Circulation Patterns and Processes in Penobscot Bay: Preliminary Interpretation of Data

A Final Report for Year 3 of the Penobscot Bay Experiment

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INTRODUCTION:

Penobscot Bay is a large oceanographically complex embayment at the mouth of the Penobscot River, which is one of the three most significant fresh water point sources for the entire Gulf of Maine. Results of Years one and two of the experiment have suggested that the two-way exchange between the bay and the Gulf plays an important role in the ecosystem of each, through the interplay of their circulation systems and the exchange of nutrients and planktonic communities.

There is growing evidence that the circulation of Penobscot Bay and the eastern Maine shelf are strongly coupled. It is often suggested that the outflow from Penobscot Bay exerts an important influence on the general circulation of the Gulf of Maine by causing a portion of the generally southwestward-flowing Eastern Maine Coastal Current (EMCC) to be deflected offshore and to recirculate cyclonically (anticlockwise) within the Jordan Basin Gyre (e.g., Brooks, 1994; Lynch et al., 1997; Pettigrew et al., 1998). However, there may also be instances in which a buoyant estuarine plume emanating from Penobscot Bay overrides the coastal current without any apparent deflecting influence (Pettigrew et al., 1998). There is some evidence of a persistent seasonal surface temperature front, offshore of Penobscot Bay, separating the eastern and western regions of the Gulf of Maine. The temperature patterns are consistent with the notion that a portion of the cold Eastern Maine Coastal Current (EMCC) turns offshore at this location, and another portion turns into Western Penobscot Bay. Recent hydrographic evidence Pettigrew et al., 1998) suggests that a portion of the EMCC may submerge or subduct beneath the warmer, less dense, Penobscot Bay outflow plume and the western Maine waters, and continue southwestward along the western Gulf coast.

Direct evidence of strong physical coupling between the outer bay and the EMCC came from the first two years of the Pen Bay experiment. Moored current measurements showed an unexpected pattern of strong near-surface and mid water column inflow in western Penobscot Bay, and net outflow in eastern Penobscot Bay. This striking circulation pattern suggested that the interactions between the bay and the EMCC dominated the circulation in the outer bay. The net inflow and outflow transports respectively on the western and eastern sides of Vinalhaven Island suggested an anticyclonic circulation pattern. In addition, a strong seasonal variability was noted between the Spring/Summer and Fall/Winter seasons during both experimental years. The transition between the two circulation regimes tends to occur in mid-April and mid-September. The Fall/Winter transition is characterized by a deepening of the outflow and a simultaneous strengthening of the deeper inflow on the western side relative to the Summer/Fall pattern. Net transport is not greatly changed, nor is the circulation on the eastern side of Vinalhaven. While these results were very exciting, we still had little idea the time variability of hydrographic and currents in the upper 10 m of the water column, and no direct knowledge of the circulation in the upper reaches of the bay.

OBJECTIVES OF THE THIRD YEAR OF THE CIRCULATION EXPERIMENT:

The primary objectives of the third year of the study were explore the seasonal circulation patterns of the previously unmeasured inner bay, to study the circulation linkages between the inner and outer bays, and the Eastern Maine Coastal Current (EMCC). Specific objectives included:

- obtain direct current measurements at strategically sited mooring locations in the EMCC, and the eastern and western sections of both inner and outer Penobscot Bay;
- obtain, for the first time, near-surface moored time-series record of currents and water properties (temperature, salinity, and density) within Penobscot Bay;
- provide direct circulation data for comparison with the other components of the Penobscot Bay experiment including the numerical circulation modeling component, and the lobster research component.

The data acquisition tasks listed above were successfully completed.

PRELIMINARY INTERPRETATION OF DATA:

Standard calibration and data processing techniques have been applied to the moored time series and hydrographic data collected in this experiment. The details of the experimental sampling scheme, and the calibration and the processing routines used, are discussed in the companion data report by Mangum et al. (2000). Plots of all hydrographic survey data and of all moored time-series data may also to be found in Mangum et al. (2000). The data presented herein are only those required to illustrate the basic findings and to support the data interpretation and synopsis. Figure 1 shows the locations of the five Oceanographic Data Acquisition System (ODAS) that were deployed in the 1998-1999, Year 3, experimental season.

Shipboard Hydrographic and Current Surveys:

Hydrographic data were taken along three tidal transects in inner Penobscot Bay. The survey lines consisted of 8-10 stations in the cross-channel direction. The stations were sampled five times (every 2.5 hours) over the semidiurnal tidal cycle, and averaged to remove the principle tidal component of the variability, and reveal the underlying mean flow. The transect lines, shown in Figure (2), were positioned to discern the inner pathways of the water that enters western Penobscot Bay as well as the route of the Penobscot River water that exits the system in the near-surface layer. The UWB and UEB transects coincide with the locations of the two inner bay buoys; the MPB transect spans the section that was originally hypothesized as the route through which the bulk of the inflowing EMCC water passes before eventually exiting the bay on the eastern side of Vinalhaven.

Figures (3-5) show the tidally-averaged salinity contours for sections MPB, UWB, and UEB respectively. Comparisons of these hydrographic sections show that freshest water (S<29.5) is found in the surface layers of section UEB. The second lowest surface

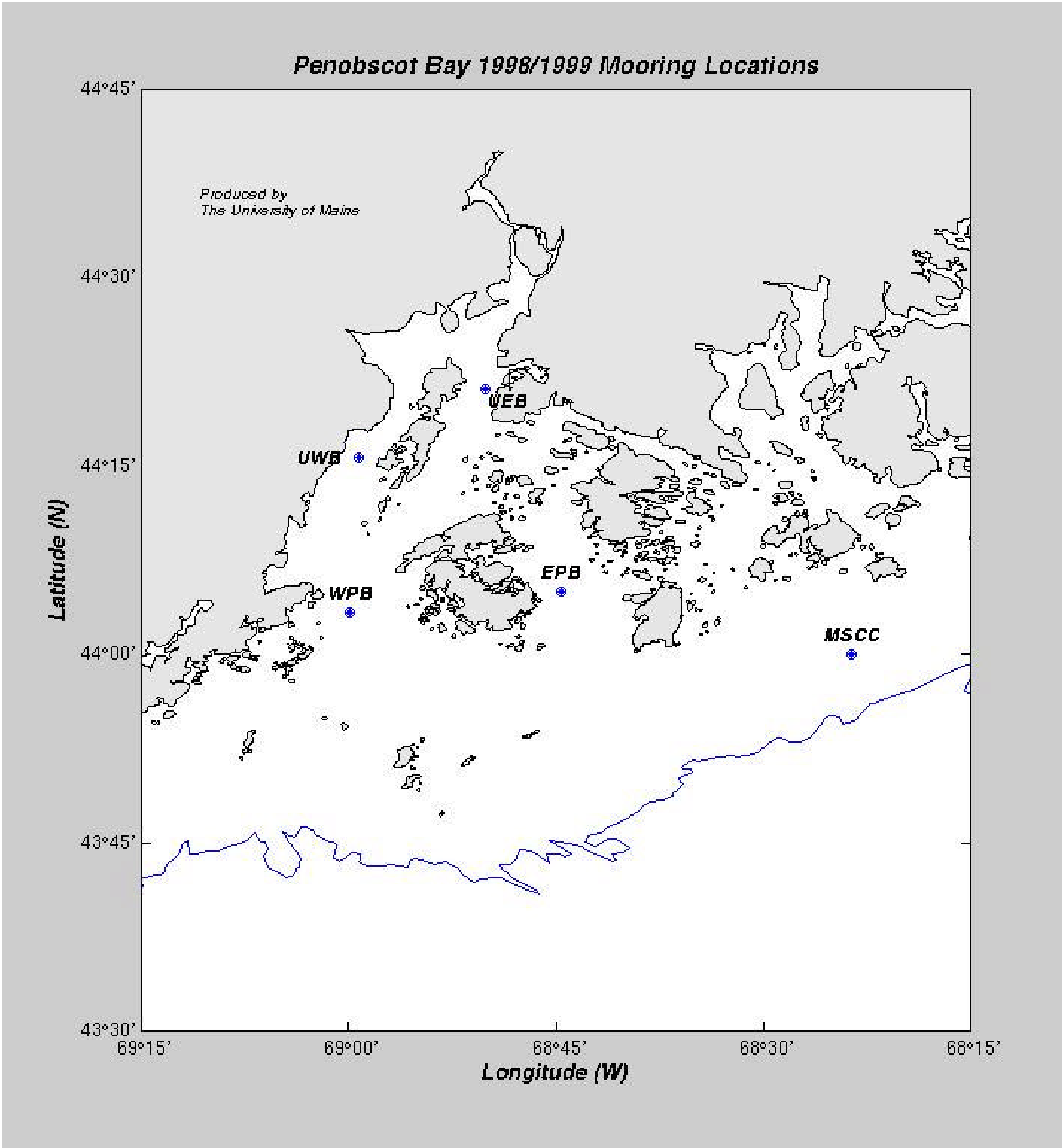

Figure 1. Locations of the five ODAS buoys used in the 1998-1999 field season.

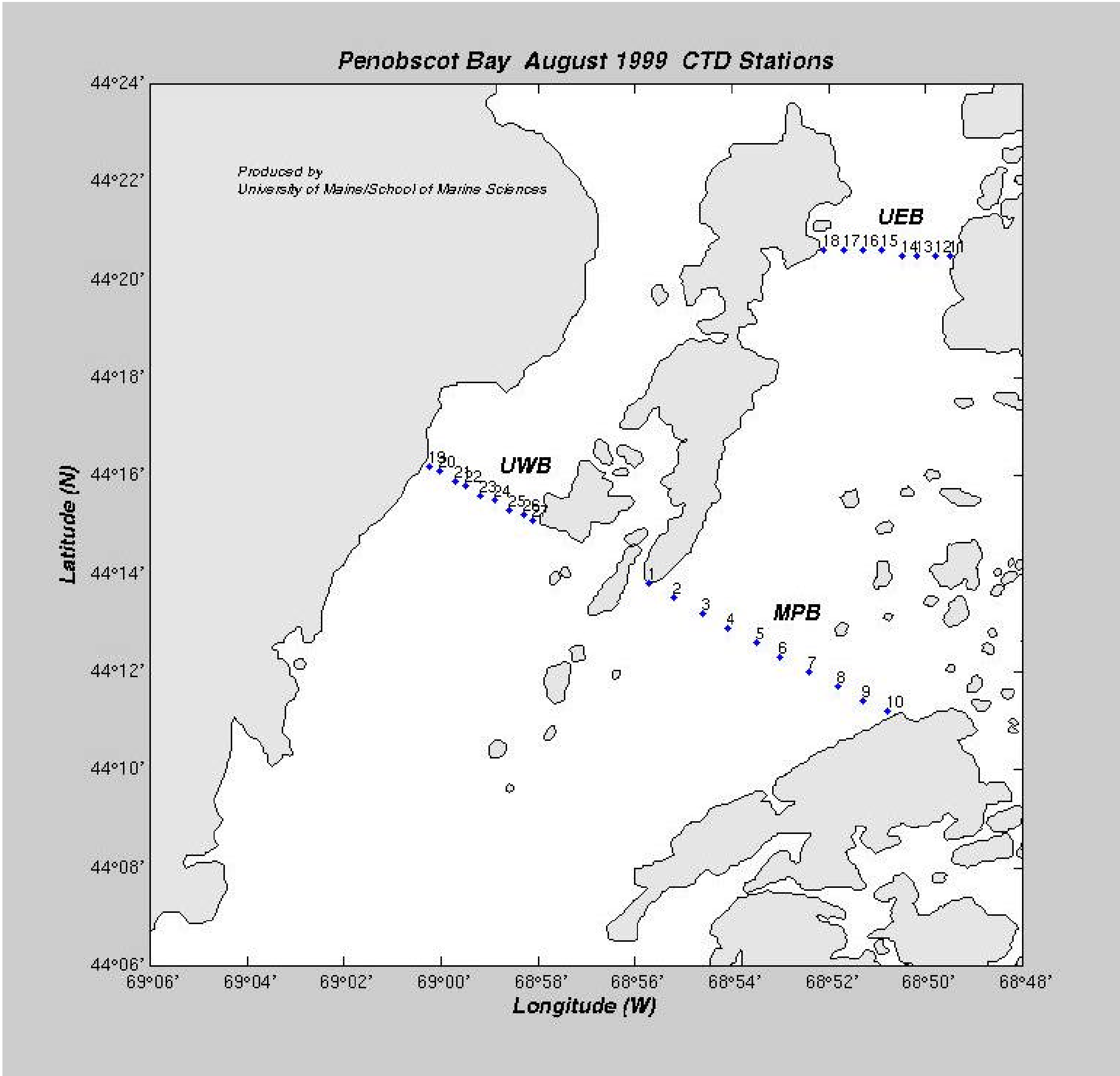

Figure 2. Acoustic Doppler and CTD stations used in tidally-averaged hydrographic and current study in upper Penobscot Bay.

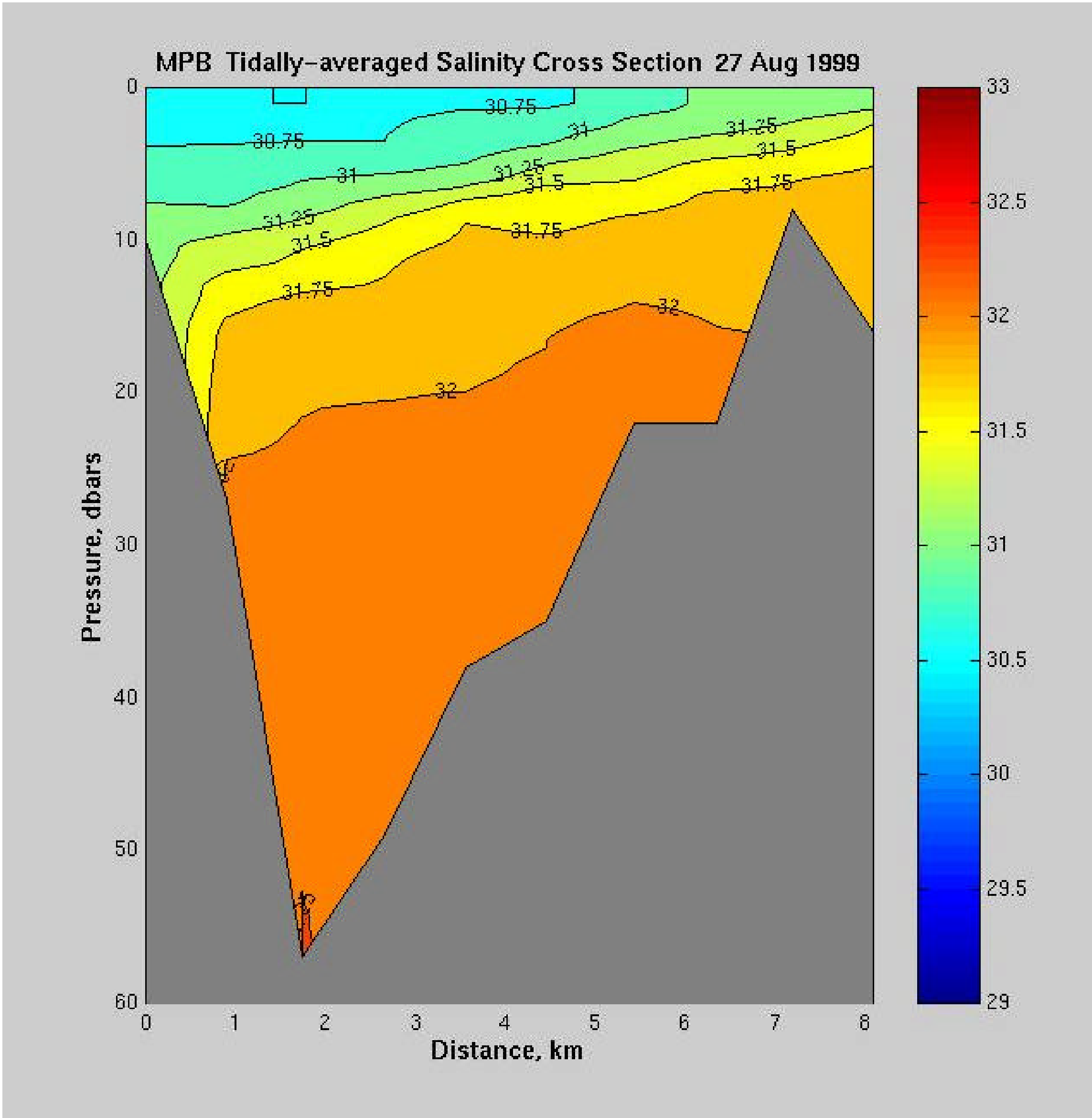

Figure 3. Tidally-averaged salinity section between Islesboro and North Haven.

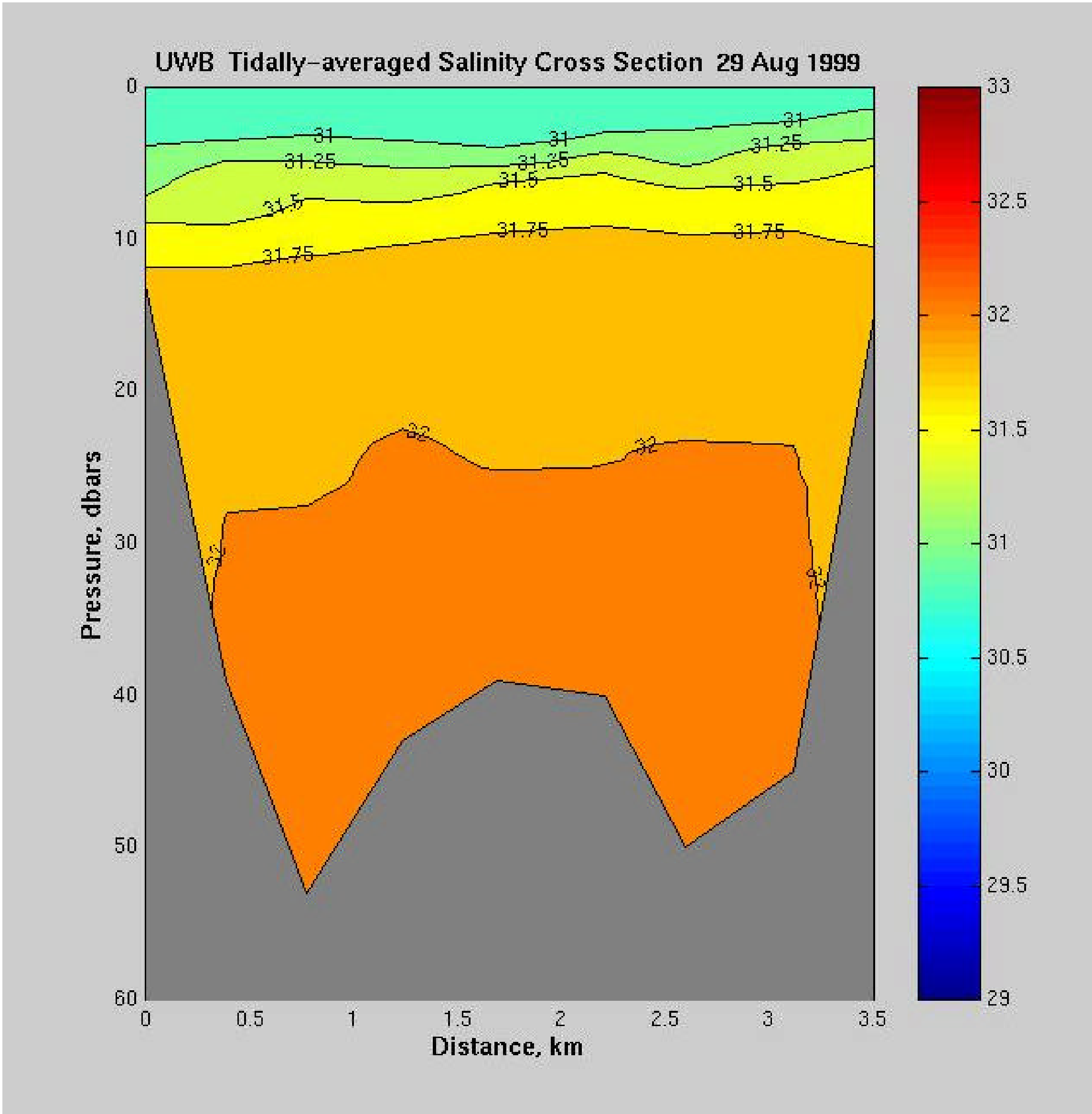

Figure 4. Tidally-averaged salinity section between Islesboro and the western shore of Penobscot Bay.

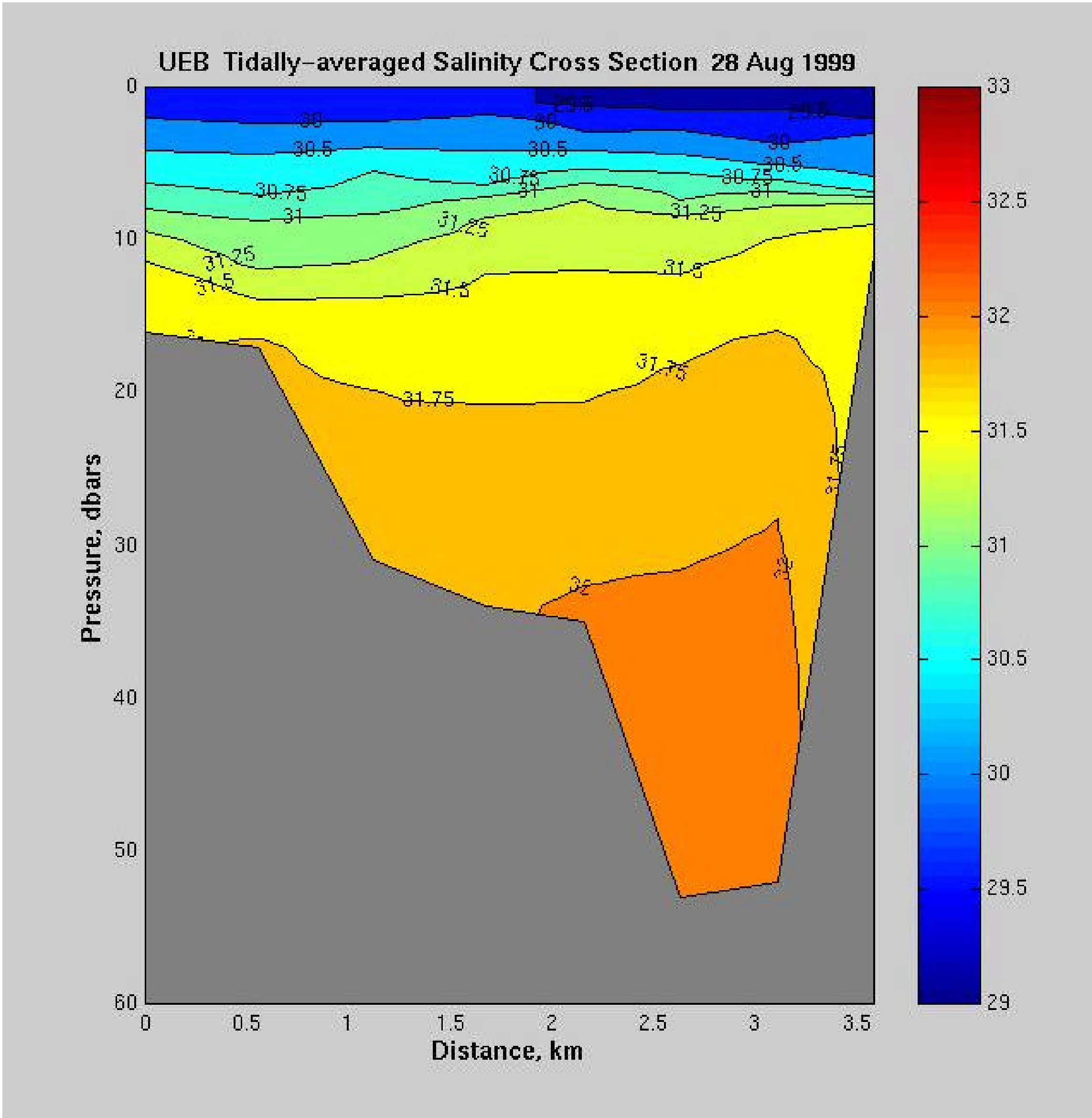

Figure 5. Tidally-averaged salinity section between Islesboro and the eastern shore of Penobscot Bay.

salinities (S<30.75) were observed at MPB; also on the eastern side of Islesboro. This evidence suggests that the river water flows seaward preferentially on the eastern side of Islesboro; data from earlier years of the Penobscot Bay Experiment has consistently shown that the fresh water from the river does not appear in the surface waters of the outflowing water east of Vinalhaven Island. Thus the primary exit route of Penobscot Bay River water appears to be east of Islesboro, and west of Vinalhaven, with a lessor amount of river-freshened water confined to a shallow layer on the west side of Islesboro.

Tidally-averaged velocity transects were obtained for sections UEB, UWB, and MPB by mounting a 600 kHz broadband Acoustic Doppler Current Profiler (ADCP) one meter below the water line of a small research vessel. The Doppler profiler was equipped with bottom track capabilities and was interfaced with a DGPS positioning system and an external fluxgate compass. After removal of data affected by acoustic side-lobe contamination and instrument noise, the good data bins were centered at depths ranging from 5 meters below the surface to about 8 meters off the bottom. Each section was sampled every 2.5 hours through the 12.42-hour tidal cycle. Residual current sections were obtained by temporally averaging the data, effectively removing the tidal currents. The residual currents in MPB and UWB sections were rotated to along-channel and cross-channel coordinates. The data from the UEB section did not require any coordinate rotation, since along-channel and cross-channel correspond to North and East, respectively.

The along-channel current residuals for section UEB (28 August, 1999) is shown in Figure 6. The figure shows that the flow was generally outward (south) in the upper 20 m with an indication of some counter flow (northward) within the first 0.5 km from the shore of Islesboro. In the deeper water, especially below 30 m, the net transport was to the north. By comparison with figure 5, showing the corresponding salinity section it is seen that the outflow through this section was primarily of a salinity <31.75. It is clear from this picture that the net transport through this section is outward (southward).

In contrast to the flow conditions at UEB, the outflow at UWB (Figure 7) was found to be limited to a thin surface layer of approximately 6 m depth. In addition, the observed outflow speeds were significantly slower than those observed at UEB. Below the surface layer the velocity was inward at speeds rarely exceeding 5 cm s^{-1}. The net transport in this section was upestuary. In combination with the results at section UEB, the net inward transport at UWB suggests an anticyclonic circulation around Islesboro. This situation is reminiscent of the anticyclonic gyre that has been deduced to flow around the combined island mass of Vinalhaven and North Haven.

The along-channel current residuals for section MBP (27 August, 1999) is shown in Figure 8. The data show clearly that there is a seaward residual flow through the section between Islesboro and North Haven islands in the upper 10 m, and an inward flow at greater depths. The net transport through the section is inward, as hypothesized from earlier results, with the strongest inflows tending toward the Islesboro-side of the channel. As in the case for UEB, the outflowing upper water is primarily of salinity less than 31.75.

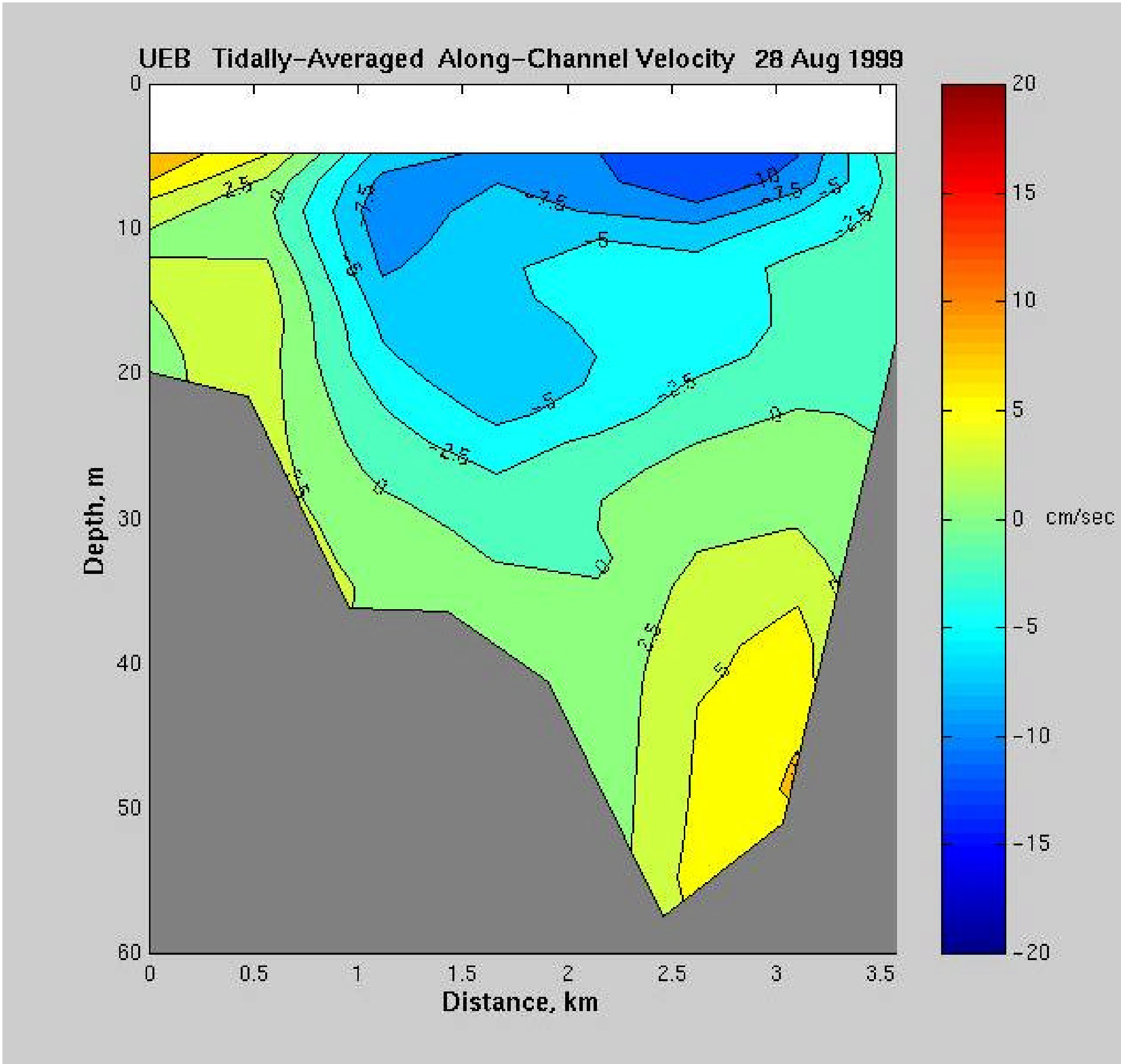

Figure 6. Tidally-average along-channel velocity for Upper East Bay between Islesboro and the eastern shore of Penobscot Bay.

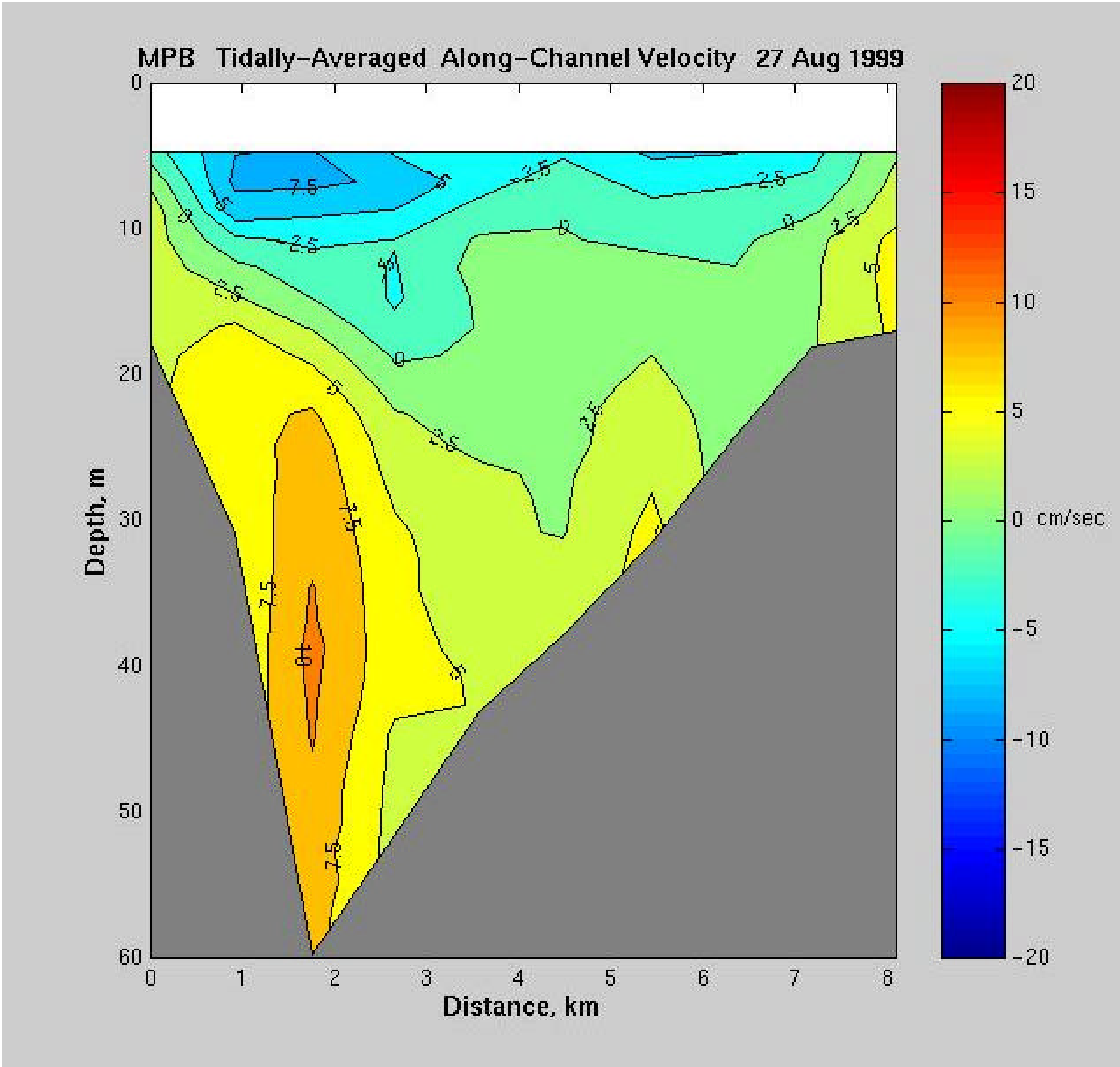

Figure 7. Tidally-average along-channel velocity between Islesboro and the North Haven.

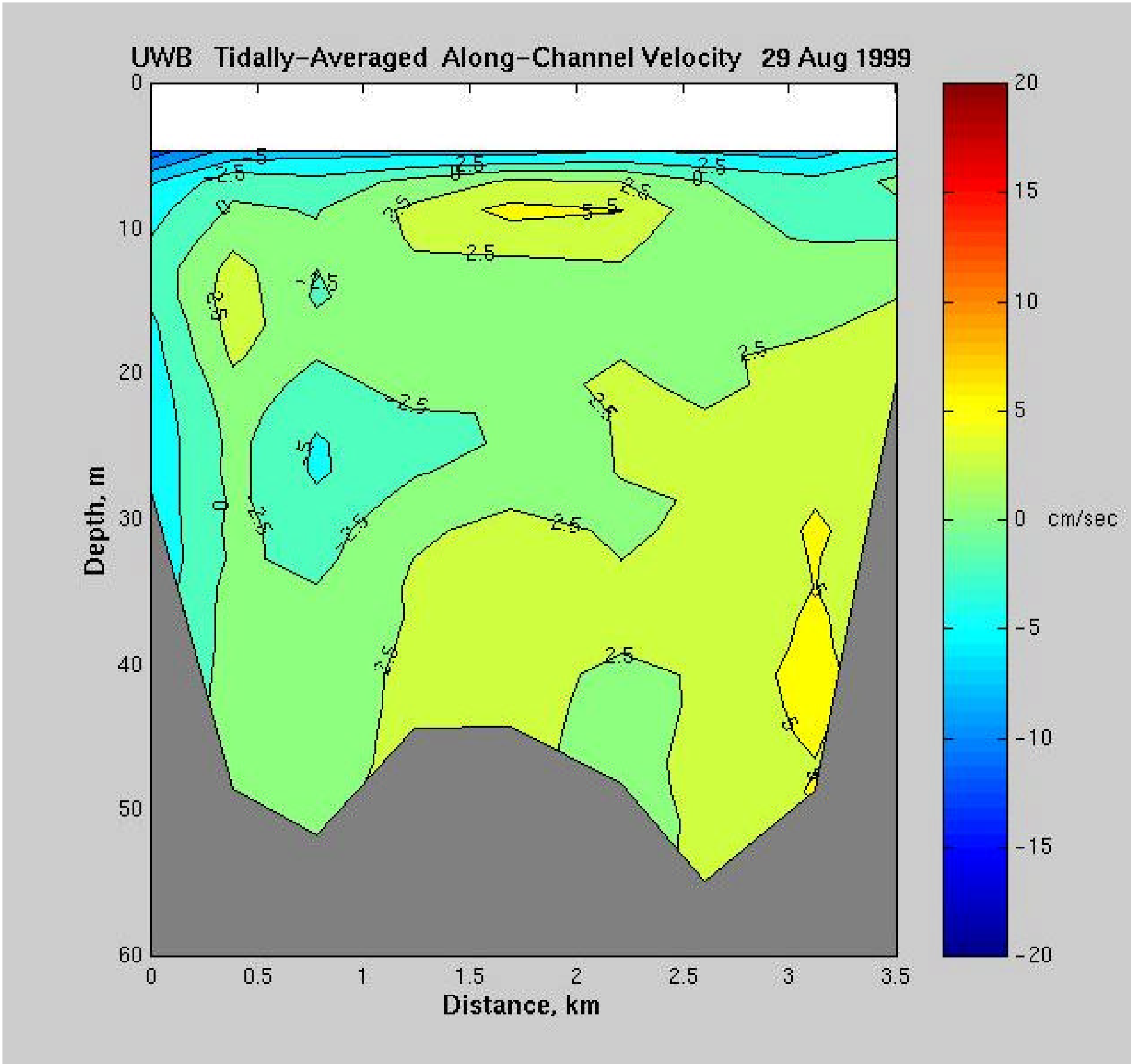

Figure 8.Tidally-average along-channel velocity for Upper West Bay between Islesboro and the western shore of Penobscot Bay.

The tidally averaged hydrographic and current transects suggest a summer circulation pattern with outflow in the upper few meters at all locations. The freshest water and the strongest surface flows are found east of Islesboro and west of Vinalhaven, suggesting that the river outflow occurs primarily at these locations. In contrast, deeper inflow at these three sections is strongest between Islesboro and North Haven (MPB). It is relatively weak but occupies most of the water column west of Islesboro (UWB) and weak and confined to somewhat less than half the water column in UEB. The circulation suggested is that the inflow (west of Vinalhaven) splits (unevenly) at Islesboro with the major part going east of the island. Part of this inflow continues inward to the Upper East Bay (UEB) but the majority of this transport probably turns eastward and eventually southward after passing North Haven and it finally exits the bay on the east side of Vinalhaven.

The vertically-averaged flow, or net transport is inward at transects MPB and UWB, and outward at UEB. This situation results in an anticyclonic flow around the northern end of Islesboro, and a convergence of net transport east of Islesboro. That is, the water flowing inward on the southeast side of Islesboro meets the outward flowing water on the northeast side of the island. This convergence probably results in the forcing of water eastward through the island archipelago northeast of North haven, where is likely forms the major part of the outflow that reenters the Gulf of Maine east of Vinalhaven.

Moored Time-Series Data:

Current Measurements:

Current time series measurements were made at 5 buoy locations (Figure 1). For all sites within the bay currents at 2m depth were measured using an in situ acoustic (travel time) current meter (manufactured by Falmouth Scientific Inc.). Deeper currents were measured using a broadband RDI 300 kHz Workhorse Acoustic Doppler Current Profiler (ADCP). The data were collected as half-hour averages with 4 m vertical resolution. The data have been filtered to remove tides and higher frequency oscillations, and are presented as time series “vector stick plots”. The directional convention is that the north/south component is plotted along the ordinate with northward being positive, and the east/west component of each vector is plotted from its time origin along the abscissa with eastward being positive. The speed, in cm s^{-1} is indicated by the length of the vector and may be measured against the scale on the ordinate.

The direct current measurements made at the outer Western Pen Bay Mooring site (WPB) are shown in Figure 9. This site has been monitored during two previous years and while some features of its temporal variability are predictable, there is also some significant new insight into the conditions at this important inflow site. These first measurements of the surface flow field (2m depth) confirm our earlier hypothesis that the surface currents are predominantly outward throughout the year. They are quite strong, with maximum subtidal velocities approaching two knots. The surface outflow has a significant seasonal variation with the largest flows occurring in winter and spring, lowest flows in the summer, and intermediate flows in the fall. Comparison with the

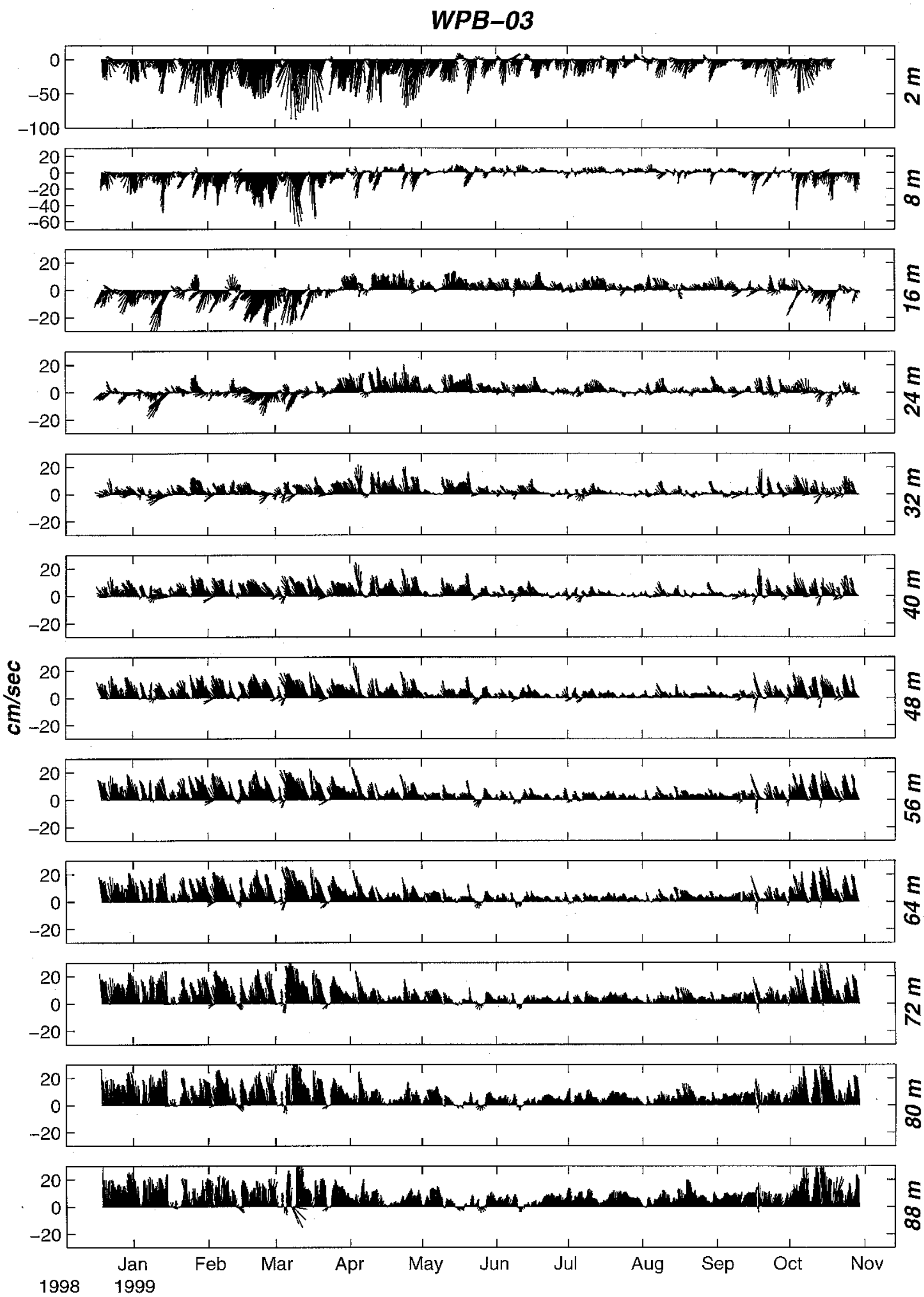

Figure 9. Vector stick plots of residual (tidally filtered) currents at West Pen Bay between Vinalhaven and the western shore of Penobscot Bay. The convention is that sticks pointing up or down depict Northward or Southward currents, while right or left depict Eastward and Westward currents.

record of the Penobscot River discharge as measured at the West Enfield Gauging station (Mangum et al., 1999) shows general, although not detailed, correlation.

The current data at 8m depth (the shallowest available from the ADCP) show marked seasonal transitions in the spring and fall (April and October). During the spring transition the currents change from strong outward flow to weakly inward flow, and during the fall transition conditions revert to strong outflow. This seasonal pattern is consistent with the observations of previous years; relatively deep (~20m) outflow during fall and winter, and shallow outflow in the spring/summer. Below 30 m depth the flow is into the bay throughout the year, although its strength is strongly modulated seasonally with strong inflows during Fall/Winter and weaker inflow during Spring/Summer.

In past years the subtidal deep inflow at WPB has approached a knot in strength. In 1999, the max subtidal currents were only half a knot. However, the most dramatic departure from previous results is the absence of the near-bottom outflow that characterized the summer season in the first two years of the study. In the past a consistent outflow was observed below about 70 m depth. This unexpected feature of the moored current meter records was verified by the shipboard Doppler surveys, and was found to be asymmetrically distributed toward the western side of the channel (Pettigrew, 1998). In 1999, not only is there no evidence of the deep summer outflow, but in fact the near bottom inflow is a local maximum. The absence of the near-bottom outflow in 1999 is an interesting development that may be related to the overall weakness of the observed summer regime in 1999. If a reduced outflow existed it may have been confined to regions west of the buoy location.

The corresponding current record for the eastern side of Vinalhaven (EPB), is shown in Figure 10. As in previous years, the surface currents at EPB were notably steadier that the currents at WPB. Since EPB is the net outflow location, and WPB the net inflow location, the lack of detailed correlation between the two records suggest storage and loss of bay volume at subtidal frequencies. That is, during periods of relatively high inflow water is gained by the bay system, while during periods of relatively low inflow water is lost from the bay system. In comparison with results from previous years, the outflow currents in penetrated deeper in 1999.

The winds and direct current measurements made at the outer Upper West Pen Bay mooring site (UWB) are shown in Figure 11. A strong seasonal signal is evident at this location; as usual, the subtidal currents are relatively weak during the summer. At 2 m depth, winter and spring currents are strongly seaward with peak values approaching one knot. In contrast, during the summer season the currents are oscillatory with a weak seaward mean. At 8 m depth (the shallowest ADCP data) the mean flow is inward. In fact, mean flows are inward at all depths 8m and below, although during summer the mean flow is very nearly zero below 24 m. The net transport in this channel is into the bay.

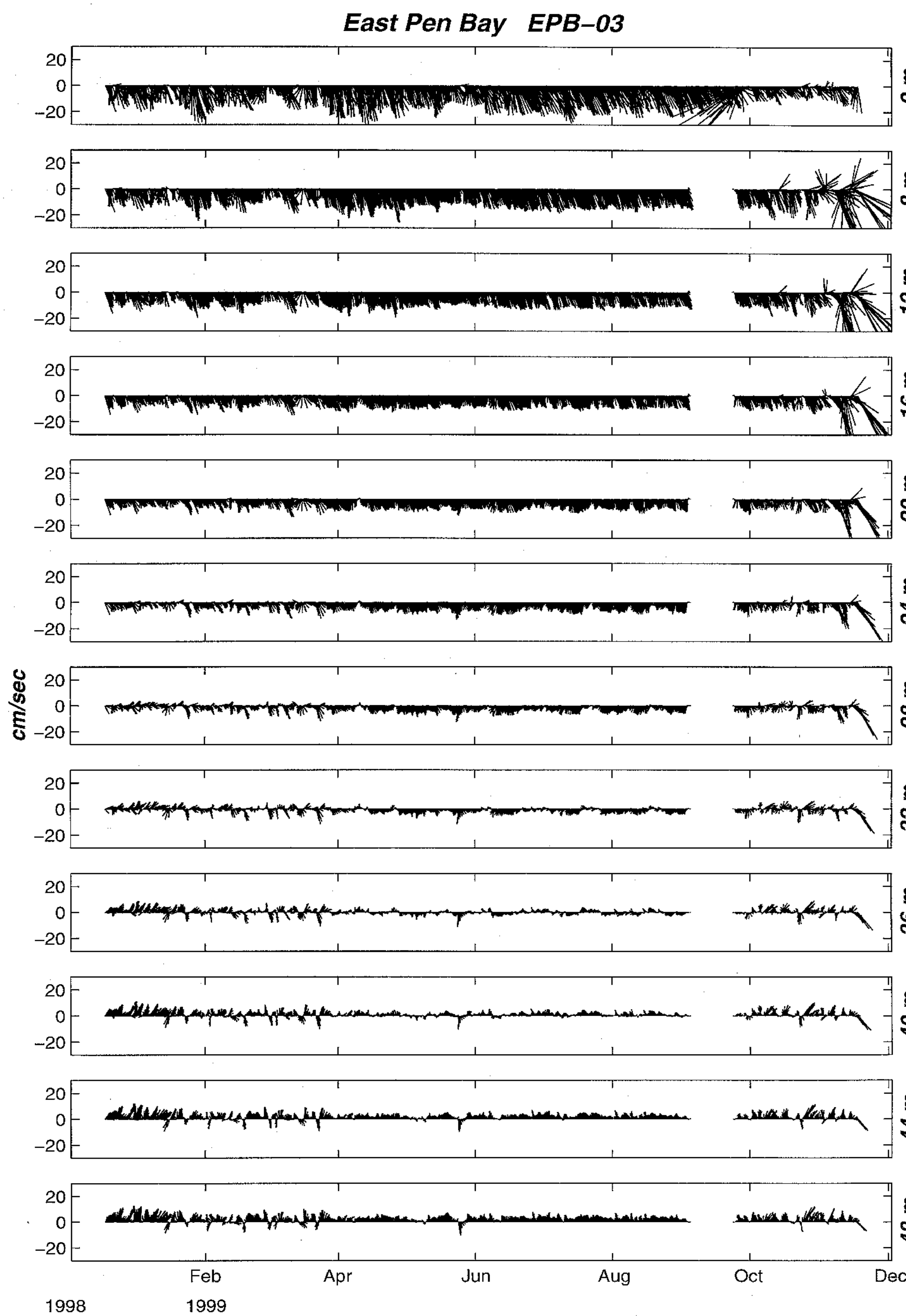

Figure 10. Vector stick plots of residual (tidally filtered) currents at East Pen Bay between Vinalhaven and the eastern shore of Penobscot Bay. The convention is that sticks pointing up or down depict Northward or Southward currents, while right or left depict Eastward or Westward flow.

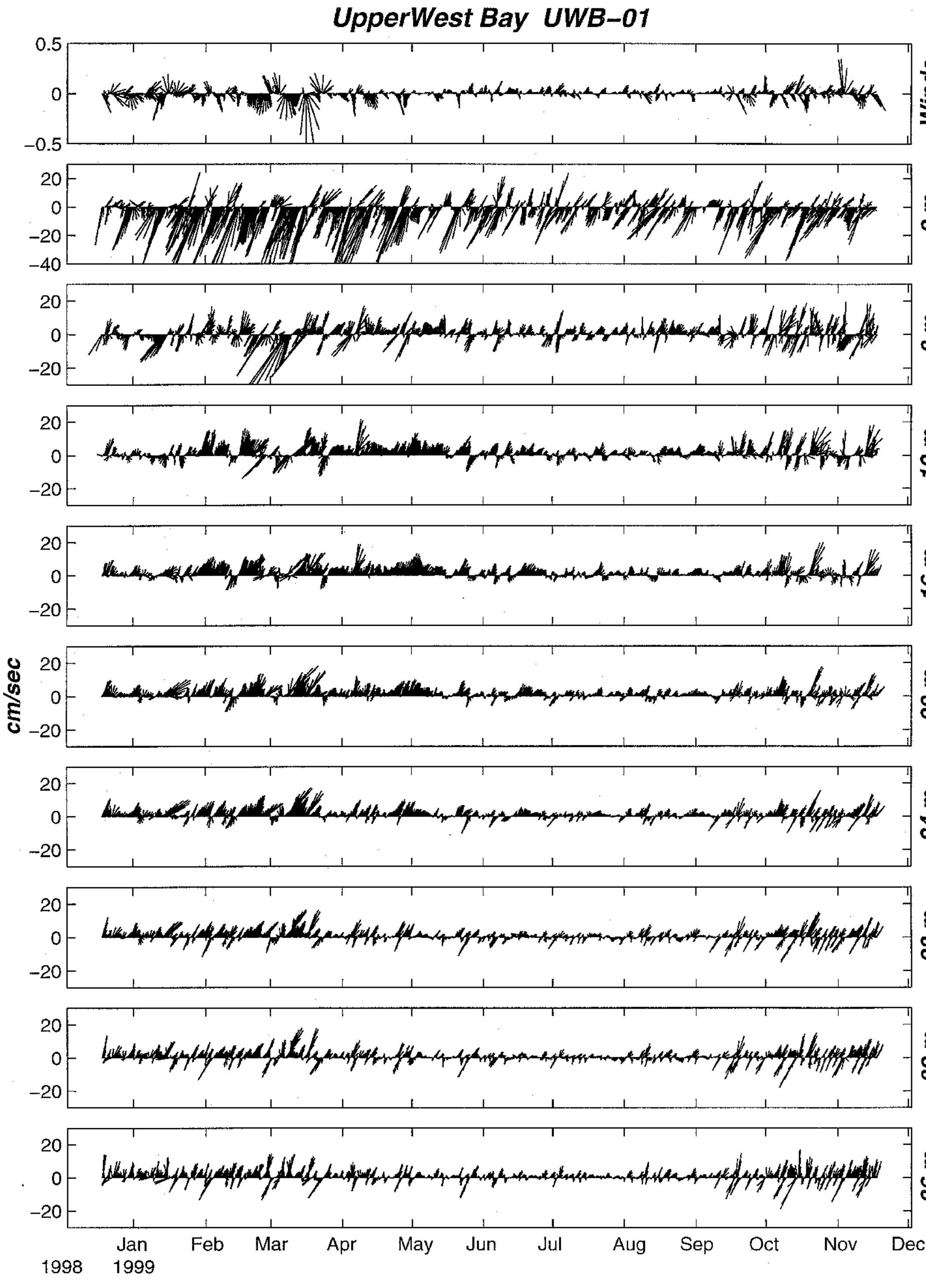

Figure 11. Vector stick plots of residual (tidally filtered) currents at Upper West Pen Bay between Islesboro and the western shore of Penobscot Bay. The convention is that sticks pointing up or down depict Northward or Southward currents, while right or left depict Eastward or Westward flow.

As shown in Figure 12, the Upper East Bay (UEB) 2 m outflow is stronger and steadier than that observed at UWB. While the net outflow is observed to penetrate to about 20 m throughout the year, it is clearly weakest during the summer season. Below about 30 m a net inflow is seen throughout the year. The Inflow becomes stronger and steadier with increasing depth. The net transport in this region is seaward. This net outflow is necessary to balance the net inflow in the UWB section and to export the Penobscot River flow.

Time series measurements of the Eastern Maine Coastal Current (EMCC) are shown in Figure 13. By comparison with the EMCC data of Year II of the Pen Bay Experiment, the currents were diminished. This finding is consistent with the generally weaker circulation observed within the Bay and the idea that the Penobscot Bay circulation and the EMCC are coupled. In the beginning of October a considerable disturbance to the normal southwestward EMCC flow regime occurred. The variance increased markedly a depth, and below 40, the mean flow direction reversed from the usual southwestward to northeastward. Since this change is coincident with the seasonal transition noted at the buoys within the interior of Penobscot Bay, it suggests that the seasonal transition within the Bay is linked to seasonal changes in the coastal current system. It is noteworthy that the relatively steady outflow at 2 m depth in EPB decreased abruptly at this same time.

Tidally-averaged Doppler current sections and the moored current measurements suggest a mean transport pattern that is schematically illustrated in Figure 14. The pattern reveals a complex anticyclonic circulation pattern with gyre-like pathways around the islands of Vinalhaven / North Haven and Islesboro. While these mean patterns reflect the vertically-averaged flow, or transport, the surface flow is seaward throughout the Bay.

Times series data of temperature and salinity at depths of 1, 14, and 38 m were obtained at WPB, EPB, and UEB. Due to decreased water depth at UWB the hydrographic time series were measured at 1, 14, and 32 m. In the EMCC (MSC) the measurements were made at two depths; 8 and 40 m. Filtered versions of these data are shown Mangum et al.(1999), which is also available at http://gyre.umeoce.maine.edu. Data show that the greatest salinity short-term fluctuations occurred in the spring and fall, and that 1 m salinity fluctuations were an order of magnitude greater at UEB than at EPB, while the fluctuations at the two western stations were intermediate, with those at UWB being about 1/3 larger than those at WPB. These results suggest that a significant amount of mixing occurred by the time the fresh surface layer exited the bay.

FUTURE WORK:

Additional analysis and field measurements need to be performed before we can have confidence in the interpretations presented above. It is imperative that direct Lagrangian current measurements (tracked drifters) to directly confirm the circulation pattern hypothesized in this report. Since the mean near-surface flows have now been confirmed to be seaward at all locations in the bay, it is important to rethink the mechanisms by which lobster larvae are delivered to the western region of the outer bay. Surface inflow

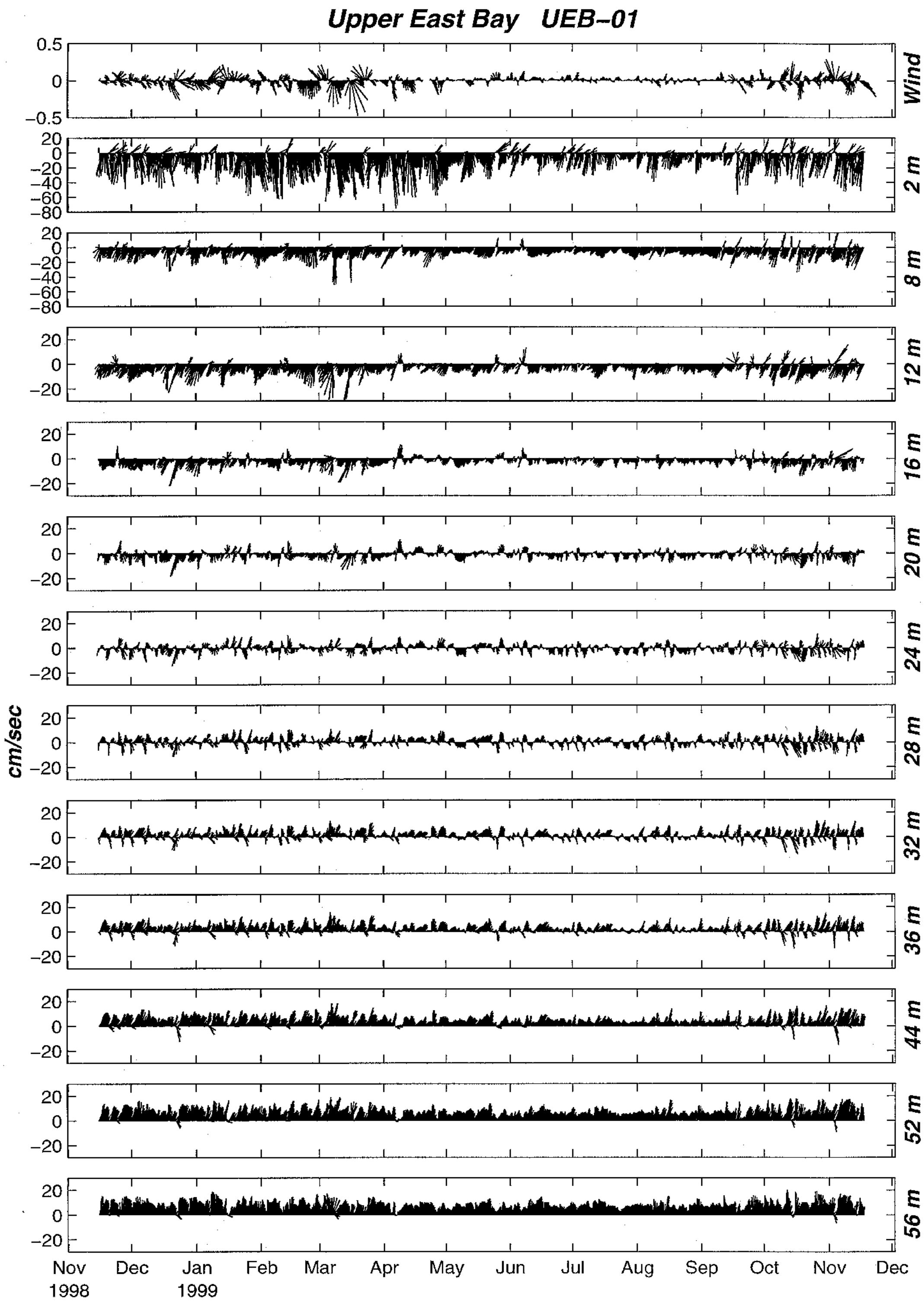

Figure 12. Vector stick plots of residual (tidally filtered) currents at Upper East Pen Bay between Islesboro and the eastern shore of Penobscot Bay. The convention is that sticks pointing up or down depict Northward or Southward currents, while right or left depict Eastward or Westward flow.

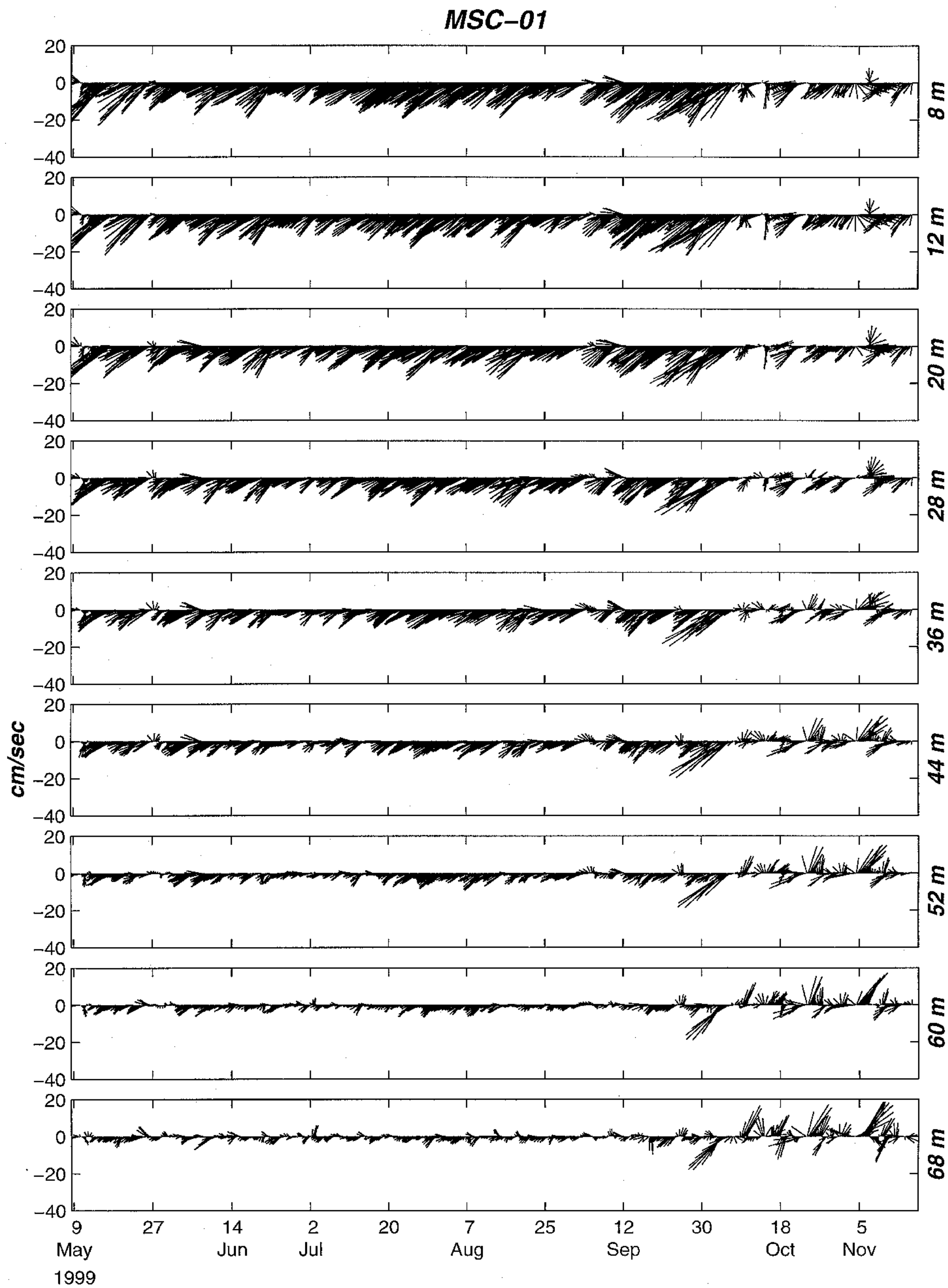

Figure 13. Vector stick plots of residual (tidally filtered) currents at station MSC in the Eastern Maine Coastal Current to the southeast of Penobscot Bay. The convention is that sticks pointing up or down depict Northward or Southward currents, while right or left depict Eastward or Westward flow.

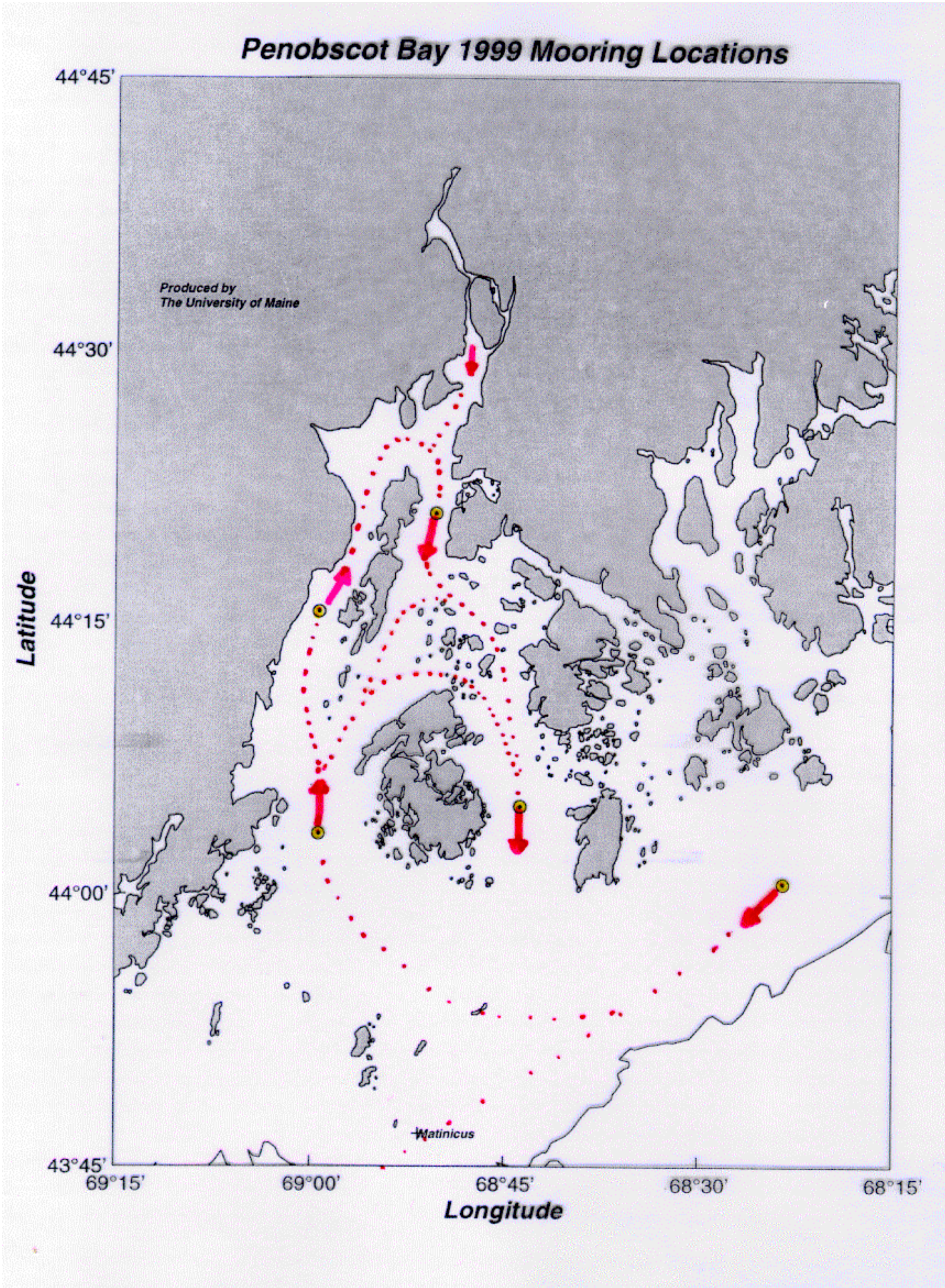

Figure 14. Mean depth-averaged circulation pattern in Penobscot Bay.

episodes are rare, especially in the outer bay, so the issue of timing and/or vertical migrations may be of crucial importance to the success of the fishery.

In the forth year of our experimental effort we will be using satellite-tracked drifters to test the hypothesis that subsurface waters enter western Penobscot Bay, generally circulate clockwise, and then exit on the western side of Vinalhaven Island. Moored current measurements west of Vinalhaven Island in year III did not show the three-layer flow that was observed in the previous two years (specifically the deep outflow at WPB was not observed). Doppler transects performed in previous years and numerical modeling results (Xue et al, 2000) suggest that the deep outflow may be confined to the western side of the deep channel west of Vinalhaven. Using two buoys in Lower West Bay (LWB) section will help clarify this issue and determine if transport estimated from monitoring buoys in this vicinity are sensitive to their exact location.

SUMMARY AND CONCLUSIONS:

I. The freshening influence of the Penobscot River observed during the spring is clear only on the western side of the bay. Within the western bay, the major portion of the waters of riverine origin flow out of the bay in the channel on the eastern side of Islesboro, and continue on in the channel on the western side of Vinalhaven. Although some of the river water does flow southward on the western side of Islesboro, this flow quite shallow and relatively weak in terms of transport

II. The net transport that enters outer Penobscot Bay west of Vinalhaven appears to split south of Islesboro Island. The inflow that goes west of the island apparently circulates clockwise around the northern end of the Island where it joins the outflow from the Penobscot river. The major portion of the inflow goes to the east side of Islesboro where it presumably converges with the outflow observed at UEB, and is eventually deflected east and south through the island archipelago northeast of North Haven.

III. The directly measured mean surface currents were observed to be outward throughout the bay. Episodes of surface inflow were rare (especially in the outer bay), and appear to be related to wind forcing.

IV. There is some indication that the marked seasonal variation of the circulation, in which the surface outflow deepens significantly is correlated to changes in the EMCC which appears to undergo large fluctuations and even reversals starting in the fall.

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References:

Brooks, D.A., 1994. A model study of the buoyancy-driven circulation in the Gulf of Maine. J. Phys. Oceangr., 24, 2387-2412.

Lynch, D.R., M.J. Holbrook, and C.E. Naimie, 1997. Dynamical influences on the Maine coastal current. Cont. Shelf Res.

L. Mangum, J. Wallinga, R. Stessel, N. Pettigrew, 2000. The Penobscot Bay Experiment: Moored Current Measurements During 1999 and Hydrographic/Current Survey from 27 - 29 August 1999. Data Report Reference 00-1, Physical Oceanography Group, University of Maine.

N.R. and J.D. Irish, 1983. An Evaluation of a Bottom-Mounted Doppler Acoustic Profiling Current Meter. Proceedings of Oceans '83, 182-186.

Pettigrew, N.R. Vernal Circulation Patterns and Processes in Penobscot Bay: Preliminary Interpretation of Data. A Final Report for Year II of the Penobscot Bay Experiment.

Pettigrew, N.R., D.W. Townsend, H. Xue, J. P. Wallinga, P. J. Brickley, and R. D. Hetland, 1998. Observations of the Eastern Maine Coastal Current and its Offshore Extensions in 1994. Journal of Geophysical Research, 103, C13, 30,623-30,639.