Figure 16—Time series of color-encoded acoustic backscatter intensity from the Chester River in May 1984. Strong scattering intensities are coded red, while regions of little or no backscatter are coded dark blue. Note the "clouds" of zooplankton scatterers separated by regions of little or no backscatter.

termittent character of the zooplankton density is clear.

The effects discussed above have a strong impact on monitoring strategies and analyses based on the historical database. It is clear from the evidence presented that single-profile, preselected depth sampling of important biological and chemical parameters is inadequate to describe the real state of the Bay. Any realistic attempt to monitor Bay quality must base its sampling strategy on the expected range of the short space-and-time variability to be encountered during the monitoring period.

Equally important are the implications with respect to historical data. The potential for misrepresenting the nature of the biophysical processes, which results

from inappropriate sampling rates, is significant, so that poorly designed sampling and averaging techniques can distort a true picture. More important, however, is the question of the utility of the large volume of single-profile data in the historical database. As shown above, a grossly inaccurate picture can result from a simplistic sampling strategy that relies on a single-profile, fixed-depth pattern. The specialized case of "slack water" sections is an appropriate example. A two-tidal-cycle average profile of salinity computed from the time series shown in Fig. 12 is compared with (or contrasted to) slack-water profiles in Fig. 17. The shape of the average profiles during this period is clearly much different from the slack-water profile, especially with respect to depth of salinity isopleths.

Finally, the direct impact of large-amplitude internal waves on the biological communities may be significant. Because of the exponential dependence of light transmission with depth, it has been estimated that vertical oscillations of 6 to 7 meters induced by internal waves can alter the light level available to phytoplankton trapped at the pycnocline by three orders of magnitude in just a few minutes. Thus, while "mean" pycnocline depths may serve to describe adequately the seasonal transport cycle, they are entirely inadequate to describe the amount of light available to phytoplankton, in an integral sense, as they are transported along the pathway.

In what we have shown, it is clear that while one may describe what one believes occurs during the seasonal cycle, the interpretation of historical data and the field measurements of biological and physical variables that are important are anything but simple.
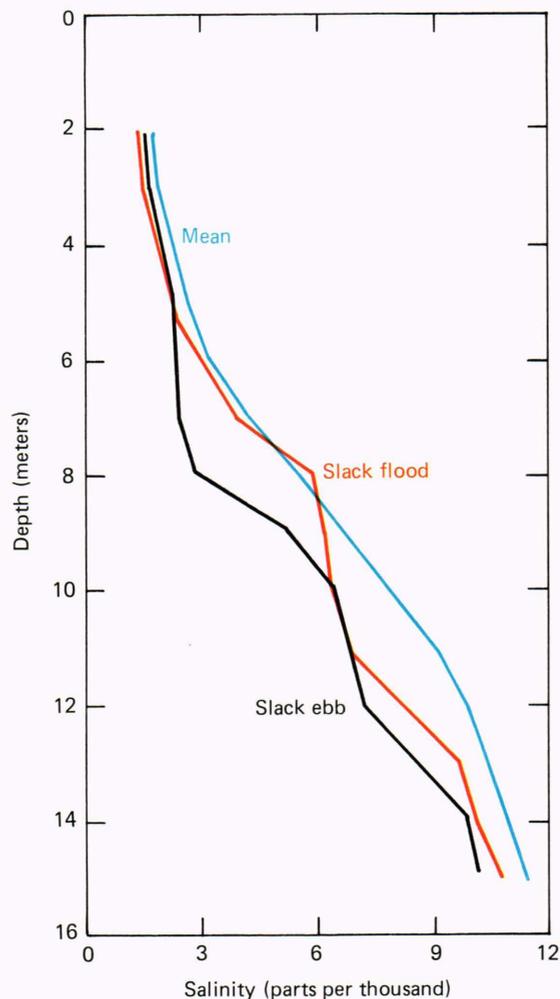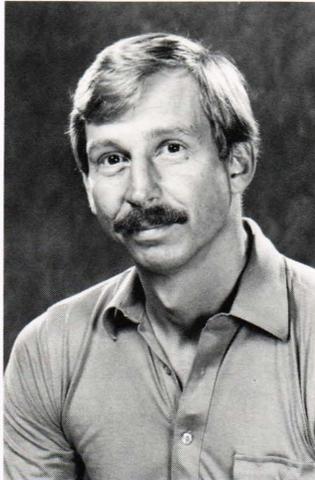

Figure 17—Vertical profiles of salinity from the 26-hour station located just below the Chesapeake Bay Bridge. Plotted are the 26-hour average profile and the profiles at slack after flood and slack after ebb for one tidal cycle.

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THE AUTHORS

CHARLES C. SARABUN, Jr., received a B.S. in mathematics from Rensselaer Polytechnic Institute in 1969, an M.S. in applied mathematics and computer science from the University of North Dakota in 1973, and a Ph.D. in marine science from the University of Delaware in 1980. After serving in the Air Force as a missile launch officer, he moved to Delaware where he worked as a marine scientist for the University of Delaware from 1976 to 1977. In 1977, he worked for Roy F. Weston, Inc., as a mathematical analyst/modeler. From 1977 until he joined APL in 1979, he was a self-employed consultant. At APL he is a member of the Environment Group of the Submarine Technology Department and also holds an appointment as a research scientist with the Chesapeake Bay Institute.

MARY A. TYLER is associate program director for the Biological Oceanography Program at the National Science Foundation in Washington. She is presently on leave from her faculty position in the College of Marine Studies at the University of Delaware in Lewes. She also holds a research position with the Chesapeake Bay Institute of Johns Hopkins. She received her bachelor's degree from Smith College in Northampton, Mass., in 1972 and a Ph.D. in 1977 in biology from The Johns Hopkins University. From 1977 to 1980, Dr. Tyler conducted research at the Chesapeake Bay Institute. In 1980, she joined the faculty as an assistant professor of oceanography at the University of Delaware. Dr. Tyler has been studying the Bay for the past 12 years. Her research interests encompass the mechanisms of plankton transport via surface and subsurface currents. She is also involved in characterizing the adaptive strategy of phytoplankton as they are translocated in bottom waters below the euphotic zone.

ALAN BRANDT was born in New York City in 1939. He received the B.C.E. degree from the Cooper Union (1959) and the M.S.C.E. (1963) and Ph.D. (1966) degrees in civil engineering and fluid dynamics from Carnegie Mellon University. In 1965, he joined APL, where he worked on the fluid dynamics and combustion of missile propulsion systems and on the flywheel energy-storage program. During 1971, Dr. Brandt was at Imperial College, London, where he did research in turbulent flow. Since his return, he has been engaged in laboratory modeling of hydrodynamic flows and ocean data analysis for the Submarine Security Technology Program. Most recently, he has been involved in developing multidisciplinary programs on estuarine and coastal oceanography, initially focusing on the Chesapeake Bay. He is group scientist in the Hydrodynamics Group and a senior scientist at the Chesapeake Bay Institute.

GORDON D. SMITH is the program manager for the Environmental Science Programs in the Submarine Technology Department and is a member of APL's Principal Professional Staff. He received the B.E.E. degree from the University of Florida in 1957 and the Ph.D. degree in 1965. He joined APL in 1958, contributed to the Transit system satellite designs over a period of five years, and then returned to graduate school. After completing his degree, he worked for Lockheed and the Bell Telephone Laboratories in the areas of communications theory and radar systems. In 1969, he returned to APL, joining the Fleet Systems Department, where he did research and development in anomalous microwave propagation. Dr. Smith transferred to the Submarine Technology Department in 1975 and investigated radar scatter from the ocean surface. This led to work in physical oceanography. He was supervisor of the Environment Group from 1977 to 1984, when he assumed his current position. He is a member of the IEEE and the Oceanic Engineering Society.