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# NEW DEVELOPMENTS IN APL CHESAPEAKE BAY RESEARCH

The Applied Physics Laboratory's Chesapeake Bay research program focuses on high-frequency mixing and transport mechanisms and their interaction with the biological and chemical regimes of the the upper Bay. The major emphasis in recent years has been on subsurface intrusions and their significance as a transport pathway for nutrients, toxics, and plankton; their formation, propagation, and dissolution; and the optimal sampling strategy required to observe and measure such features. Data collected during the springs of 1984 through 1993 will be used to characterize intrusions more fully.

## INTRODUCTION

The general decline in the health of the Chesapeake Bay is a major problem facing the region today. Its problems stem, for the most part, from the increasing stress of population growth and the demands of commercial, municipal, and recreational exploitation. These problems are not unique to the Chesapeake Bay, but they may be more obvious there. Clearly, the anthropogenic stresses will always exist. The task is to find the means to manage the stress to maintain a healthy, even if not pristine, Chesapeake Bay environment. Knowledge of the physical transport and mixing mechanisms is fundamental to understanding and managing the complex biological and chemical systems of the Chesapeake Bay.

Application of the expertise that APL developed in its research and development role for the Navy to problems in the Chesapeake Bay has afforded a unique opportunity to transfer military technology to an important area of civilian endeavor under the Laboratory's public service charter. Since 1984, APL has been fielding an instrumentation suite specifically designed to study high-frequency mixing and transport mechanisms and their interaction with the biological and chemical regimes in the upper Chesapeake Bay. The mechanisms have included estuarine surface fronts, high-frequency internal waves, and subsurface intrusions. The results discussed here were acquired from 1984 through 1991 and summarize the work on fronts and internal waves. Our main emphasis is on the recent investigations of subsurface intrusions.

## BACKGROUND

The objective of the APL Chesapeake Bay research program has been to investigate small-scale circulation and mixing processes and their relationship to larger-scale flows and to the mixing and transport of passive scalar variables such as sediments, plankton, nutrients, and pollutants in the estuarine environment. In the spring, freshwater runoff from tributary rivers establishes a two-layer system in the Bay with warm fresh water overlying cold salty water. The two relatively well-mixed layers are separated by the pycnocline, in which density (temperature and salinity) changes rapidly with depth. Mixing and dispersion in the estuary and across the pycnocline may be determined by the gravitational circulation,* wind events, tides, and many smaller-scale, higher-frequency features such as fronts, shear instabilities, and breaking internal waves. Defining the characteristics of higher-frequency features and their role in mixing and dispersion in the upper Chesapeake Bay has been our principal concern.

The initial focus of APL's studies has been high-frequency (2/3 to 1 cycle per minute), large-amplitude internal waves. In recent years, we have elucidated the ubiquity, energy level, contribution to vertical mixing, relation to tide stage, directionality, and generation mechanisms of higher-frequency internal waves. That work primarily emphasized high-frequency (HF) internal waves with peaks at the local Brunt-Väisälä frequency. The research results, presented in a series of papers delivered at professional society meetings, showed that the internal wave field can be highly directional and presented measurements of that directionality.[1] Root-mean-square energy levels for both space and time distributions of the wave field were computed, and data were generated to estimate the percentage of time internal wave breaking events occur. The 1988 tow data show that the piers for the Chesapeake Bay Bridge form a major source of high-frequency activity. Tow data from 1989 reveal that the western shoal edge was also a source of internal waves. This result is consistent with some laboratory findings on internal wave generation by stratified flow over a ridge. Another conclusion is that there is a distinct correlation of rms energy levels with tide stage, which within any year is the same from station to station. This relationship, however, seems to vary from year to year.

In addition to the characterization of the high-frequency internal wave field, high-resolution measurements of estuarine tidal fronts have been obtained. They reveal that the light-water pool above the frontal interface is much

*Gravitational circulation occurs because of freshwater inflows to the Bay. As the fresh water flows seaward over top of the more saline deeper water, some of the salt is mixed upward into the outflowing river water. The net consequence of this vertical salt flux is to generate a residual circulation that is up-estuary in the lower layer and down-estuary in the upper layer.

more turbulent than the underlying water[2] and show internal wave activity on the interface with episodic overturning and wave-breaking events. Current-meter data have demonstrated a pronounced shear in the velocity field across the front, and decomposition of the velocity vectors has disclosed that the light-water pool moves with a speed $c$ close to the speed appropriate for an internal wave, as defined by the following equation:

$$c = \sqrt{gh\frac{\Delta\rho}{\rho}}\,, \tag{1}$$

where $h$ is depth of water, $\rho$ is the density, and $g$ is gravitational acceleration. That the light-water pool moves at such a speed, and that the residual along-front speed was nearly zero, demonstrates that the front was not in quasigeostrophic equilibrium. That is, the cross-front pressure gradient within the light-water pool was not balanced by the Coriolis force and an along-front current.[3]

The ongoing studies of internal waves produced many long time-series of thermistor chain data, which revealed the frequent occurrence of thin layers, or intrusions. These layers had vertical extents of 0.5 to 2.5 m and lifetimes of a few tens of minutes to a few hours (note that the vertical resolution of the chains limited observation to intrusion thicknesses greater than or equal to 0.5 m). Vertical temperature and salinity profiles have shown a great deal of "steppiness," (i.e., repeating layers of well-mixed water) with vertical scales of a few tens of centimeters. Recent field work by APL has focused on the study of these intrusions as significant transport mechanisms in the Chesapeake Bay; the results of this work and the previously collected data examined for intrusions in the upper Bay are discussed in subsequent sections. Among the many unanswered questions regarding these intrusions, the following are central to the current analysis and research:

1. Do such features appear often enough and have sufficient size to play a significant role in transport and mixing?
2. What are the main observable spatial and temporal characteristics of these features? What are their physical, biological, chemical, and optical signatures?
3. What are the potential sources for intrusions, and what is the mechanism by which they dissipate and mix their scalar components?
4. What sampling strategy and instrumentation suite should be used for optimal detection, characterization, and tracking of these features?

## INSTRUMENTATION AND METHODS

Among the instruments used for investigating intrusion events were several vertical thermistor chains, a high-resolution vertical profiler and water sampler, a high-accuracy navigation system, and a 200-kHz narrow-beam fathometer. Additional instrumentation furnished by ship's personnel or other investigators included a conductivity-temperature-depth-fluorescence (CTDF) profiler, a profiling current meter, meteorological devices, and Niskin bottles for volume water samples.

The fathometer was a Wesmar VS3000 color video sounder operating at 200 kHz with a pulse length of 150 $\mu$s (at about a 25-cm range resolution) and a pulse repetition rate of 5 Hz. The color-encoded video output was recorded on videotape, and an APL modification allowed direct access to the analog backscatter intensity data, which could be digitized and recorded. The transducer was deployed at the end of a 7.62-cm galvanized pipe, which held the transducer about 1 m below the surface.

The principal thermistor chain was 8 m long and consisted of sixteen thermistors spaced at 0.5-m intervals and two pressure transducers located at the top and bottom. The system was faired to reduce drag and hydrodynamic (flow) disturbances that might falsify the data. The resolution of the thermistors was 0.007°C, and their response time was 20 $\mu$s. The accuracy of the thermistor sensor was 0.05°C using a 5-point calibration and a second-order fit. The pressure transducers (Stratham or Entran were used on different experiments) had a resolution of 0.01 m. The thermistor and pressure sensors were interfaced to a Metrobyte 16-channel multiplexer extension (EXP-16) board. Signal digitization was performed by a Metrobyte 16-channel analog-to-digital conversion board (DASH-16G2). The digitized output from the Metrobyte board was transferred to a Compaq 386 PC, which used Labtech Notebook as the control software.

During the 1984 through 1991 period, data for all channels were sampled at 4 Hz using an analog prefilter of 1 Hz and stored on 20-MB Bernoulli hard disks. The thermistor chain was generally deployed from a ship in a static mode and weighted at the lower end, but this system could also be towed at a maximum boat speed of 5 kt. The thermistor data were displayed in real time using the Labtech Notebook data acquisition software package. After each experiment, the data were transferred to a DEC VAX 3500, where they were edited and transformed into engineering units for analysis.

The high-resolution vertical profiler (HRVP) system measured ocean temperature, conductivity, depth, chlorophyll-a concentration, optical beam attenuation, bioluminescence potential, and backscatter. Table 1 lists the specifications of the sensors. The vertical profiler was a modified General Oceanics Model 1015-24-51 Rosette Multibottle Array. The deck unit, a shipboard HP 9826 computer system, interacted asynchronously with an HP 9920 computer, which provided averaged data profiles and quick-look graphics.[4]

The data from all sensor systems on the vertical profiler deployed during the 1991 Chesapeake Bay field test were collected at a 12-Hz sampling rate. Data were collected every hour during the onstation period (along with the ship's CTDF and Doppler current profiler). At the onset of a front or intrusion, the profiler system was deployed every 15 to 20 min. Water samples were also collected. Species enumeration and chlorophyll-a fluorescence measurements were made aboard the ship. After the conclusion of the experiment, data were transferred to a DEC VAX3500, where they were edited and post-test calibrations were applied.

**Table 1.** Vertical profile instrument specifications.

| Parameter | Sensor type | Range | Resolution | Absolute accuracy | Response time (s) |
|---|---|---|---|---|---|
| Water temperature (°C) | Sea-Bird Electronics SBE-3 thermistor thermometer | 0–35 | 0.001 | 0.01 | 0.07 |
| Conductivity (S/m) | Sea-Bird Electronics SBE-4 conductivity cell | 0.05–6 | $5 \times 10^{-5}$ | $1 \times 10^{-3}$ | 0.17 |
| Depth (m) | Parascientific quartz pressure sensor | 0–633 | 0.05 | 0.63 | 0.07 |
| Chlorophyll-a concentration (μg/L) | APL fluorometer | 0.04–30 | 0.01 | 1% (full scale) | 0.7 (estimated) |
| Beam attenuation coefficient (% transmission) | APL transmissometer | 0–100 | 0.01 | 1.0 | 1.4 |
| Bioluminescence potential (photons/s) | APL bathyphotometer | $50–10^6$ | 1.0 | 10 | 0.08 |
| Backscatter (170°) (1/sr·m) | APL backscatterometer | 0–0.01 | $2 \times 10^{-6}$ | $5 \times 10^{-6}$ | 0.7 (estimated) |

## OBSERVATIONS

The data discussed in this section were acquired from field tests conducted in the springs of 1984 through 1991. During the tests, several standard stations were occupied for a minimum of 25 hours while the ship was anchored fore and aft to minimize contamination in the chain data caused by the ship's swinging at anchor. Figure 1 shows the locations of our standard stations.

Thin (1- to 2-m thick) intrusions occurred regularly in the time series of the ship-moored thermistor chain data and persisted for periods of 10 min to several hours. The thermistor temperature-time series of Figure 2 shows the onset of one such event from a thermistor chain moored at Station 838. The well-mixed water of the intrusion was colder than the overlying water and warmer than the underlying water. Thus, in the time series the start of the event is apparent in the temperature drop at thermistor T6 as it encountered the relatively colder water of the well-mixed intrusion. A temperature rise is registered instead at T3 and T4 in response to the relatively warmer water of the intrusion. Since the spacing between thermistors was 50 cm, the thickness of the intrusion event was about

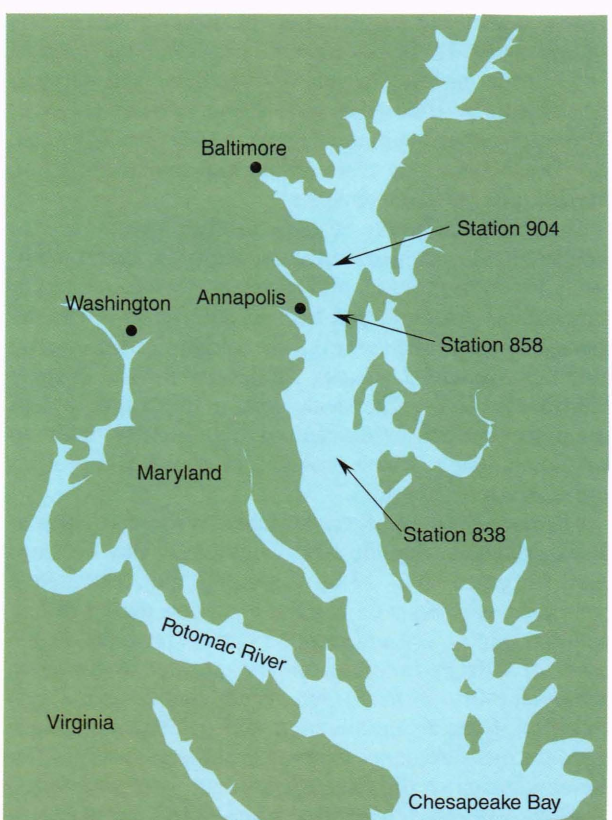



**Figure 1.** Standard station locations.

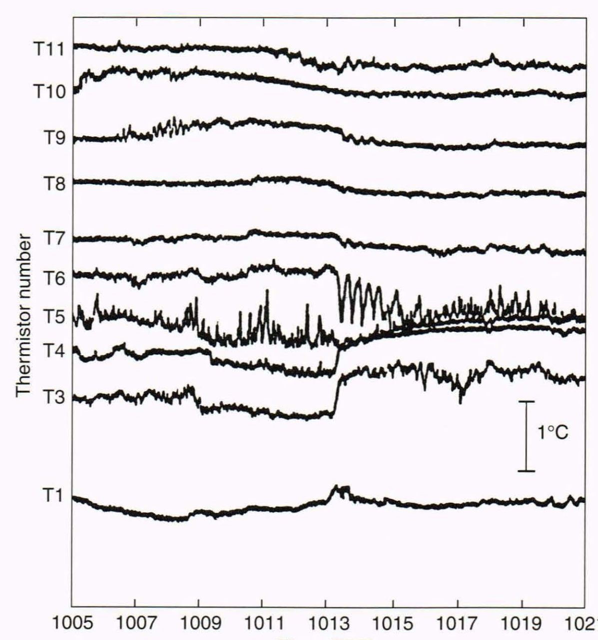



**Figure 2.** Thermistor chain time series obtained in 1986 at Station 838. The temperature drop in the T6 tracing and the temperature rises in the T3 and T4 tracings denote the start of the intrusion. Note the internal waves on the upper leading edge of the T6 tracing at 1013 EDT.

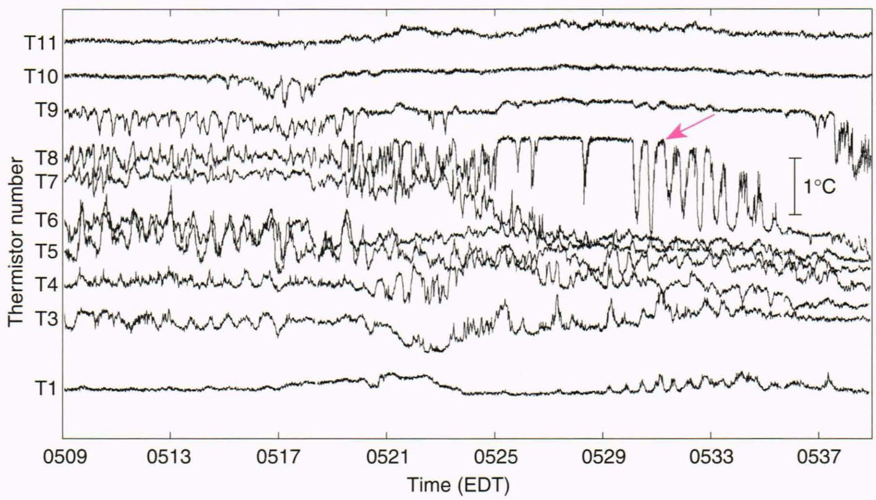
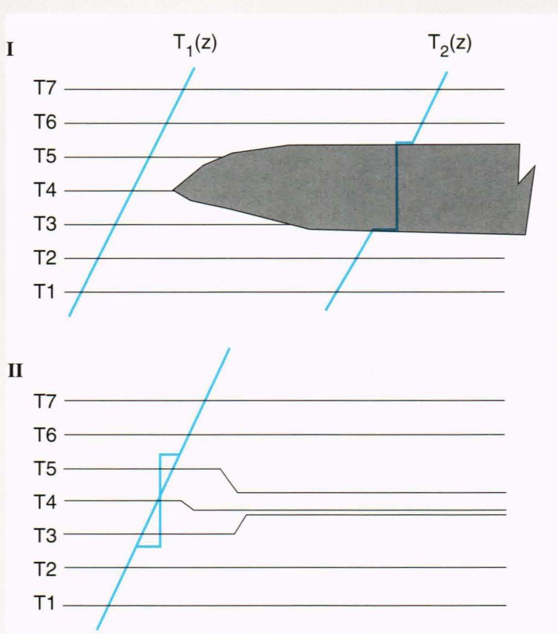



**Figure 3.** Thermistor chain time series obtained in 1986 at Station 858 showing the onset of an intrusion. Note the internal waves on the upper leading edge of the intrusion starting at about 0531 EDT in the T8 tracing (red arrow).

1.5 to 2 m. Note the internal wave activity on the upper leading edge of the intrusion (T6) beginning at about 1013 EDT. (See the boxed insert on the thermistor chain signatures of intrusions.)

INTRUSION THERMISTOR CHAIN SIGNATURE

The left side of Figure I shows an idealized pycnocline region with a linear temperature profile $T_1(z)$ being sampled by thermistors T1 through T7. Over time, the thermistor traces will appear as straight lines, since the temperature is not changing at a given depth. The right side of the figure shows a well-mixed intrusion in the pycnocline and the resulting temperature profile $T_2(z)$. Figure II depicts traces typical of a thermistor chain's encounter with an intrusion. Thermistor T3 registers a temperature rise as warmer water in the intrusion is suddenly intersected, whereas T4 and T5 report a temperature drop in response to an area of colder water.




A similar observation (Fig. 3) during the spring 1986 field test revealed once again the internal wave activity on the upper leading edge of the intrusion. Although the thermistor chain data obtained during the 1980s were not processed for intrusion events, a preliminary review has revealed their presence in each year of historical data. In addition, intrusions were observed at all of the station locations shown in Figure 1. During the spring 1986 field test, Stations 904, 838, and 858 were each occupied for 25 hours. The data set generated permitted a cursory look at the prevalence of intrusions. As noted in Table 2, the incidence of observed intrusions ranged from 3 to 8 events with durations categorized by three time intervals: less than 30 min, between 30 min and 1 h, and greater than 1 h. The vertical thickness of these features varied from 0.5 to 2.5 m. Frequently, but not always, the thinnest intrusions had the shortest durations.

In the spring of 1991, a field test extending over several days was conducted specifically to begin the study of intrusions seen in thermistor chain data from previous years. Although the test was interrupted by strong winds, resulting in extensive wind mixing, one intrusion-like event was observed at Station 858 before the onset of the wind event. Figure 4 shows a 1-h time series of thermistor chain data recorded during the event. Just before 0500 EDT, T6 registered a sudden temperature drop. In the real-time display, the appearance of such a feature caused more frequent vertical profiling with the *Cape Henlopen* CTDF and the APL HRVP (every 15 to 20 min rather than hourly). Figure 5A shows a series of APL HRVP temperature profiles collected before and during the passage of the intrusion. Note the distinct, well-mixed layer between

**Table 2.** Possible intrusion events observed during spring 1986.

| Station | Hours on station | Number of intrusions | Duration of intrusions <30 min | 30 min to 1 h | >1 h |
|---|---|---|---|---|---|
| 904 | 25 | 7 | 2 | 3 | 2 |
| 858 | 25 | 3 | 0 | 2 | 1 |
| 838 | 25 | 8 | 4 | 2 | 2 |

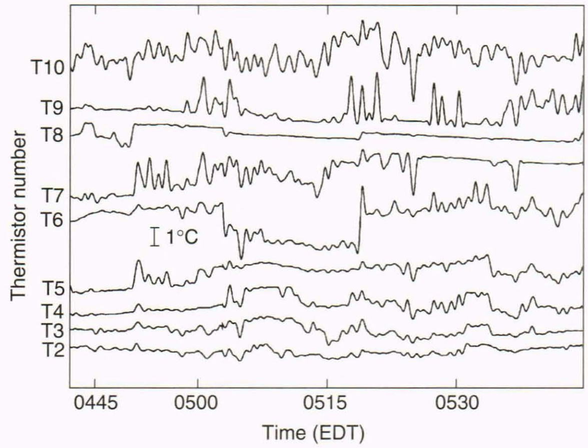



**Figure 4.** Thermistor chain time series obtained in 1991 at Station 858. The temperature drop in the T6 tracing marks the onset of the intrusion event.

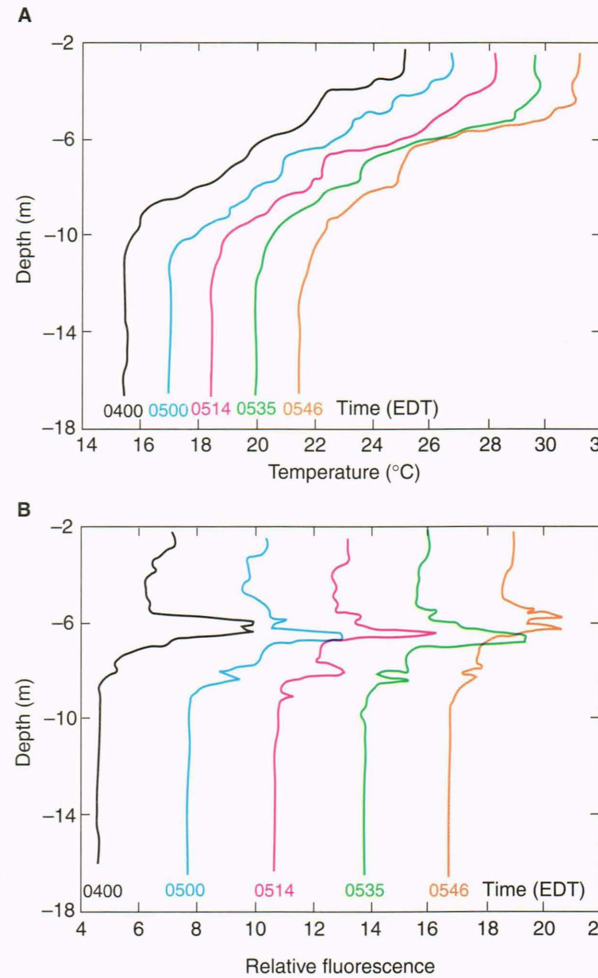



**Figure 5.** Profile series obtained with the high-resolution profiler before the intrusion at 0400 EDT and during the intrusion event (0500 EDT on). **A.** Temperature profiles. **B.** Chlorophyll-a fluorescence profiles. Note the step at about 7 to 8 m in the temperature profiles from 0500 EDT on and the corresponding feature in the fluorescence profiles.

7 and 8 m at 0500 EDT and subsequent temperature profiles. The 0400 EDT profile collected before the intrusion event during regular hourly operations does not show a homogeneous layer at that depth. Note also that the layer is evident in the corresponding chlorophyll-a fluorescence profiles in Figure 5B. The layer was tracked for 2 h in the CTDF and HRVP profiles until high surface winds forced abandonment of the station.

Figure 6 shows profiles of temperature, salinity, beam attenuation, and fluorescence from the rapid profiling series collected with the R/V *Cape Henlopen* CTDF. Note that the layer is evident in all of the parameters measured. Concomitant profiling with the APL HRVP showed that the layer had a distinct optical backscatter and transmission signature as well. Note too that the depth of the layer gradually increases in each succeeding profile.

These results suggest that intrusions may be important to transport and mixing in the estuarine environment, but much uncertainty exists about the origin and role of such features. Although no data are available to remove the uncertainty definitively, one can speculate about the origin of such events. In the following paragraphs, we describe four possible source mechanisms.

## FORMATION MECHANISMS

In a stable and continuous, density-stratified fluid, the breaking of internal waves, local shear instability, or the penetration of denser fluid from a near-surface layer may result in a mixed, turbulent region or layer of homogeneous fluid.[5] The mixed-fluid layer evolves, gradually becomes flattened, and begins to penetrate as tongues or intrusions into the stratified fluid. Under the influence of the excess pressure brought about by the differences in the densities of the mixed layer and surrounding stratifed fluid, the fluid in the mixed layer begins to spread outward into the stratified fluid at the density level that corresponds to the density of the mixed region. Finally, the entire fluid in the mixed regions falls to this level, thus resulting in the collapse of the constant-density region. This phenomenon, which has been called mixed-region collapse, is one of the mechanisms for the formation of vertical finestructure in the oceanic pycnocline. According to Benilov,[6] it typically forms layers with a vertical-to-horizontal scale ratio of 2 to $3 \times 10^{-3}$. Homogeneous layers 0.5 to 1 m thick with horizontal extents on the order of 250 to 500 m have been observed in our data sets.

Three principal stages are associated with the evolution of the mixed turbulent region. The first includes the initial collapse[7] in which the radiation of internal waves occurs. This stage is completed after an interval of $10N^{-1}$, where the Brunt-Väisälä frequency $N$ is the natural frequency of oscillation of the system defined by

$$N = \sqrt{\frac{g\delta\rho}{\rho_0 \delta z}}\,, \tag{2}$$

where $\rho$ is density , $\rho_0$ is a constant reference density, $g$ is the gravitational constant, and $z$ is depth.[5,7,8] Assuming a cylindrical mixed layer with a horizontal axis, the rate

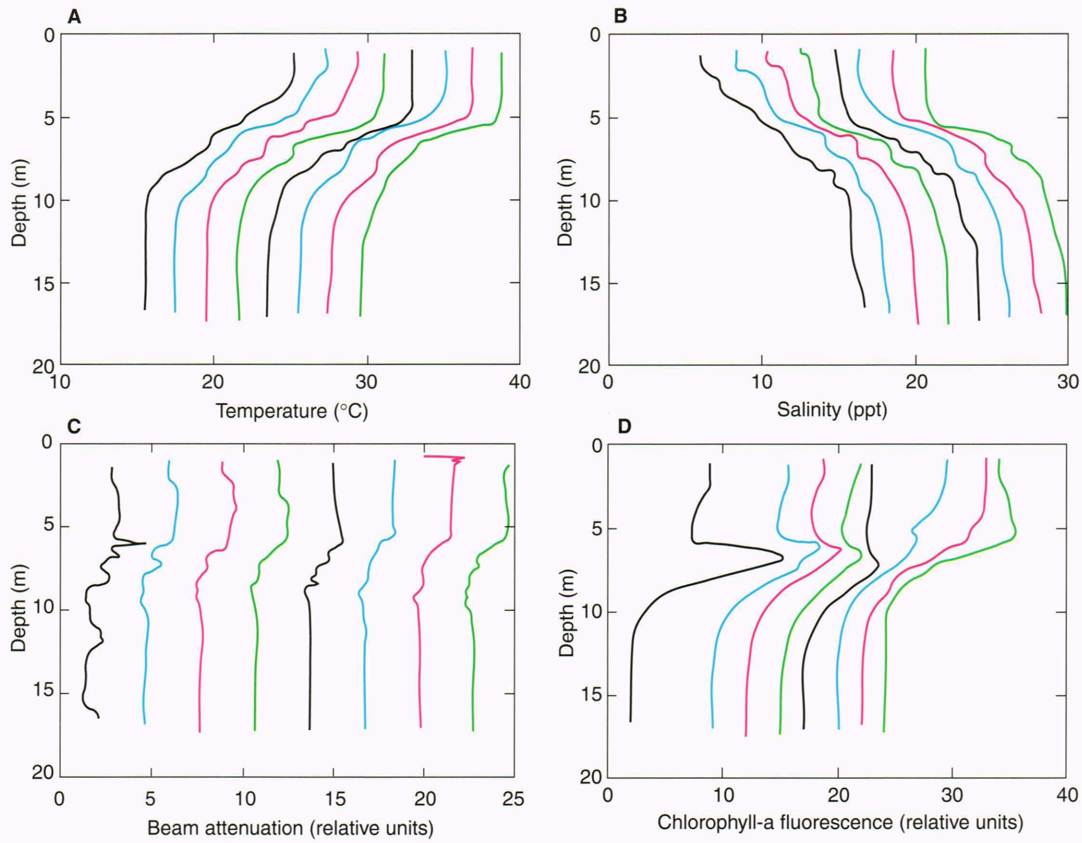



**Figure 6.** Successive profiles obtained in 1991 with the ship's conductivity-temperature-depth-fluorescence profiler. **A.** Temperature. **B.** Salinity. **C.** Beam attenuation. **D.** Chlorophyll-a fluorescence. The first profile in each series was obtained at 0410 EDT before the intrusion event. The remaining profiles were taken, in order (left to right), at 0512, 0522, 0544, 0559, 0633, 0654, and 0750 EDT. (ppt = parts per thousand.)

of change in the area of the layer's horizontal dimension is proportional to the product of the current area of the layer and the rate of fluid inflow into the horizontal plane on which the density of mixed fluid equals that of the stratified fluid.[5] The rate of fluid inflow is a product of $N^2$ and time $t$. Thus, the resulting characteristic dimension of the mixed, turbulent layer in the initial stage varies proportionally to time squared, as follows:

$$L/L_0 \sim 1 + N^2 t^2 \tag{3}$$

and

$$dL/dt \sim L_0 N^2 t\,, \tag{4}$$

where $L$ is the characteristic horizontal dimension, $L_0$ is the initial horizontal dimension of the turbulent layer, and $L$ and $L_0$ are valid for $Nt \leq 2.5$.[5]

Since the driving force of the layer/intrusion in the intermediate stage is counterbalanced by form drag, frictional drag, or wave drag,[7] the layer's spreading rate is determined by the stratification $N$ and the current height of the layer $h$:[5]

$$dL/dt \sim Nh\,. \tag{5}$$

During the final stage of collapse, the emission of internal waves ceases, and the spreading process slows down drastically, since it is determined by the ratio of the buoyancy and viscous frictional forces.[7,9] In the viscous stage, the spreading of the intrusive layer proceeds proportionally to a power of time equal to 1/6 for a cylindrical patch. Thus, the spreading of the intrusion in the viscous stage is slowed relative to the preceding stages.[5]

It is possible that the features we have observed are the result of the breaking, mixing, and subsequent mixed-region collapse associated with large internal waves. We have measured frequently occurring large-amplitude (crest-to-trough heights up to 6 m) internal waves and their subsequent breaking.[10] The wavelengths of internal waves are on the order of 200 m.[1] Using that wavelength and a wave amplitude of 3 m, we can estimate the size of a layer formed in this way. Assuming a mixed region with dimensions approaching those of the original wave, which collapses into a layer 1-m thick through circular spreading, the resultant layer would have a length scale of a few hundred meters. For current speeds of near 25 cm/s (Doppler current profiler data), such a collapsed region would appear to persist for less than 30 min. Some intrusion features in our historical data had durations on this order. Although some of the intrusions observed may have resulted from internal wave-breaking events, it seems unlikely that this mechanism could have produced the other longer and more sustained events that have also appeared in our historical data.

A second, related possible source of intrusions is turbulent, diffusive mixing in the high-gradient region between the deeper more saline water in the main channel and the overlying Susquehanna River plume. Laboratory studies by Ruddick et al.[11] have shown that turbulent mixing in such a situation can result in vertical profiles such as those obtained during a 1991 APL field test. Recall the profile at 0500 EDT from Figure 5 in which a distinct, well-mixed layer can be seen between 7 and 8 m. That this layer is the result of mixing between the upper and lower water masses is supported by the temperature-versus-salinity diagram for the 0500 EDT profile (Fig. 7), in which the layer at 7 to 8 m lies on a straight line between the upper water type and the lower water type. The issue, however, is not completely clear-cut, since the fluorescence-versus-salinity diagram for the same profile (Fig. 8) leaves open the possibility that the event represents a third intruding water mass if one accepts the argument of Boyle et al.[12] regarding the characteristics of scatter plots of salinity versus an apparently nonconservative property such as, in this case, chlorophyll-a fluorescence. Boyle argues that scatter plots similar to Figure 8 that can be approximated by straight line segments indicate that more than two water types are present; thus, on this basis, the intrusion shown in Figure 5 derived from a third water type. This position was supported by a cluster analysis, which showed that the intrusion more nearly resembled water from the mouth of Eastern Bay (Fig. 1).

A third mechanism explaining the existence of such layers, sinking tributary water, is suggested by Tyler's[13] dye study of the Chester River. Figure 9 shows Chester River water exiting the mouth of the Chester River and then sinking below the Susquehanna River water to form a thin intrusive layer. The leading edge of such an intruding layer may well exhibit the characteristic internal wave structure seen in some of our thermistor chain data, as exemplified in Figure 2. The internal wave features are also consistent with recently presented results by Yamazaki[14] about propagating, intruding layers in which a similar feature was observed on the leading edge of an intrusion.

Phillips et al.[15] speculated that turbulent mixing at the side boundaries of the main channel in a stratified system is a potentially significant mixing mechanism, thus yielding a fourth possible explanation for what has been observed. Their laboratory studies showed that such a mechanism produced enhanced dispersion along slope in the boundary layer and convection at the boundaries, causing the intrusion of thin laminae into the main body of the fluid outside the boundary layer. The dye study conducted by Tyler[13] was cited as offering support for such a mechanism's operation in the Chesapeake Bay. Such a mechanism cannot be confirmed or denied from the data we have obtained thus far. Our data were taken under sampling strategies designed to answer questions related to internal waves, and the present data sets are not suited to resolving this issue. Note that the theoretical treatment by Phillips et al.[15] indicated that decreasing slopes increased the effectiveness of the generation mechanism. Our data show some of the intrusions to be 3 to 5 m deep, which is the depth range at which the bathymetry changes from channel side to shoal edge.

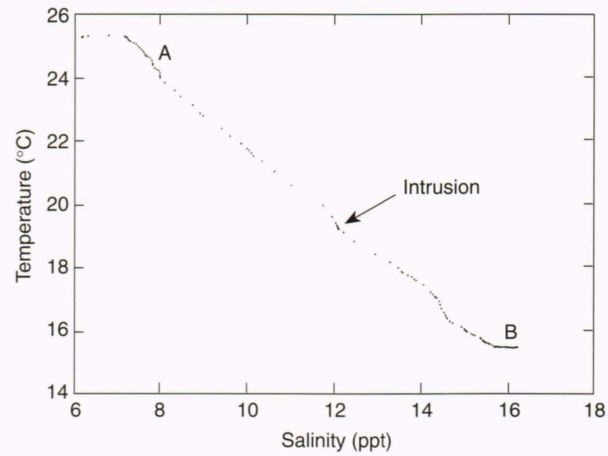



**Figure 7.** Temperature-versus-salinity diagram from a vertical profile through the intrusion event observed in 1991. Upper and lower water masses are labeled A and B, respectively. (ppt = parts per thousand.)

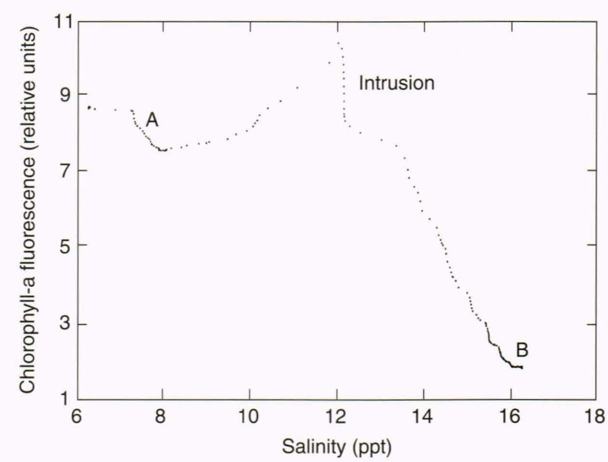



**Figure 8.** Diagram of chlorophyll-a fluorescence versus salinity for the profile shown in Figure 7. Upper and lower water masses are labeled A and B, respectively. (ppt = parts per thousand.)

## FUTURE ACTIVITIES

Our approach to the study of intrusions can be divided into the following three phases: (1) a detailed examination of our eight years of high-resolution thermistor chain data along with associated profile data for intrusion events; (2) a comprehensive field test conducted in the spring of 1993 to address temporal and spatial extent, dissipation rate, and source mechanisms; and (3) analysis of the resulting 1993 data set.

### Analysis of Historical Data

Since 1984, APL has been conducting one- to five-day field tests in which the principal instrument has been a high-resolution thermistor chain developed in support of

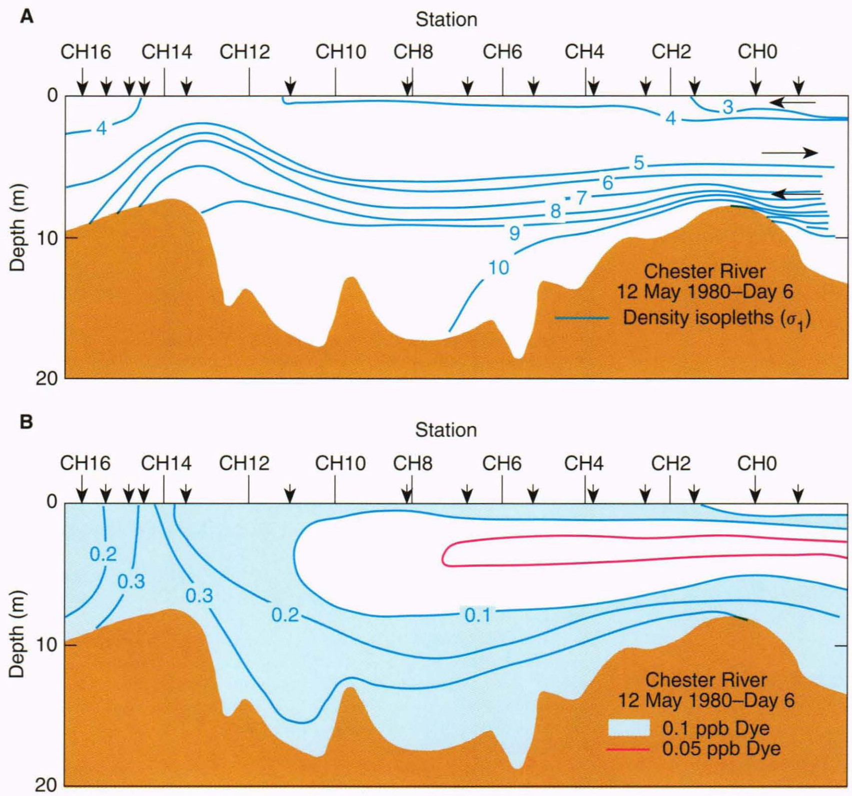



**Figure 9.** Chester River isopleths in 1980. **A.** Density. **B.** Dye. Note the thin sinking layer of surface water at Station CH0. (ppb = parts per billion.) (Reprinted, with permission, from Ref. 13, p. 295; © Springer-Verlag, Inc.)

other Navy programs. The thermistor chain data are sampled at 1 to 4 Hz continuously for the period of each test. Vertical resolutions are 0.5 to 1 m, and the chain measurements are supplemented by vertical profiles of temperature, conductivity, fluorescence, and currents. The high-resolution thermistor chain data are well suited to resolving the intrusion-like features. We are reviewing the historical data sets to provide complete statistics on the incidence of the intrusions, their persistence, and their relation to tide stage. These results will be augmented, where possible, by corresponding vertical profile data. Simultaneous current data will give some limited estimates of size, but since these are point data only they are insufficient to answer questions of true spatial (volume) extent, persistence, and source.

## 1993 APL IR&D Field Test

Because 1993 (January to September) is the final year for APL-sponsored research in the Chesapeake Bay supported entirely by the JHU/APL Independent Research and Development Fund, a four-day field test was conducted in the spring specifically aimed at measuring the characteristics of intrusions to obtain a well-defined signature of those events. The high-resolution instrumentation suite included a vertical chain that consisted of temperature, conductivity, and chlorophyll-a fluorescence sensors; an HF Doppler current profiler; and a vertical profiler that measured temperature, conductivity, chlorophyll-a fluorescence, beam attenuation, optical backscatter, and bioluminescence. The profiler, developed under Navy sponsorship, provided pumped water samples collocated with the sensors for species enumeration and for nutrient and priority pollutant post-test analysis. The main platform was the R/V *Cape Henlopen,* which was two-point anchored at the site of previously observed intrusion events. The *Henlopen* also provided meteorological data and obtained vertical profiles of temperature, conductivity, and dissolved oxygen.

A principal goal of the test was to secure *in situ* biological, physical, optical, and chemical signatures of the intrusions. Real-time displays of the chain data were used to identify the onset of intrusion events. Identification of an incipient intrusion event cued the start of continuous vertical profiling by the HRVP. Clear multiparameter signatures for such features are key to spatial mapping and tracking over time. A single mobile platform (separate from the *Cape Henlopen*) employed a battery-operated multiparameter profiling and data acquisition system and Global Positioning System tracking to measure size and lifetimes. A cluster analysis of the multiparameter profile data from 1991 showed that each intrusion had a multiparameter signature distinctly different from that of the water above and below it. We anticipated that this distinctive signature would act as a sufficiently clear tracer to allow intrusion tracking. The spatial tracking capability allowed near-synoptic mapping of the size of the intrusion as well as continuous tracking in time to measure its lifetime and dissipation rate. In addition, we investigated some possible source mechanisms. A particular sampling run was cued by the appearance of an intrusion in the moored thermistor chain data. In addition to the increased vertical profiling rate aboard the anchored ship, the event triggered the spatial and temporal sampling strategy.

## Analysis of 1993 Data

With the conclusion of the 1993 field test, we have accumulated three sets of information for the intrusions encountered: (1) historical APL station data generated from thermistor chain, CTDF, and current measurements; (2) focused 1991 APL multiparameter profile, temperature-fluorometer chain, and HF Doppler current station data; and (3) comprehensive 1993 multiparameter profile, temperature-fluorometer-conductivity chain, and HF Doppler current station data, along with spatially and temporally distributed multiparameter profile data from concurrent measurements.

The 1984 to 1993 data should be sufficient to generate distributions of incidence and persistence for intrusions at a moored station. The same data set will be used to address the relationship between intrusion events and tide stage, although, as shown by Sarabun and Dubbel,[10] any such correlation may include a location-dependent phase component. The intensive multiparameter profile data sets and analyzed water samples of 1991 and 1993 should provide the information to characterize the physical, biological, chemical, and optical signatures of the intrusions. Data from the spatial mapping and temporal tracking of intrusions performed during the 1993 field test will be used to specify the volume(s) of water affected and the persistence and dissipation rates of the events.

## CONCLUSIONS

Our historical data clearly show that the intrusions we have observed occur frequently and persist, suggesting a large size. Our historical data do not, however, provide sufficient information to determine the origin of such features. It is entirely possible that all of the source mechanisms described are active at one time or another. Our 1991 data are consistent with the recent results of Donaghay et al.[16] in that the layer observed exhibited a well-defined signature. The 1991 data set by Frizzell-Makowski et al.[17] reveals that a thin intrusive layer was present with physical, biological, chemical, and optical characteristics distinctly different from those of the waters both above and below. Thus, regardless of origin, such events are potentially important transport pathways—not only for natural biological and chemical constituents but also for anthropogenic inputs such as toxic materials.

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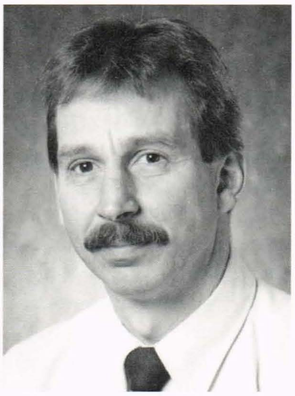

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