CHARLES C. SARABUN, JR., and DANIEL C. DUBBEL

HIGH-RESOLUTION THERMISTOR CHAIN OBSERVATIONS IN THE UPPER CHESAPEAKE BAY

Selected results from four years (1984–87) of thermistor chain data and coincident measurements of conductivity, temperature, and depth, current speed and direction, and acoustic backscatter are presented. The data exemplify some supertidal features that were ubiquitous during the measurement periods: subsurface intrusions with mixing and high-frequency internal waves on their surfaces; estuarine surface fronts; monochromatic, high-amplitude internal wave trains; breaking internal waves; and broadband internal wave fields. We will discuss the effects of these features on mixing and transport in estuaries and their implications for sampling strategies and the interpretation of results.

INTRODUCTION

Until relatively recently, research in the physical processes in estuaries focused primarily on tidal and seasonal time scales. Such a focus was to be expected, given the dominance of the motions at such time scales in the transport of sediments, plankton, nutrients, pollutants, and other important scalar variables. Motions at other time scales, although acknowledged, were not studied intensively until recent decades, when researchers[1-7] began to examine the importance of estuarine motions at time scales of weeks to days. Organized motion at time scales of less than a tidal cycle did not come under heavy scrutiny, for the most part, until the 1970s, when studies such as Ref. 8 showed that there were strong, energetic motions at time scales much less than tidal (e.g., fronts) that significantly affected the distribution and mixing of biologically and chemically important variables.

Recently, considerably more attention[9-15] has been paid to much higher frequency motions such as jumps, internal waves, and seiches (periodic oscillations of an enclosed body of water) and their role in the transport and mixing of important scalars. In addition to the physical studies, some investigators[16-18] began to explore the biological and other consequences of these features.

The data presented here were acquired as part of cooperative, interdisciplinary field studies with Robert Biggs (University of Delaware), Howard Seliger (The Johns Hopkins University), Mary Altalo (National Science Foundation), and Lawrence Harding (Chesapeake Bay Institute).

INSTRUMENTATION AND METHODS

Since 1984, APL has been fielding a suite of instrumentation specifically designed to study high-frequency physical processes in the Chesapeake Bay. The principal instruments are several vertical thermistor chains and a 200-kHz, narrow-beam fathometer. Instrumentation furnished by ship personnel and other investigators included a conductivity-temperature-depth-fluorescence (CTDF) profiler, a profiling current meter, and Niskin bottles for volume water samples.

Each thermistor chain had 2 to 16 thermistors with 20-ms response. Chains of more than two thermistors carried two or three Stratham pressure transducers. The thermistors had a resolution of about 0.007°C, and the pressure gauges had a resolution of about 0.01 m. The sensors were calibrated at APL before each deployment and were interfaced to Sippican bridge circuits. Data were acquired by means of an IBM PC-XT. (See Ref. 19 for more details regarding the instrumentation, calibration, and sensor specifications.) The data were actively filtered at 0.5 Hz and sampled at 2 Hz. The thermistor chains were deployed in a static mode and were weighted at the lower end. Post-test, the data were transferred to a DEC VAX 11/750 where they were edited, transformed into engineering units, and plotted. At selected intervals, the temperature traces over depth and time were converted to isotherm displacements using the mean vertical temperature profile.[20] Sample spectra of displacements or temperature variances were computed using standard fast Fourier transforms.

The fathometer was a Wesmar VS3000 color video sounder operating at 200 kHz with a pulse length of 150 μs (about 25-cm range resolution) and a pulse repetition rate of 5 Hz. The color-encoded video output was recorded on video tape; an APL modification allowed the analog backscatter intensity data to be digitized and recorded directly. The transducer was deployed at the end of a 3-in. galvanized pipe that held it about one meter below the surface. The CTDF profiles and the current profiles at a vertical resolution of 1 m typically were made every hour. The data were provided to APL on nine-track tape, and the current meter data were digitized at APL.

The data to be discussed were acquired during field tests in the springs of 1984 through 1987. Several standard stations (Fig. 1) were occupied for a minimum of 25 hours, while the ship was anchored fore and aft to minimize contamination of the chain data as a result of the ship swinging at anchor.

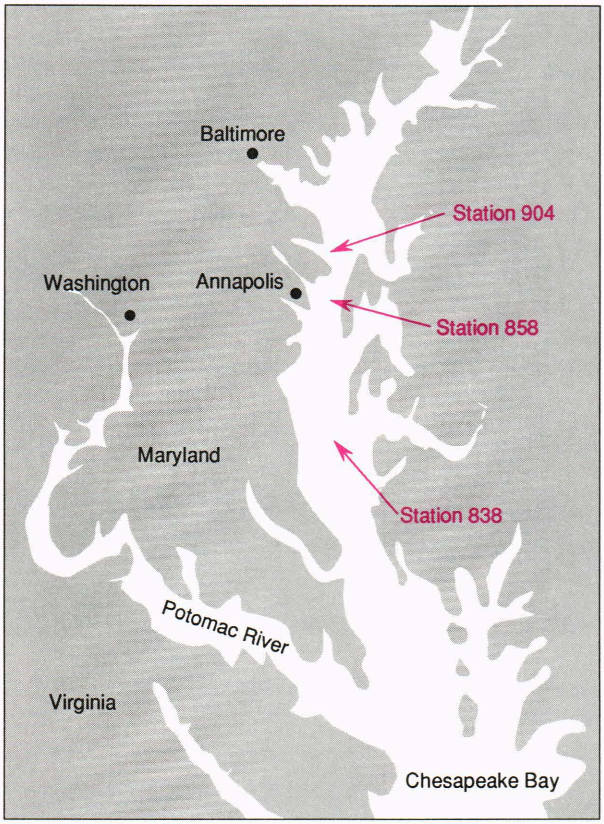

Figure 1. Standard station locations.

HIGH-FREQUENCY FEATURES IN THE CHESAPEAKE BAY

Subsurface Intrusions

While the ship was at Station 858 in May 1986, a number of subsurface intrusions passed through the station. Figure 2, an example of one intrusion, shows temperature–time series from thermistors spaced 0.5 m apart vertically across the thermocline. Note the divergence between the top and middle traces. The middle trace shows a dramatic temperature drop, suggesting the appearance of a cold intrusion at 6 m. Note also the oscillatory behavior of the temperature trace at the onset of the temperature drop, suggesting strong interfacial waves on the edge of the intrusion. The depth of this intrusion is well below the edge of the shoal areas bounding the main channel, at Station 858. It is possible that such subsurface intrusions are examples of the boundary mixing discussed by Phillips et al.[21] Both warm and cold intrusions were seen frequently in the thermistor chain data but were not obvious in the fathometer data. Virtually all of the intrusions exhibited rapid wavelike oscillations on the leading edge, as in Figure 2.

Estuarine Surface Fronts

In 1985 at Station 858, a surface foam line, usually associated with the surface convergence of an estuarine front, approached the ship. At that time, the current meter was suspended 3 m deep. The CTDF began a series of repeating, rapid vertical profiles. Figure 3 is an overplot of 7 of 16 sequential sigma-*t* ([density − 1]1000) profiles in which the progressively deeper pool of lighter water can be seen as the plume front migrated through the anchor station. It is obvious that the asymptotic depth of the front is about six meters. Figure 4 is a composite view of isotherm displacement time-series and current vectors as the leading edge of the front passed through moving west–southwest. Note the sudden drop in depth of the upper two isotherms as the front passes by the thermistor chain, while the lower two isotherms, between 7 and 8 m deep, are virtually undisturbed by the frontal passage. There is a dramatic change in current direction (shown by the arrows) as the front migrates past the station.

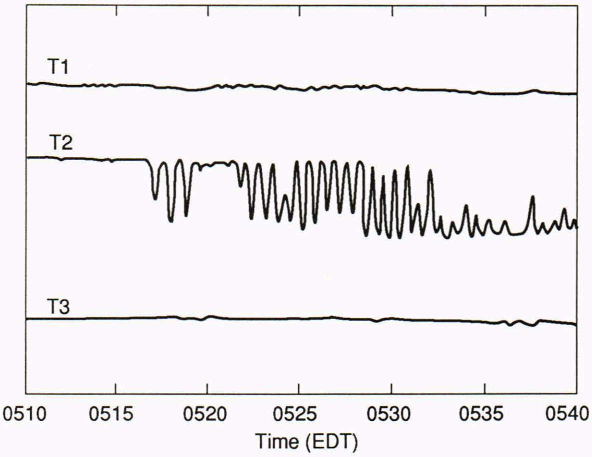

Figure 2. Temperature traces from three thermistors at 5.5 (T1), 6.0 (T2), and 6.5 (T3) m depth during the passage of a subsurface intrusion at Station 858. Note the wavelike oscillations in the middle temperature trace.

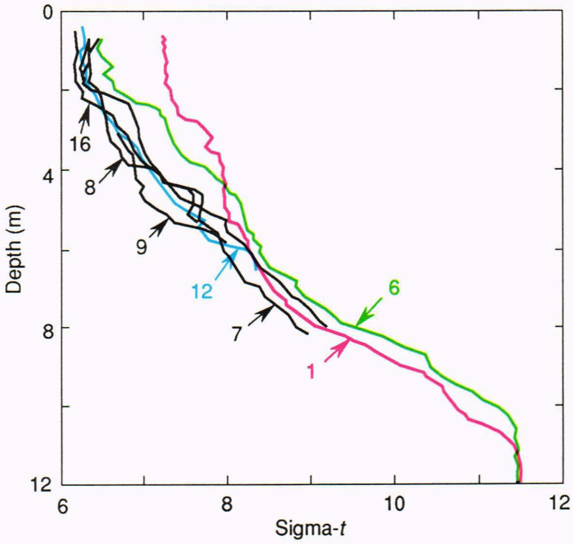

Figure 3. Overplotted density profiles during the passage of a buoyant surface plume front. Note the successive deepening of the lighter water pool as indicated by the color-highlighted profiles 1, 6, and 12, down to an asymptotic depth of 6 m.

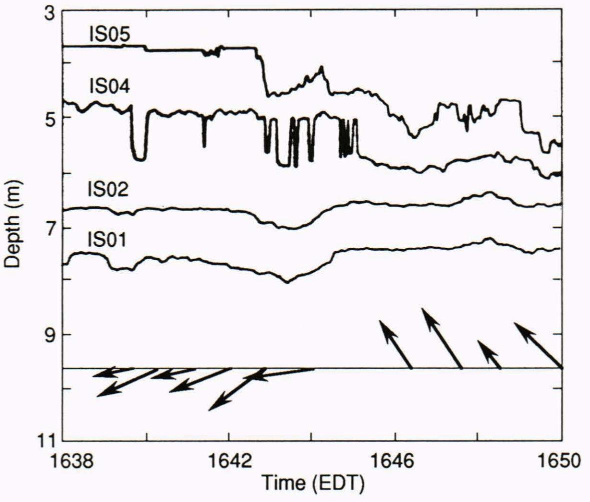

Figure 4. Isotherm displacements and current vectors at 3 m during the passage of the surface plume front in Figure 3. The arrows indicate the change in current direction.

The thermistor temperature–time series of Figure 5 gives a much clearer picture of the front as a distinct demarcation zone. The leading edge of the front is seen first as a temperature rise at T11, the shallowest thermistor, and then successively at thermistors T10 to T4. Thermistor T3 is located at about 6.5 m, below the asymptotic depth of the frontal interface. There is a considerable increase in high-frequency temperature activity within the light-water pool, consistent with the accepted view of the local circulation pattern of such fronts. The fathometer records show that sizable interfacial waves developed on the boundary of the light-water plume and grew in size until they finally broke. Figure 6 is a magnified view of such an event occurring about 30 minutes after the surface front passed through the station.

Internal Waves

Although surface fronts and subsurface intrusions were regularly recurring phenomena, by far the most ubiquitous features in the four years of thermistor chain data were internal waves. Internal waves were observed in every field test, although their character was highly variable. Three distinct types can be identified: random, homogeneous wave fields similar in spectral character to their oceanic counterparts; very monochromatic, large-amplitude internal wave trains; and very short, high-frequency internal waves on subsurface intrusions and fronts. As the latter have already been discussed, only the first two types will be considered.

In a stratified medium, internal waves can be supported at frequencies out to the local Brunt–Väisälä frequency, which is the natural frequency of oscillation of the system, N, defined by

$$N = \left(\frac{g}{\rho}\,\frac{\delta\rho}{\delta z}\right)^{1/2}, \qquad (1)$$

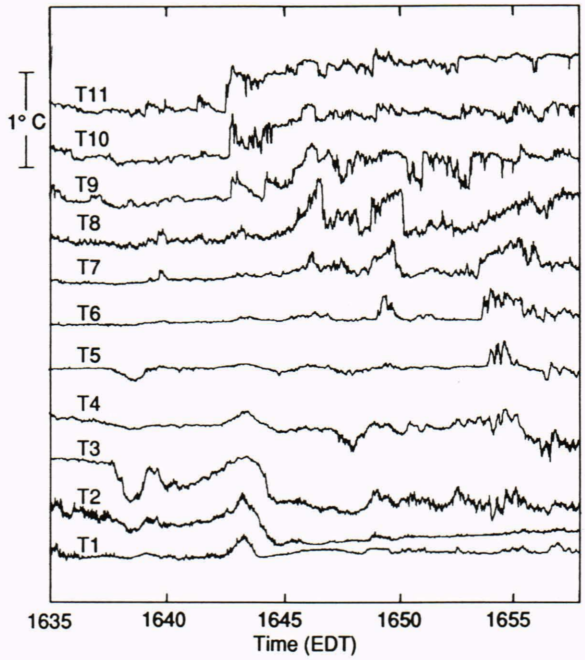

Figure 5. Temperature traces for 11 thermistors, showing the passage of a surface plume front.

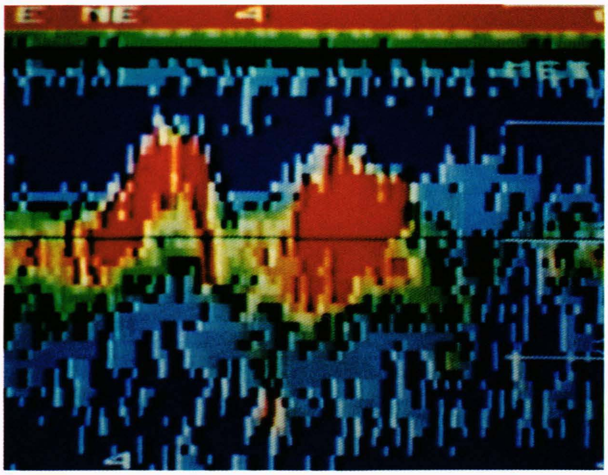

Figure 6. Color-encoded acoustic backscatter intensity as a function of time and depth for an overturning internal wave. The time span of the figure is 3 min, the depth is 4 m, and the color scale is red (high intensity) to blue (low).

where ρ is density, g is the gravitational constant, and z is depth. Figure 7 shows an occurrence of a very monochromatic internal wave train whose frequency is the same as the local Brunt–Väisälä frequency. In contrast, Figure 8 shows an internal wave field with significant contributions at frequencies other than the local Brunt–Väisälä frequency. Plots of power spectral density versus frequency show a strong peak at the local Brunt–Väisälä frequency for the wave field of Figure 7 and a smooth, red spectrum that is more like those of oceanic internal wave fields in the example of Figure 8.

Internal waves are common in the Chesapeake Bay during stratified periods, as demonstrated by the large

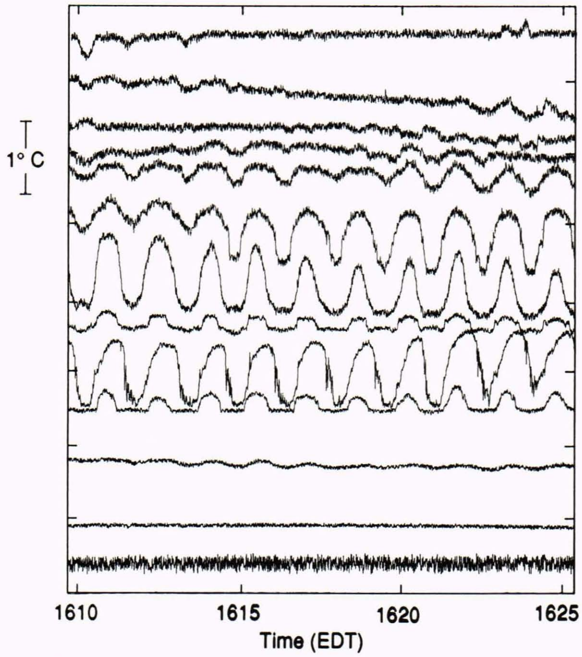

Figure 7. Temperature traces for thermistors spanning the pycnocline. Note the monochromatic internal wave activity in the middle of the thermistor string.

volume of data accumulated by APL over the past several years. It is interesting to ask what relationship, if any, the level of internal wave activity has to the phase of the tide and to the location in the Bay. To answer that question, root-mean-square displacements were calculated for several stations and for several tidal cycles. Despite a significant difference in seasonal conditions, the data from 1984 to 1985 showed a regular relationship of location along the Bay axis to tidal phase, with one maximum per tidal cycle and a regular phase shift relative to tide stage. The 1986 data, however, seem to be inconsistent with the 1984 to 1985 pattern; several peaks per tidal cycle are seen, but an examination of root-mean-square displacement for other stations shows the same pattern of multiple peaks, despite the delay of several days between data sets. This behavior, although different from the 1984 to 1985 data, still supports the notion of a tidal link to root-mean-square internal wave displacement levels. The exact nature of the connection is not evident in the limited number of data sets available at this time.

The prevalence of large-amplitude internal waves has implications for sampling strategies and the interpretation of some historical data that will be discussed later. Of equal interest is the fact that the overturning or breaking of internal waves was observed frequently. Figure 9 shows a gray-scale representation of a fathometer record taken in 1984. In the early part of the record, at about 28 min, there is evidence of an overturning event, or "rotor." Similar features occurred regularly all four years in both the fathometer records and the isotherm displacements.

DISCUSSION

While the higher-frequency features are of intrinsic interest, they may also directly affect mixing and circulation in the Chesapeake Bay and may influence biological and chemical regimes of importance. In this discussion, we consider some ways in which the high-frequency features may influence vertical mixing and also consider their implications with respect to modeling estuarine circulation, how they may affect biological communities, and how they might influence the design of optimal sampling strategies and the interpretation of historical data.

It has been held that the principal sources of turbulence and mixing are bottom interaction with the tides and atmospheric forcing (wind). Although these are clearly the largest energy sources, the mechanism by which that energy ultimately translates into vertical and horizontal fluxes is not clear. Also not clear is the distinction between turbulent erosion of the pycnocline through bottom- or surface-generated turbulence and instability and mixing at the pycnocline itself. At this time, there are no estimates of the relative amount of internal wave-field energy available to mixing processes (similar to the oceanic process discussed by Belyayev and Geyentsvey[22] and modeled by Bretherton[23]) compared to that directly available as a result of bottom- or surface-generated turbulence. Goodrich et al.[4] showed that a sudden, almost catastrophic, destruction of the pycnocline occurs, and that such a process may begin at the pycnocline itself. The results of Itsweire and Osborn[24] and less clear evidence shown by Dubbel et al.[25] indi-

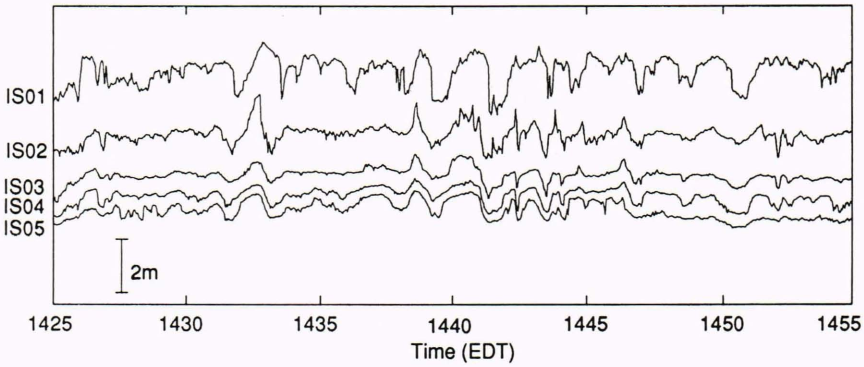

Figure 8. Isotherm displacements for a random, homogeneous internal wave field.

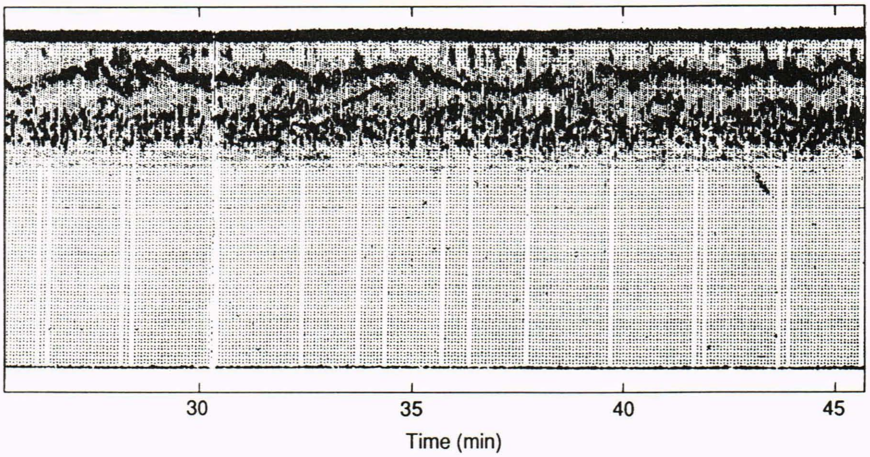

Figure 9. Gray-scale-encoded acoustic backscatter intensity versus depth and time. Note the "rotor" at about 28 min, in the early part of the series.

cate that the region just above and below the pycnocline exhibits, not surprisingly, large changes in the horizontal velocity with depth. Such a situation is conducive to the generation of interfacial waves, shear instabilities, and breaking waves, leading to episodic vertical mixing. Indeed, Partch and Smith[9] found during a study in the Duwamish River that about half the vertical flux of salt occurred during less than one-fifth of the tidal cycle and that it was driven by internal hydraulic jumps.

The evidence collected in the Chesapeake Bay shows a clear, though unexplained, link to tide stage of the amount of energy in the internal wave field. It is tempting to suggest that some fraction of the energy lost from the tides, or from wind forcing, goes directly into the excitation of internal waves and subsequently into turbulence and mixing. The mechanism by which internal waves are generated by the tides is not clear, although various mechanisms have been proposed.[9,13,14,26,27] Internal wave directionality determined in 1986 by means of a chain array suggests that tidal interaction with the irregular western edge of the main channel may be a source, as well as other mechanisms.

Internal wave energy is not uniformly distributed in time but is highly intermittent. Therefore, caution must be exercised in parameterizing such high-frequency activity as time-mean quantities in high-resolution hydrodynamic models or when interpreting specific data sets in the context of averaged vertical diffusion coefficients.

In the latter context, it is worthwhile to consider the effect such high-frequency motions may have on biological communities in the Bay. Work by Tyler and Seliger[28,29] and others has shown that during certain times of the year, important biological communities may be confined in vertically thin bands near the pycnocline. They may be strongly affected by energetic, large-amplitude internal waves there, as well as by overturning and mixing events. Fronts and intrusions may act variously as strong barriers to lateral and vertical mixing or as transport conduits controlling the advection of these relatively nonmotile organisms.[16,18,30,31] The supertidal features discussed by these authors are frequent events in the Chesapeake Bay, which implies that they are an important source of variability in the spatial and temporal distribution of biologically and chemically important species in the Bay.

In conclusion, the high-resolution data show that there is a wide spectrum of motion at time scales much less than tidal, and that the motions are ubiquitous and often fairly energetic in the Chesapeake Bay. The three features discussed—intrusions, fronts, and internal waves—have implications with respect to sampling strategies, to the parameterization of the processes as smooth, time-mean quantities, and to the transport and mixing of biologically and chemically important components of the Bay.

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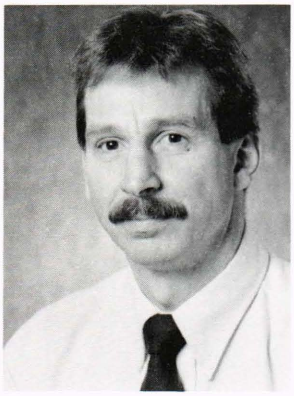

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