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

A Final Report for Year 4 of the Penobscot Bay Experiment

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INTRODUCTION:

The Penobscot Bay circulation experiment was designed four years ago as part of a collaborative, multidisciplinary study of the ecosystem of Penobscot Bay. In its early inception the circulation component was envisioned principally as a quantification of the anticipated classical estuarine pattern of circulation anticipated in one of the largest estuaries of the eastern seaboard. However, early results showed clearly that we first had much to learn about even the qualitative nature of the circulation patterns. Results of the first experimental season showed dramatically that the principal feature of the circulation pattern was not the classical estuarine pattern, but rather an unexpectedly vigorous and complex circulation that was characterized by an anticyclonic, or clockwise, gyre-like flow pattern in which net inflow occurred on the western side of Vinalhaven Island and net outflow occurred on the eastern side of the island. It was hypothesized that the source of the inflowing water was the Eastern Maine Coastal current that flows southwestward along the eastern Maine shelf during much of the year. Initial calculations suggested that the two-way exchange between the outer Bay and the Gulf of Maine shelf was dominated by the gyre-like circulation pattern, rather than the estuarine component associated with the outflow of the Penobscot River. It quickly became clear that this two-way exchange could play an important role in the ecosystem of the Bay and the Gulf, through the interplay of their circulation systems, and the exchange of nutrients and planktonic communities.

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. 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. 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.

The principal objectives of the third year of the circulation experiment were to expand the seasonal circulation study into the previously unmeasured inner Bay, to study the circulation linkages between the inner and outer Bays and the Eastern Maine Coastal Current (EMCC), and to monitor the here-to-fore unmeasured currents in the near-surface layer (2m). These objectives were achieved by deploying five buoys in the experiment (two in the inner Bay, two in the outer Bay, and one in the EMCC), adding acoustic current meters at 2 m depth on each of the four Bay buoys, and maintaining this coastal ocean observing system for a period of approximately 12 months.

The results of the third year of the Pen Bay experiment revealed much that was new or unexpected about the general and seasonal circulation pattern. While the freshening influence of the Penobscot River during the spring was known to be largely confined to the western side of the outer Bay the data from the inner Bay showed that, the major portion of the waters of riverine origin followed a pathway east of Islesboro and then continued 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.

SUMMARY OF RESULTS AFTER THE 1998-1999 FIELD YEAR:

I. 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 eastern side of Islesboro where it presumably converges with the outflow observed farther to the north. After convergence, the bulk of the transport is deflected east and south through the island archipelago northeast of North Haven and eventually flows southward out of the Bay on the eastern side of Vinalhaven.

II. 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.

III. 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.

YEAR-FOUR EXPERIMENTAL PLAN:

In the year-four proposal, there were three principal goals:

1. Directly verify the clockwise general circulation pattern in the intermediate waters of Penobscot Bay via tracked-drifter or dye studies;
2. Monitor the currents in the WPB site, which had been occupied for at least the summer season 1997-1999, in order to maintain a context for the interpretation of the Lagrangian (drifter or dye) measurements, and for the other experimental programs in the Penobscot Bay Experiment;
3. Attempt to correlate surface current fluctuations with surface temperature fluctuations in order to evaluate the feasibility of utilizing satellite-derived SST fields to deduce circulation features or changes in Penobscot Bay.

The newly-funded Gulf of Maine Ocean Observing System (GoMOOS) has chosen WPB as its first monitoring site in the Gulf of Maine. As a result, we were able to deploy a second buoy in the channel west of Vinalhaven using the Pen Bay funds that were freed up by GoMOOS. The placement of this second buoy allows the evaluation of the practice of estimating transport using current measurements from a single buoy. In addition, a second question that arose from the analysis of the Year 3 experiment was whether or not the observation of the deep western Penobscot Bay outflow was sensitive to small changes in the east-west position of the WPB buoy. The locations of the two buoys deployed in the Penobscot Bay Experiment (Year 4) are shown in Figure 1.

THE DRIFTER EXPERIMENT:

The purpose of the drifter experiment was to confirm directly the clockwise circulation that had been deduced from moored current measurements to occur around Vinalhaven and North Haven islands. Four satellite-tracked drifters were deployed in outer Penobscot Bay on September 7, and the last drifter was recovered on September 27. Three drifters were deployed in and east/west line at about 44^{o}06'N and another at about 44^{o}08'N just offshore of North Haven Island (see Figure 2). The positions were chosen to monitor the summer inflow in west Pen Bay and the drifters were drouged to follow the water at 15m. The three-drifter line was intended to map the trajectory of the inflowing waters around Islesboro and Vinalhaven. Since we had some doubt as to the ability of the drifters to survive without fouling on lobster gear or running aground, a single drifter deployed farther to the northeast in the channel between Islesboro and North Haven to improve the chances that at least one drifter would make the turn around North Haven and exit the Bay on the eastern side of Vinalhaven.

The drifters followed erratic tracks through the Bay acted upon by tidal currents, eddies, etc. Therefore the tracks shown in Figure 2 have been filtered to remove tides and fitted with a cubic spline for presentation purposes. The tracks are marked with a noontime asterisk to help delineate periods of fast and slow net flow.

The results show a complex and interesting flow pattern. For the first four days or so all the drifters behaved in a manner consistent with the general circulation pattern previously deduced (Figure 3); with one drifter apparently headed northward on the western side of Islesboro, and the other three moving into the Bay between Islesboro and North Haven. After a few days the near-surface outflow began to deepen and approach the 15 m depth of the drogues. As a result, the motion slowed and became erratic, and in most cases reversed and began to move out of the Bay. Never-the-less the results conformed were very well to our expectations for the anticyclonic circulation that had been deduced from the years of moored observations. Two of the drifters were apparently headed clockwise around the Vinalhaven / North Haven land masses when they ran aground; one in the island archipelago northeast of North Haven and the other on the north shore of North Haven. One of the two drifters was reset beyond the most shoal sections of the channel and eventually made a convincing transit southward on the eastern side of Vinalhaven, thus confirming the existence of the "Island Gyre".

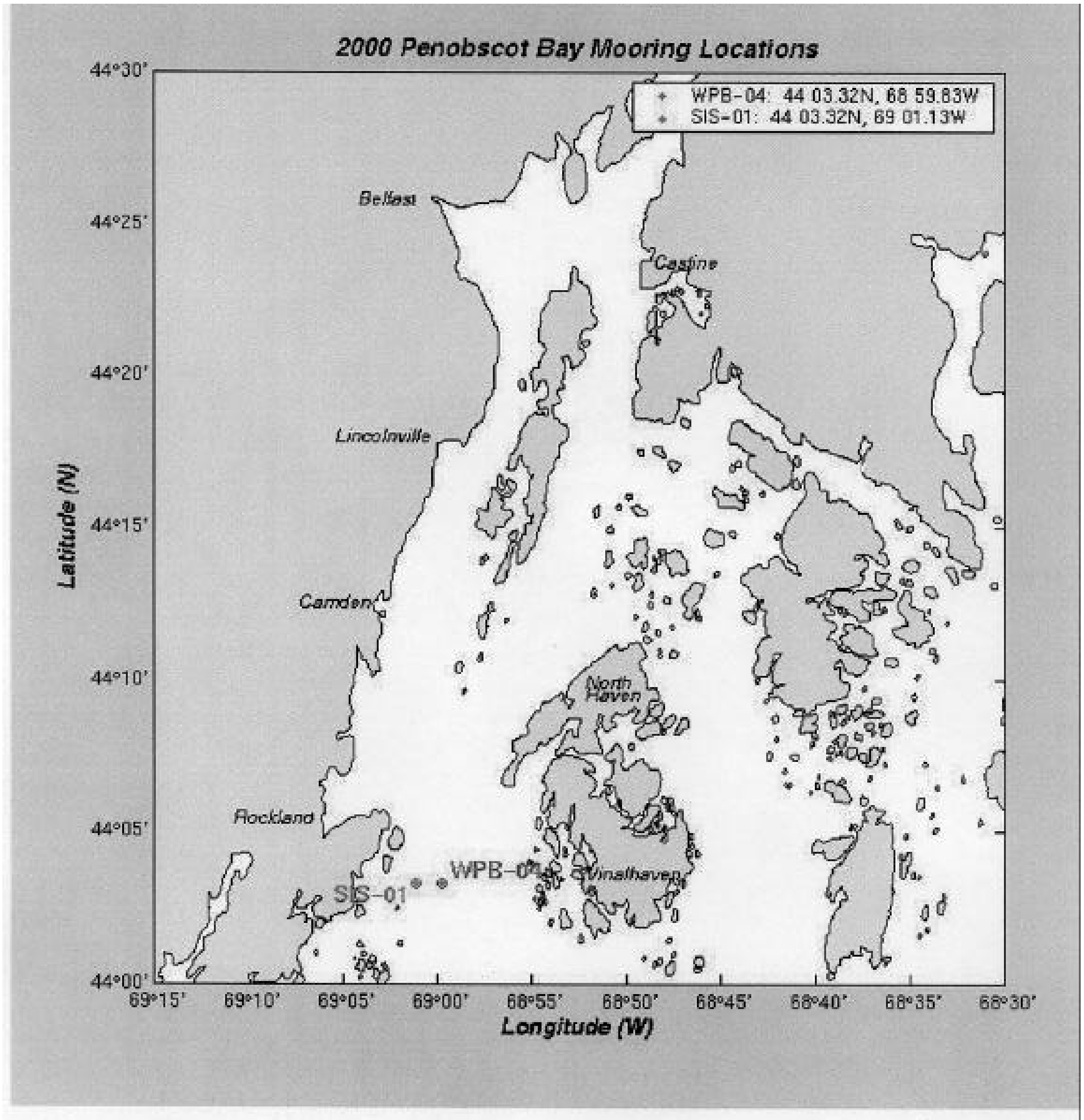

Figure 1. Locations of the two moorings in the 2000 Penobscot Bay Circulation Experiment.

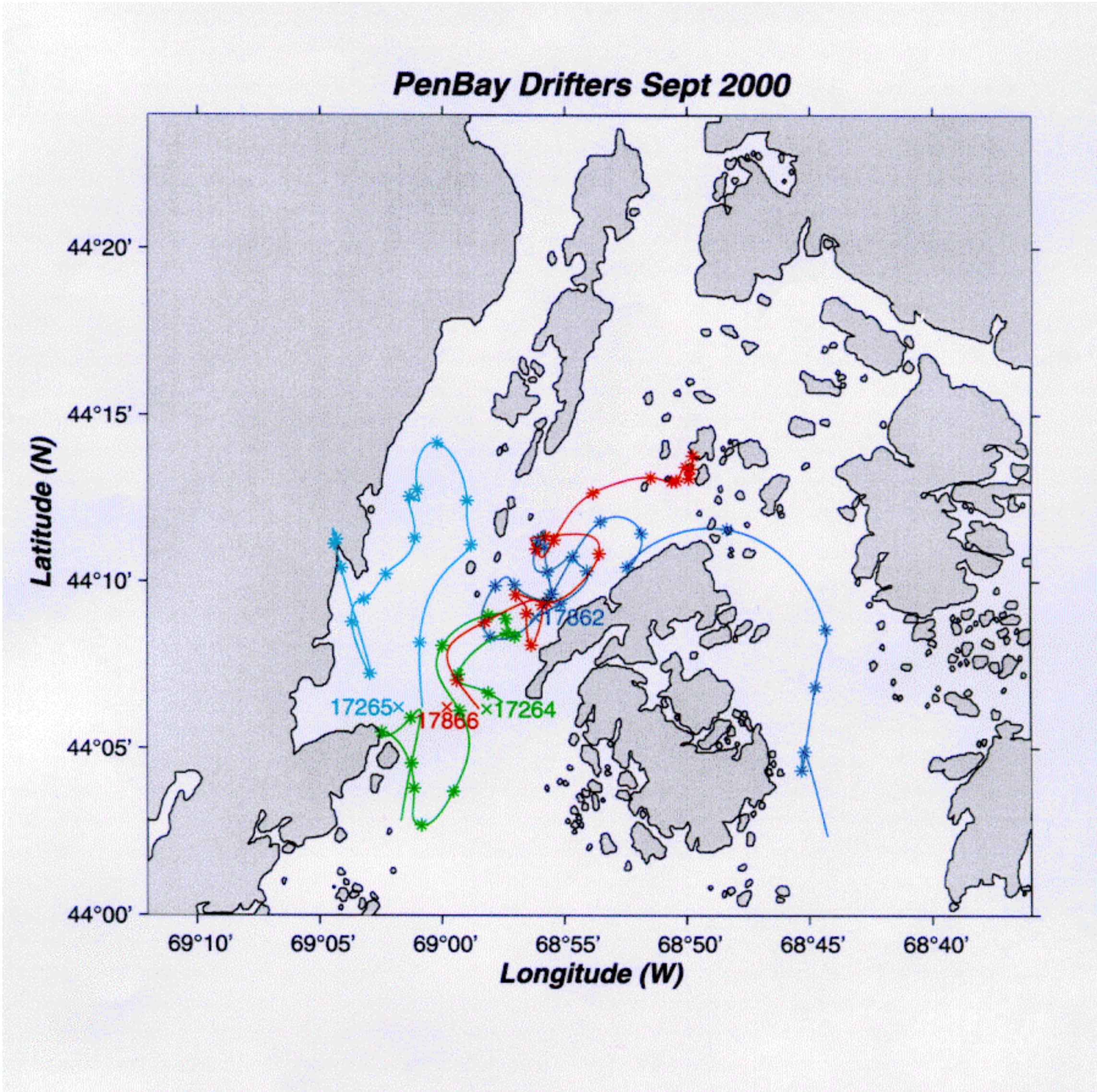

Figure 2. Drifter tracks from the satellite-tracked drifter experiment that ran from September 7-september 27, 2000. Starting locations of each of the four ARGOS drifters are denoted by an x, and daily (noon) positions are denoted by asterisks.

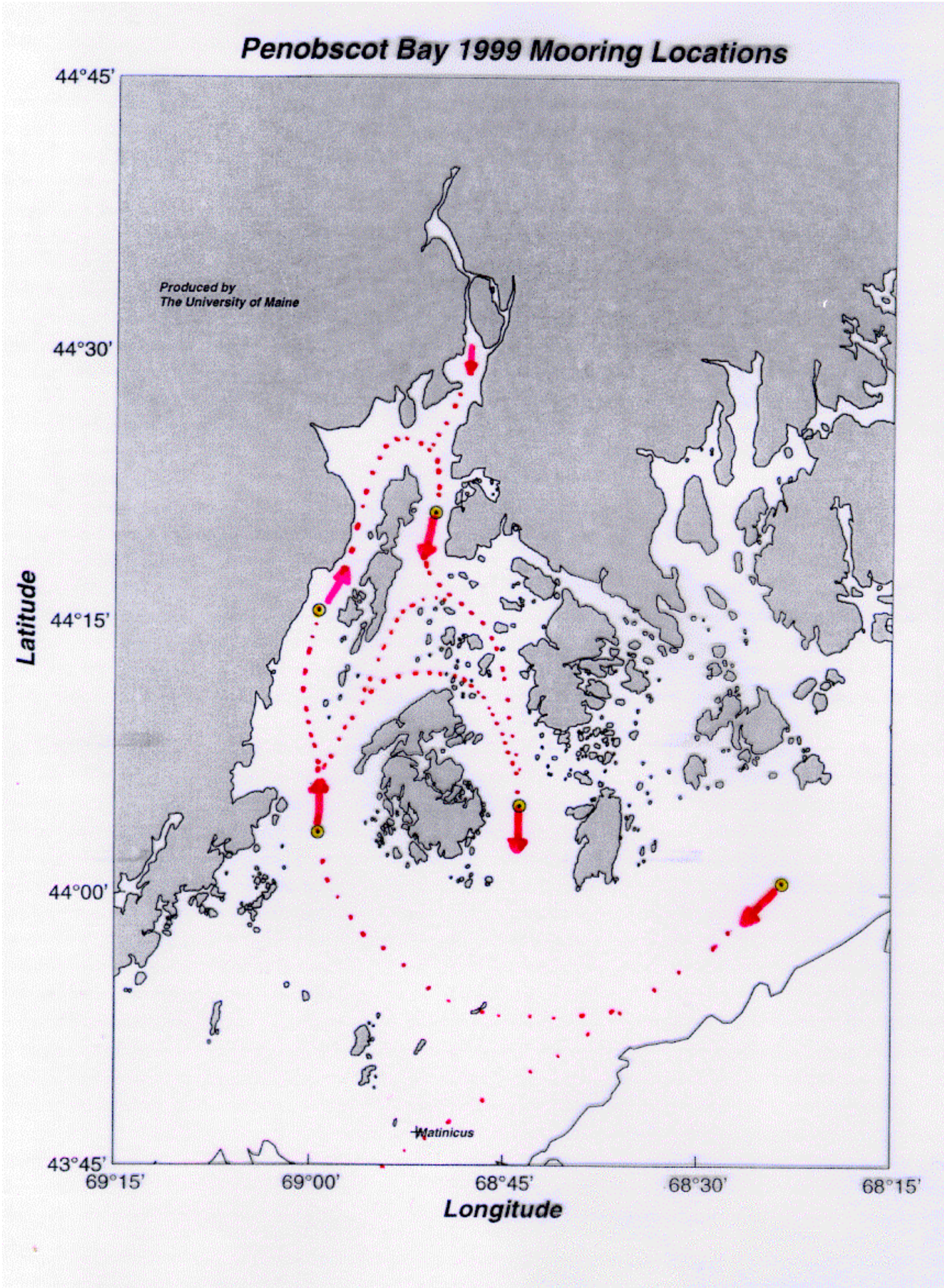

Figure 3. Mean depth averaged summer circulation pattern in Penobscot Bay deduced from moored current measurements in the 1998-1999 circulation experiment.

MOORED CURRENT MEASUREMENTS:

Current time series measurements were made at 2 buoy locations (Figure 1). For both 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 4. These data have been obtained via the real-time telemetry system since the mooring is presently still in the water. This site has been monitored during three previous years and while some features of its temporal variability are predictable. This year's measurements of the surface flow field (2m depth) confirm our earlier results that the surface currents are predominantly outward throughout the year. The Year 4 measurements, shown in Figure 4, began in July and extend through December 10. In comparison with the equivalent period of the 1999 field season, they are similar in strength throughout the summer season, but fail to show the strong fall transition to stronger outflow.

The current data at 10m depth (the shallowest available from the ADCP) show marked seasonal transition at the end of August, with the mean flow changing from in to out at that time. This seasonal pattern is consistent with the observations of previous years; relatively deep (~20m) outflow during fall and winter, and shallow outflow (<10 m) 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 (especially below50 m) and weaker inflow during Spring/Summer.

The buoy location for WPB was changed slightly from previous years in 1999 and 2000, and the near-bottom outflow that characterized the summer season in the first two years of the study was not observed. In addition, the observed deep inflow was relatively weak in 1999 and 2000. We believe that the weaker inflow was due to a weaker EMCC in 1999 and 2000 relative to 1998 as observed by moorings form the EcOHAB program. The absence of the near-bottom outflow may be related to the EMMC weakening as well, but it is also at least partly due to the fact that the buoy was moved eastward. Cross-channel Doppler surveys in 1998 showed that the deep outflow was asymmetrically distributed on the western side of the channel.

This year we placed a second mooring at a location approximately 2 km to the west of the WPB site (1 km west of the WPB site of Years one and two) that has been designated Sheep Island Shoals (SIS). The corresponding current record for SIS is shown in Figure 5. Although this buoy is believed to be still operational, its telemetry system malfunctioned in mid September. As a result, data are only shown for the summer

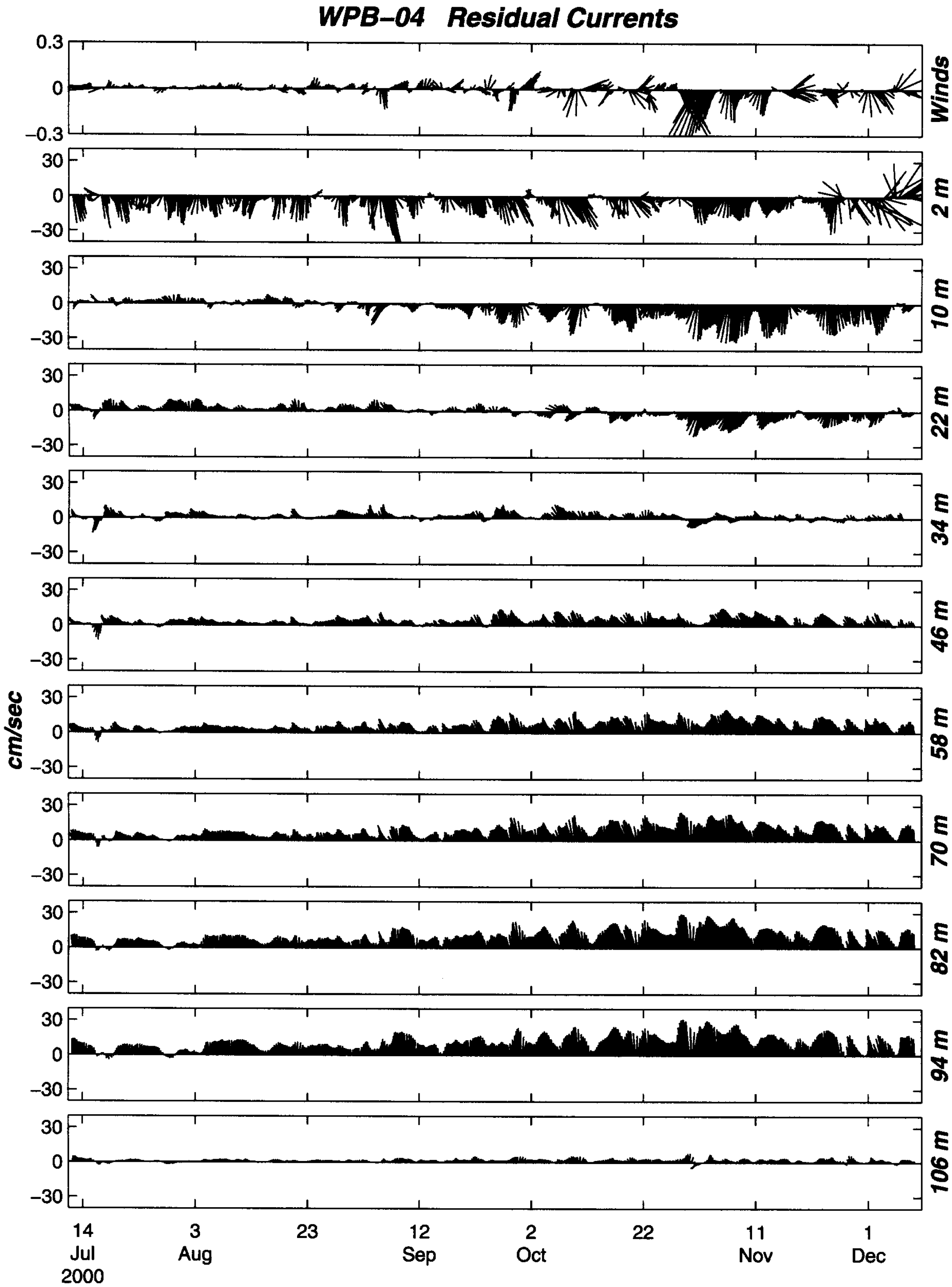

Figure 4. Vector stick plots of residual (tidally filtered) currents at West Pen Bay between Vinalhaven and the western shore of Penobscot Bay. The convention is that sticks pointing up or down depict Northward or Southward currents, while right or left depict Eastward and Westward currents.

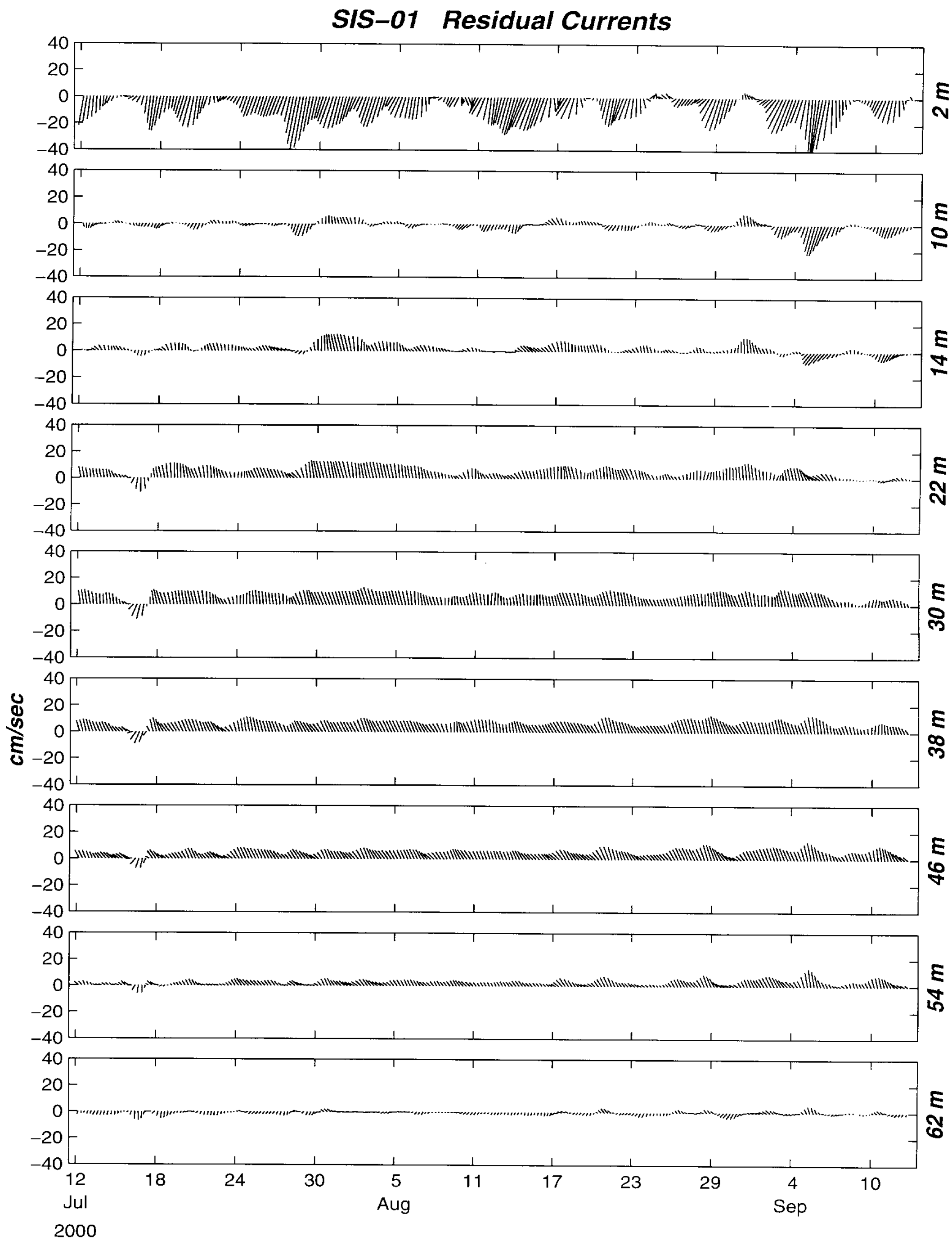

Figure 5. Vector stick plots of residual (tidally filtered) currents at Sheep Island Shoals (SIS) between Vinalhaven and the western shore of Penobscot Bay. The convention is that sticks pointing up or down depict Northward or Southward currents, while right or left depict Eastward and Westward currents.

season. In comparison with the observations at WPB very little difference was found in the upper 20 m. However, between 20 and 50 m the inflow at SIS was significantly stronger on average and a little steadier. Below 50 m the SIS currents dropped rapidly toward the shoaling bottom and, infact, reversed at about 58 m.

The mean comparison between the SIS and WPB current measurements is shown in Figure 6, which shows mean profiles for the period July 10 – September 1. Both moorings show strong outflow in the near surface with a current reversal occurring at 8-10 m. Both moorings also show a weak westward flow (<0.05 m s^{-1}) throughout the water column.

Transport calculations for the summer season have been performed using each mooring separately and in combination. The results agree to within 10% error, with a best estimate of net inflow of 5.6×10^3 m^3 s^{-1}. In 1999 the estimate was 7.0×10^3 m^3 s^{-1}. These net transport figures may be compared to the estimates of the Penobscot River transport of 0.2×10^3 m^3 s^{-1} based upon the gauging station at West Enfield.

TEMPERATURE / VELOCITY CORRELATIONS AT 2M DEPTH:

An attempt to find a relationship between the near-surface current and temperature in Penobscot Bay, with the goal of eventually deducing something about the circulation from satellite SST measurements. Prior to the analysis, it was supposed that during periods in which there existed a surface temperature difference between the Bay and the coastal current water, fluctuations in the surface flow field would be reflected in changes in the temperature. For example, during the summer season when the Bay and river waters are generally warmer than the EMCC, it would be anticipated that stronger outflow would result in warmer near surface temperatures, and outflow decreases, or even reversals, would result in colder temperatures.

In Figure 7, the top two panels show the West Pen Bay northward velocity and temperature records (filtered to remove tidal fluctuations) at 2 m depth for the Year 3 experiment, for which we had the most extensive records. A seasonally fitted signal is superimposed on both series for reference. There is a clear visual seasonal correlation with stronger outflow in the winter being related to low (winter) surface temperatures. The seasonal signals of velocity and temperature were in phase with the strongest outflow and lowest temperatures co-occurring in March, and the maximum temperature and the minimum mean outflow co-occurring in August. These relationships were evident at other locations within the Bay as well.

In order to discern the higher-frequency correlation, which is of greater interest, the fitted seasonal signal was removed from both the velocity and temperature time series to produce the residual series. The residual time series of velocity and temperature are shown in the third and fourth panels, respectively, of Figure 7. A scatter plot and regression of the residual series for West Pen Bay are shown in Figure 8 . Clearly there is no significant statistical relationship between residual currents and temperature between the seasonal and tidal periods. The lack of correlation at the West pen Bay mooring site was also found at other sites within the Bay.

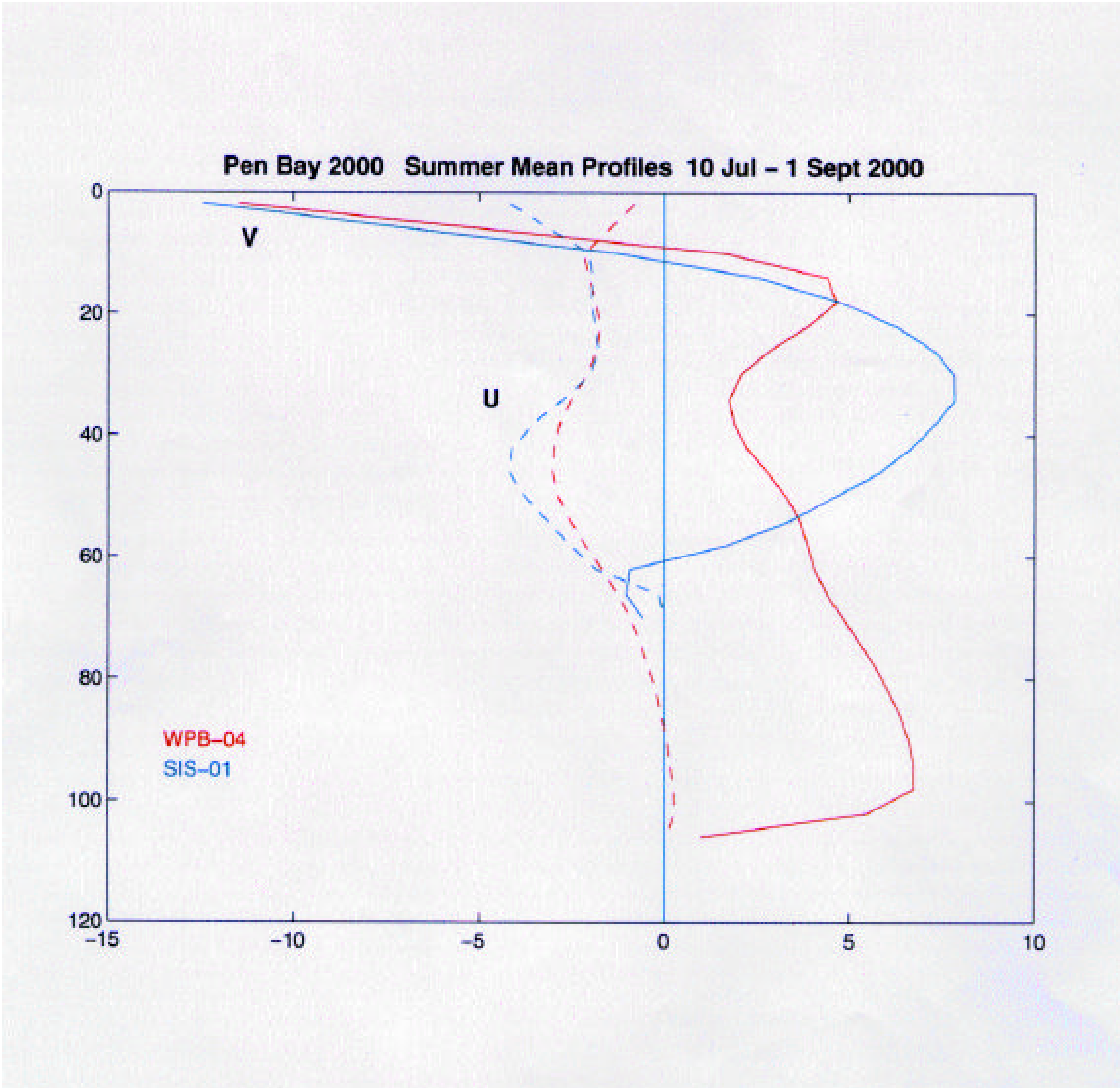

Figure 6. Comparison of mean profiles from the two buoys in Western Penobscot Bay 2000 (WPB and SIS).

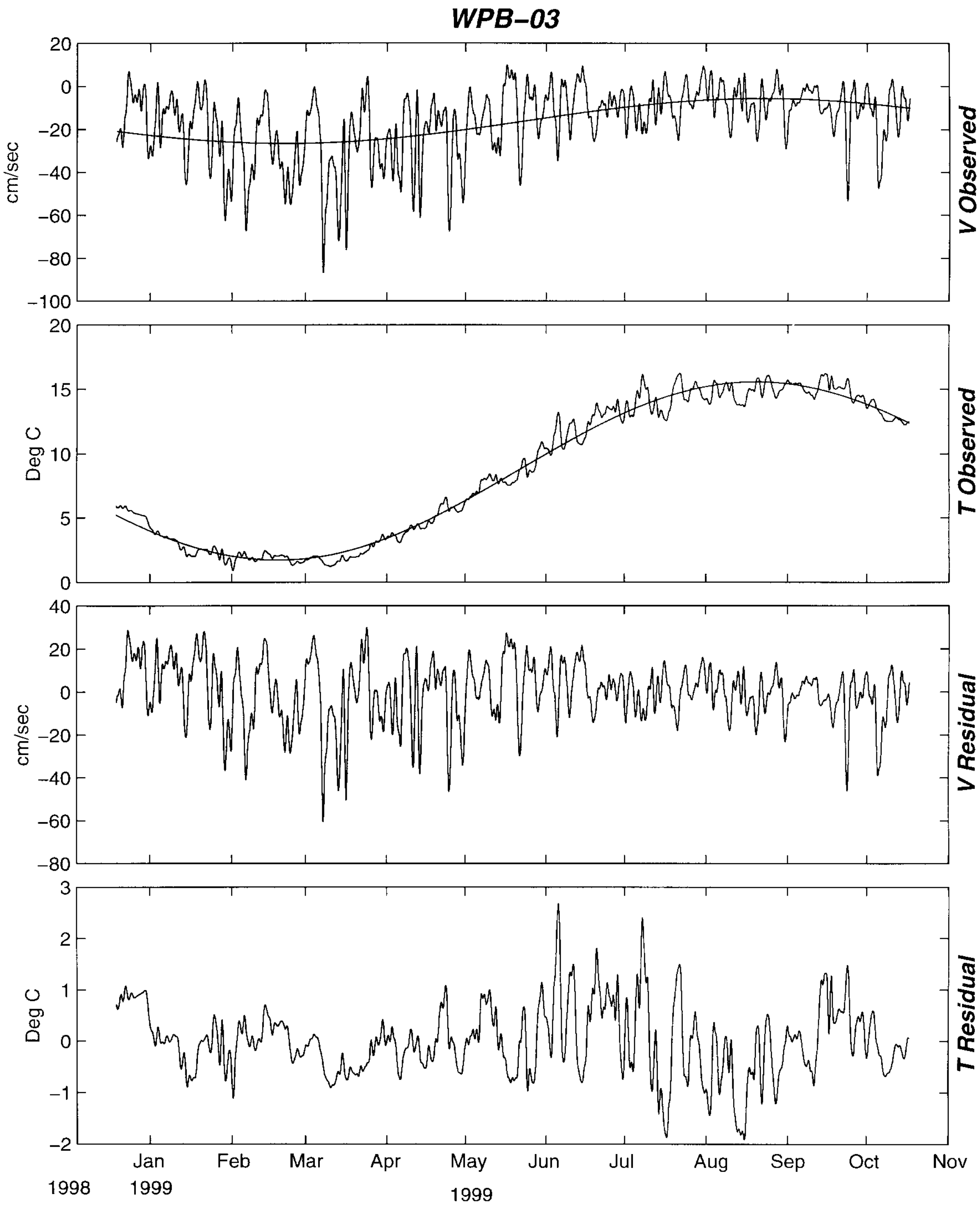

Figure 7. ***Top panel*****: Near-surface northward tidally-filtered currents and seasonal cycle from WPB mooring in 1998-1999 . Second panel: Near-surface tidally-filtered temperature and seasonal cycle from WPB mooring in 1998-1999. Third panel: Near-surface tidally-filtered northward currents with seasonal cycle removed. Fourth panel: Near-surface surface tidally-filtered temperature with seasonal cycle removed.**

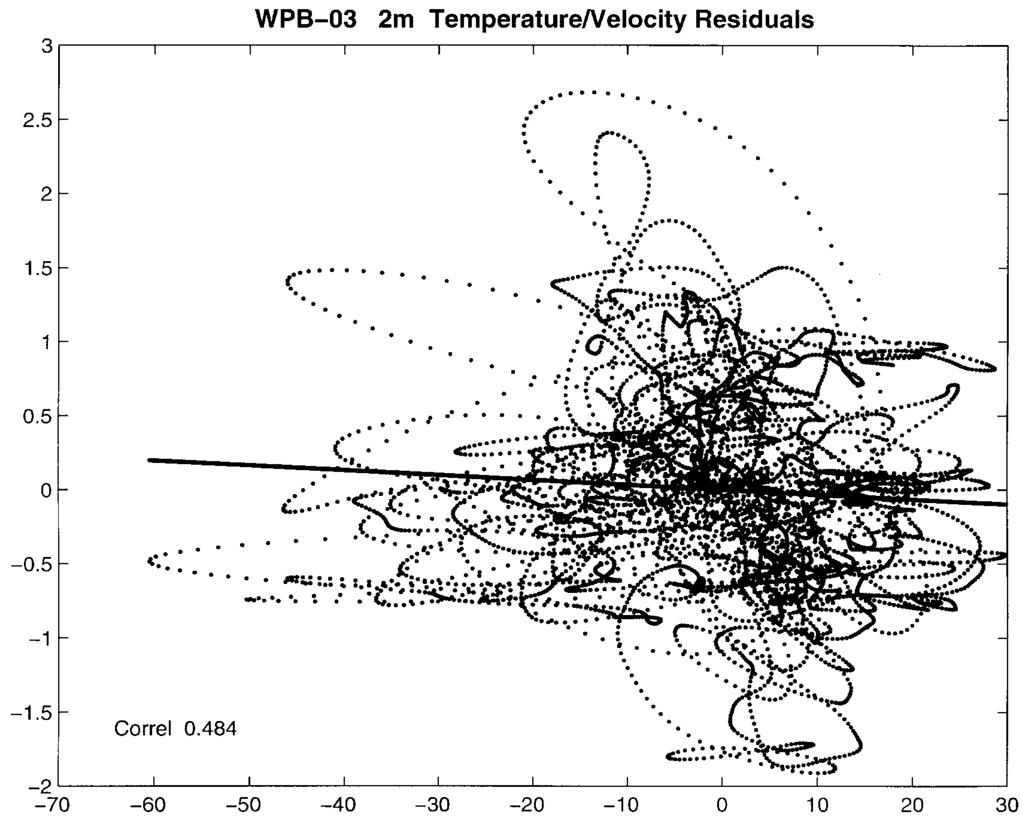

Figure 8. Scatter-plot of the Current and temperature residuals at 2 meters for the WPB mooring. Note lack of statistical correlation.

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) be repeated in the spring/summer so that the positive results achieved this year can be verified.

The most important task of year five of the Pen Bay project will be to perform detailed comparisons of the results from the first four years of field work (including tidal current analysis), and to attempt to integrate the data from other experimental components of the experiment including especially the model results, the satellite derived SST, and the lobster distribution data, and the hydrographic data collected in different years by many different investigators.

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 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. Finally, a detailed analysis of the wind-driven component of the surface currents will be an important addition to our understanding of the surface current fluctuations in the Bay.

SUMMARY AND CONCLUSIONS:

I. Although the Drifter Experiment was conducted during the fall transition period, the drifter tracks tended to verify the conceptual model of the summer flow pattern in Penobscot Bay. Drifters drouged at 15 m were consistent with the idea that the net transport that enters outer Penobscot Bay west of Vinalhaven appears to split south of Islesboro Island. The major portion of the inflow goes to the east side of Islesboro and is eventually deflected east and south through the island archipelago northeast of North Haven before turning southward east of Vinalhaven.

II. General inflow conditions in west of Vinalhaven were a little weaker than in previous years. Transport calculations using both moorings exceeded the calculation using only WPB by only 10%. Best estimates of the net inward transport dropped from 7.0 x 10^3 m^3 s^{-1} to 5.6 x 10^3 m^3 $s^{-1}$from 1999 to 200; a decrease of approximately 20%. Using only WPB in each year yielded a drop from 7.0 x 10^3 m^3 s^{-1} to 5.1 x 10^3 m^3 s^{-1}; a decrease of 27%. It is believed that the weaker inflow is related to a weakening of the EMCC.

III Correlations between 2 m currents and 2m temperature in the 1999 field season yielded only seasonal correlation. No significant correlation was found in the band between seasonal and tidal periods.

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